DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2009/30

Neogene dinocyst zonation in the eastern North Sea Basin, Denmark

Med dansk sammendrag

Karen Dybkjær & Stefan Piasecki

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

G E U S

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Dansk sammendrag

Neogen dinocyste zonering i det østlige Nordsø Bassin, Danmark

Karen Dybkjær og Stefan Piasecki

Her præsenteres en dinoflagellat cyste (dinocyste) zonering for hele den neogene lagserie i den østlige del af Nordsø Bassinet (Danmark). Zoneringen er baseret på data fra mere end 50 landboringer og 4 Nordsø boringer, samt omkring 25 blotninger. Der er opstillet 19 dinocyste zoner, hvoraf de fleste er defineret her. Zoneringen er korreleret med såvel tidligere publicerede dinocyste zoneringer indenfor Nordsø Bassinet (Köthe, 2003; Strauss et al., 2001; Munsterman og Brinkhuis, 2004) fra Nord Atlanten (de Verteuil og Norris, 1996), samt med den reviderede nordvest-europæiske zonering (Powell og Brinkhuis, 2004). Zoneringen for det danske område adskiller sig fra de tidligere ved en detaljeret opdeling af intervallet omkring Oligocæn-Miocæn grænsen, af Nedre Miocæn, samt af Øvre Miocæn og Pliocæn. Den tidligere opstillede zonering for det danske Mellem Miocæn diskuteres og er delvist omdefineret. Zoneringen korreleres desuden til andre biostratigrafiske opdelinger af den neogene lagserie i det danske område, samt til litostratigrafi og sekvensstratigrafi. Absolutte aldre af de nye dinocyste zoner foreslåes, baseret dels på korrelation til internationale zoneringer og stratigrafiske skemaer og dels på strontium isotop analyser af mollusk skaller fra dele af danske lagserie.

Neogen biostratigrafi i Nordsø Bassinet har været problematisk på grund af perioder med afgrænset forbindelse til Nord Atlanten, især med hensyn til stratigrafi baseret på kalkskallede foraminiferer og nannoplankton. Mange af de stratigrafisk vigtige taxa, d.v.s. dem, der definerer de stratigrafiske grænser i typesektionerne, er ikke fundet i Nordsø Bassinet. Dette problem lader nu til at være løst ved korrelation baseret på den nye dinocyste stratigrafi, da de stratigrafisk vigtige dinocyste-arter forekommer i Nordsø aflejringerne, selv i marginalt marine aflejringsmiljøer.

Den nye neogene dinocyste stratigrafi for det danske område har givet os et stratigrafisk redskab med en højere opløselighed og en bredere anvendelse end nogen tidligere anvendte stratigrafiske redskaber. Denne stratigrafi giver os mulighed for at adskille og korrelere sedimentære enheder, f.eks. deltaiske sandsystemer og -lober i boringer, og at korrelerer disse enheder på seismiske sektioner i en detaljegrad, der ikke tidligere var mulig.

Integrationen af biostratigrafi, sedimentologi, sekvensstratigrafi, geofysiske logs fra boringer, samt seismiske data har ført til løsningen af flere historiske geologiske problemstillinger i det danske Miocæn:

Stratigrafien af den øvre oligocæne – nedre miocæne lagserie i Jylland er forstået for første gang (se bl.a. Dybkjær og Rasmussen, 2000; Dybkjær, 2004a, 2004b; Rasmussen og Dybkjær, 2005) og lag, som man tidligere troede var midt-miocæne henføres nu til den nedre miocæne Vejle Fjord Formation (se bl.a. Rasmussen et al., 2006). Den detaljerede, men fragmenterede øvre oligocæne – nedre miocæne lagserie i Jylland er blevet sammenholdt med den tilsvarende, men mere komplette, lagserie i Nordsø-boringen Frida-1. Dette studie viste at dateringerne baseret på dinocyster af den fragmentariske lagserie i Jylland er korrekte. Desuden er Oligocæn-Miocæn grænsen blevet lokaliseret (Rasmussen, 2004a; Rasmussen og Dybkjær, 2005; Dybkjær og Rasmussen, 2007).
Den stratigrafiske placering og den regionale udbredelse af tre større deltasystemer i Nedre – Mellem Miocæn er fastlagt på basis af dinocyste stratigrafien. Resultaterne illustrerer hvorledes samspillet mellem eustatiske havniveau ændringer, regional og lokal tektonik, samt tilstedeværelsen af Ringkøbing-Fyn Højderyggen har styret aflejringen af den miocæne lagserie i Danmark (se bl.a. Rasmussen, 2004a, b; Rasmussen og Dybkjær, 2005; Rasmussen et al., 2006).
Alderen af Gram Formationen er indsnævret til sen Serravallien – Tortonien (sen Mellem Miocæn til tidlig Øvre Miocæn). Dette er i modsætning til foraminifer stratigrafien, men generelt i overensstemmelse med den gamle mollusk stratigrafi (Piasecki, 2005). Palæoaflejringsmiljøet og de palæoklimatiske forhold under aflejringen af Hodde og Gram formationerne er blevet belyst på basis af dinocyste floraerne og det organisk indhold af sedimentet.
Ved at inkludere materiale fra Nordsø-boringerne Tove-1, S-1 og Lone-1 blev dinocyste studierne udvidet til at omfatte den yngre del af Neogenet. Derved blev det muligt at kortlægge denne del af den neogene lagserie, der ikke er repræsenteret på land i Danmark, samt at illustrere tiltningen og erosionen af den neogene lagserie (Piasecki og Rasmussen, 2004; Rasmussen et al., 2005b).

Abstract

A dinocyst zonation for the Neogene succession in the eastern part of the North Sea Basin (Denmark) is presented. The zonation is based on a huge database comprising data from more than fifty onshore and offshore boreholes and about twentyfive outcrops. Nineteen dinocyst zones are described, most of them are new and defined herein. The zonation is correlated both with previous published dinocyst zonations within the North Sea Basin, in the North Atlantic and with the revised Northwest European zonation. The presented zonation is remarkable for its detailed subdivision of the Oligocene–Miocene transition, of the Lower Miocene and of the Upper Miocene and Pliocene successions. The previous zonation of the onshore Danish Middle Miocene is reconsidered and partly redefined.

The zonation is correlated with other biostratigraphic subdivisions of the Neogene succession in the Danish region as well as litho- and sequencestratigraphy. Absolute ages of the new dinocyst zones are proposed based on correlation from the studied succession within the North Sea Basin with the international zonations and stratigraphic schemes. In addition, parts of the succession have been dated by strontium isotope analysis of mollusc shells.

Neogene biostratigraphy in the North Sea Basin has been problematic due to the periodically, limited connection from the North Sea Basin to the North Atlantic Ocean, especially with respect to stratigraphy based on foraminifers and calcareous nannoplankton. Many of the stratigraphically most important taxa, e.g. those defining stratigraphic boundaries in typesections, have not been found within the North Sea Basin. This problem seems to be solved by correlation based on the new dinocyst stratigraphy, because stratigraphic significant taxa do occur in the North Sea deposits, even in marginal marine settings.

Keywords: Miocene; biostratigraphy; palynology; dinoflagellates; North Sea Basin; Denmark

Introduction

The knowledge and understanding of the Danish Neogene succession has increased significantly during the last decade (see references below) due to the application of modern geological methods and due to a huge amount of new data.

Historically, petroleum exploration in the North Sea Basin has focussed on deeper lying targets and drilling rushed through the Neogene preferentially without collecting samples or other data. The sampling density in the Neogene succession is therefore low and the sample quality is generally rather poor – most available samples are ditch cuttings samples and caving is in many cases a severe problem. A slowly growing understanding of the need for detailed stratigraphic knowledge of the Neogene in relation to modelling of petroleum systems within the North Sea Basin and other areas has, however, increased the interest for this succession (e.g. Rasmussen et al., 2005a) and thus for the need of a high-resolution dinocyst stratigraphy.

Outcrops of Neogene deposits onshore Jylland are few and each of them represents very short timespan and most of the old clay- or browncoal pits are abandoned. Fortunately, a national program was initiated in Denmark from the year 1999, aiming to map all major subsurface reservoirs for drinkingwater (aquifers). Part of this program focused on the Miocene succession in Jylland which comprises several sandlayers at relatively shallow depths and with potential as drinkingwater reservoirs. Consequently, this program financed a large number of new stratigraphic boreholes and seismic surveys to clarify the thickness and distribution of the potential reservoirs. Cooperation between the local authorities and the Geological Survey showed the complexity of the succession and the need for high resolution stratigraphy to distinguish separate deltas, deltalobes and pro-delta-sands. Fossil dinoflagellate cysts (dinocysts) appeared to be most reliable for detailed biostratigraphy as they occurred in all depositional environments, even in marginal marine facies, where other marine fossils vanished.

In the following we present a detailed dinocyst zonation for the Neogene succession in the Danish area. The zonation is based on data from more than fifty onshore and offshore boreholes and a series of outcrops (Fig. 1).

Geological setting

During the Cenozoic, the North Sea Basin was an epicontinental basin, confined by landmasses (Fig. 2). The basin was flanked by the Fenno-Scandian Shield to the northeast and the Rheinish-Bohemian Massif to the south, while the western border probably was located in the eastern England, Scotland and the Shetland Isles (Ziegler, 1990). A narrow strait between the Shetland Isles and Norway was the only connection to open sea-ways, to the North Atlantic Ocean (Rundberg, 1989; Ziegler, 1990). The deepest part of the basin was concentrated to the Central Graben area, while the northeastern border was strongly controlled by the Sorgenfrei-Tornquist Zone. The Ringkøbing-Fyn High, which subdivides the Norwegian-Danish Basin and the German Basin, formed an elevated element with pronounced halogenetic movements both north and south of the structure.

The North Sea Basin formed as a result of thermal relaxation after the Late Jurassic – Early Cretaceous rift tectonics. During the Late Cretaceous and early Paleocene, former graben structures were elevated due to inversion tectonics (Vejbæk and Andersen, 1987; Liboriussen et al., 1987; Ziegler, 1990). This occurred both within and at the margins of the basin. Progradation from Fenno-Scandia and siliciclastic infill of the basin was initiated in the Late Paleocene (Heilmann-Clausen et al., 1985). The Paleocene and Eocene deposits are dominated by marine clay, while progradation of major systems and influx of coarse-grained sediments is documented from the Oligocene (Jordt et al., 1995; Michelsen et al., 1998).

The Danish region was from the beginning of the Neogene characterised by a depositional system of coastal plains and deltas prograding into the North Sea Basin and interfingering with marine mudstone. The depositional system was controlled by the interaction of significant climatic alterations (Zachos et al., 2001; Rasmussen, 2004a) that combined with large-scale tectonic events, caused significant sea-level changes (Fig. 3). The Danish Miocene succession reaches thicknesses up to 1200 m, while the Pliocene succession (incl. Galesian) reaches a thickness of 700 m (pers. comm. E.S. Rasmussen, 2007). Generally, the basinal strata thin up-dip towards Jylland (Fig. 4a). Onshore Denmark Neogene deposits are present in the mid- to southern parts of Jylland (Fig. 4b). Here the succession comprises uppermost Oligocene (uppermost Chattian) to Upper Miocene (Tortonian) strata separated from the Paleogene and Pleistocene/Holocene by significant unconformities. Messinian and Pliocene strata are missing onshore Denmark. Due to uplift of Fennoscandia in the latest Neogene (Japsen, 1993; Japsen et al., 2002), the Miocene and Pliocene succession is tilted and the layers dip towards the southwest. The following glacial erosion has resulted in a pattern with the oldest Miocene strata outcropping towards the northeast, while the outcropping parts gradually get younger towards the southwest (Fig. 4b) (Rasmussen, 1966).

Paleoenvironments and lithostratigraphy

The Danish onshore Neogene succession is dominated by fluvio-deltaic systems with associated back-barrier deposits and inner and outer shelf deposits (Sorgenfrei, 1958; Larsen and Dinesen, 1959; Rasmussen, 1961; Koch, 1989; Friis et al., 1998; Rasmussen, 2004b; Rasmussen and Dybkjær, 2005). During the Early and early Middle Miocene the northwest-southeast running coastline was situated across the present day Jylland (Fig. 3). Mainly due to eustatic sea-level changes, the position of the coastline changed resulting in three overall periods with delta-progradation followed by transgressions (Rasmussen et al., in prep.)(Figs. 3 and 5). The two oldest delta systems, deposited in the Early Miocene, were sourced from the north, from the western part of Fenno-Scandia (present day Norway) and prograded southwards (Michelsen et al., 1998; Gregersen et al., 1998; Clausen et al., 1999; Rasmussen and Dybkjær, 2005), while the source area for the third delta system, deposited in the early Middle Miocene, seems to have changed to the northeastern and eastern parts of the Fenno-Scandian Shield (the present day southern Sweden and the Baltic area) (Clausen et al., 1999). Due to accelerated subsidence of the North Sea area in the Langhian and Serravallian (Middle Miocene) a distinct overall transgression occurred and marine clay was deposited far towards eastern Denmark and possibly Sweden. In the latest Tortonian (Late Miocene), resumed progradation resulted in deposition of deltaic and coastal plain deposits. Neogene deposits younger than Tortonian has not yet been recorded onshore Denmark.

The lithostratigraphy of the Neogene succession onshore Denmark, proposed by Sorgenfrei (1958), Larsen and Dinesen (1959), Rasmussen (1961) and Koch (1989), has recently been revised (Rasmussen et al., in prep.) (Fig. 5). The uppermost Oligocene (upper Chattian) to lowermost Miocene (lower Aquitanian) Brejning Formation comprises shallow marine, glaucony-rich, silty clays and shows a shallowing upwards trend in the upper part.

In the early Aquitanian, the Ringkøbing-Fyn High seems to have formed a structural barrier between mid- and southern Jylland (Fig. 3a and 3b). At the same time, north of the high, the Brande Trough constituted a major north-south oriented depression. Within the Brande Trough, a major river-system existed, which delivered freshwater sediments and terrestrial organic particles to the restricted area north of the Ringkøbing-Fyn High. To the south, on the seaward side of the Ringkøbing-Fyn High along the shoreline, spit systems developed, while washover fans were deposited during storms landwards of the barriers. The sandrich deltaic deposits of this complex succession are referred to the Billund Formation, while the clayey deposits are referred to the

Vejle Fjord Formation. A major hiatus seems to occur in the proximal area of the delta, comprising the late Aquitanian and the earliest Burdigalian.

A transgression in the earliest Burdigalian resulted in deposition of marine clay and silt, referred to the Klintinghoved Formation, widely over the region (Fig. 3c). Timeequivalent sediments deposited within barrier complexes associated with the transgression are referred to the Kolding Fjord Formation. In the early to mid-Burdigalian a sandsystem of fluvio-deltaic deposits, referred to the Bastrup Formation, prograded far southwards (Fig. 3d). These deposits are overlain by the mid- to upper Burdigalian marine clay, referred to the Arnum Formation (Fig. 3e). Another prograding system of fluvio-deltaic sand, the Odderup Formation, was deposited in the late Burdigalian to Langhian (Fig. 3f).

A major, overall transgression in the late Langhian – Tortonian resulted in the deposition of marine clay, referred to the Hodde, Ørnhøj and Gram Formations, all over the region (Fig. 3g). Reworked glacony and goethite in the upper part of the Ørnhøj Formation indicated a minor sealevel fall at the Serravallian–Tortonian transition. Sandrich deposits from a prograding coastline occur in the uppermost Tortonian and are referred to the Marbæk Formation and the coastline prograded to the Central Graben area (Fig. 3h).

The Miocene – Pliocene succession in the area offshore Denmark comprises marine clay with variable influx of sand from prograding deltas. The offshore Neogene lithostratigraphy comprises the pre- to Middle Miocene Westray Group and the Middle Miocene to Pleistocene Nordland Group (Deegan and Scull, 1977; Knox and Holloway, 1992; Schiøler et al., 2007). The clayey deposits of the Westray Group are referred to the Lark Formation, while a minor sand-dominated unit of latest Oligocene to earliest Miocene age is referred to the Freja Member. The Nordland Group is undivided.

Sequencestratigraphy

Michelsen (1994) and Michelsen et al. (1995, 1998) presented the results of a comprehensive, multidisciplinary study aiming to make a sequence stratigraphic subdivision of the Cenozoic succession in the eastern North Sea Basin (offshore). The study combined seismic data, petrophysical logs and biostratigraphic data (foraminifera, calcareous nannofossils and dinocysts). The succession was subdivided into seven "major sequencestratigraphic units" and twenty-one sequences. Sequences 5.2 to 7.4 were referred to the Miocene and Pliocene. Based on combinations of seismic data and well-logs the Middle to Upper Miocene and Pliocene succession was further subdivided into sequences in a series of publications (Sørensen et al., 1997; Gregersen et al., 1998; Clausen et al., 1999). These studies gave detailed information about the depositional history of the North Sea Basin.

A sequence stratigraphic subdivision of the complex succession onshore has been developed gradually during the last decade (Rasmussen, 1996, 1998, 2004a; Dybkjær, 2004a; Rasmussen and Dybkjær, 2005; Rasmussen et al., 2006) based on a combination of seismic data, geophysical logs, detailed sedimentological studies of outcrops and materials from boreholes and biostratigraphy, especially dinocyst stratigraphy. The succession is subdivided into six sequences, A to F (Rasmussen, 2004b). This subdivision has recently been applied to the basinal setting in the eastern North Sea, based on correlation of seismic data and on dinocyst stratigraphy (Rasmussen, 2004b; Dybkjær and Rasmussen, 2007). Here the younger parts of the Neogene are also present and in addition the sequences G to I have been defined (Piasecki and Rasmussen, 2004; Rasmussen et al., 2005b).

Biostratigraphy

The understanding of the Danish onshore Miocene succession was initially based on fossil plants and molluscs. The identification of Danish Miocene strata and the first subdivision of these strata into Lower, Middle and Upper Miocene, based on molluscs, was actually rather precise, especially considering the limited material (Ravn, 1907). The results from the contemporaneous study of fossil plants were more limited but did not contradict the earlier conclusions (Hartz, 1909). Much later, extensive studies of the marine faunas lead to a mollusc zonation of approximately 8–10 zones, most precise and detailed in the Middle and Upper Miocene (Sorgenfrei, 1940, 1958; Rasmussen, 1961, 1966, 1968). These fossil faunas were correlated with German faunas and to the local, German stratigraphy. The conclusive age of the strata was therefore not very succesfull considering the abundant material; especially not for the lowermost Miocene which, however, partly is due to unfavorable depositional environments for marine faunas and partly bad preservation. Correlation of this zonation with the dinocyst zonation presented here has therefore only been possible in parts of the Middle – Upper Miocene succession. Schnetler and Beyer (1987, 1990) studied some rich mollusc faunas from the Brejning Formation from outcrops in Jylland and correlated them with the German “Chattian B”. These deposits are in the present study dated as latest Chattian (latest Oligocene). Also in the outcrops studied by these authors, the lowermost Miocene succession yielded hardly any molluscs and was chronostratigraphically referred to ?Upper Oligocene – Lower Miocene.

The application of foraminifer stratigraphy on the Miocene strata introduced a much more detailed biostratigraphy. First of all, A. Dinesen dated the Vejle Fjord Formation as Oligocene – earliest Miocene on the basis of a miserable foraminifer fauna (Larsen and Dinesen, 1959). The foraminifer biostratigraphy was then slowly established and finally crystallised in a North Sea stratigraphy for bentonic and planktonic foraminifers, respectively (Kristoffersen, 1972; King, 1983, 1989; Laursen, 1995; Laursen and Kristoffersen, 1995). Laursen and Kristoffersen (1995, 1999) applied the North Sea foraminifer stratigraphy (King, 1983, 1989) to the Danish Miocene succession and suggested comprehensive revision and calibration of the chronology of the foraminifer stratigraphy. Ten planktic foraminiferal zones and eleven benthic foraminiferal zones were recognised in the Danish, marine Neogene**.** However, the applicability of foraminifer stratigraphy in the lowermost Miocene succession is restricted due to poor benthonic, near-shore faunas and possibly also to secondary dissolution of the calcareous microfossils (Laursen and Kristoffersen, 1999).

Since the publication by Hartz (1909), spores and pollen as well as fossil plants, have mainly been used for stratigraphy on limited exposures of the terrestrial succession but modern stratigraphic studies of the brown coal bearing unit, the Fasterholt Member of the Odderup Formation, applied spores and pollen, as well as makroskopic plants (e.g. Christensen, 1975, 1976; Friis, 1979; Koch, 1989). The Fasterholt Member was suggested deposited at the Lower – Middle Miocene transition. New studies of the spores and pollen flora in the marine, Miocene strata as well as the terrestrial succession, take presently place at the universities both in Copenhagen, Denmark, and in Lund, Sweden (Larsson et al., 2006).

Strontium isotope stratigraphy

Strontium Isotope Stratigraphy (SIS) is used for high resolution chronostratigraphic control of sedimentary sequences, and is here used to support the biostratigraphical correlation. The $^{87}Sr/^{86}Sr$ ratio of seawater is very uniform on a global scale, which is a reflection of the long oceanic residence time of strontium (2–4 My), combined with a relatively short (<2000 years) oceanic mixing rate.

Fragments of mollusc shells from strategic horizons were analysed for $^{87}Sr/^{86}Sr$ ratios. The shell fragments were sampled from cores and outcrops. The analytical work was conducted by the Mass Sepctrometry Laboratory at the University of Bergen, Norway. All the Sr isotopic ratios were normalized to $^{86}Sr/^{88}Sr$ = 0.1194 and to NIST 987 = 0.710248. Measured $^{87}Sr/^{86}Sr$ ratios were converted to age estimates using the SIS Look-up table of Howard and McArthur (1997), see McArthur et al. (2001) and Eidvin and Rundberg (2001, 2007) for more details about the use and precision of the method.

Neogene dinocyst studies in Denmark

The following is a brief summary of previously published dinocyst studies based on material from Denmark:

The first study of Neogene dinocysts in Denmark focussed on the Middle and Upper Miocene Hodde and Gram Formations in western Jylland (Piasecki, 1980). Four biozones were defined: *Labyrinthodinium truncatum* Zone, *Nematosphaeropsis aquaducta* Zone, *Achomosphaera andalousiensis* Zone and *Dinopterygium verriculum* Zone. This early zonation was used by succeeding, stratigraphic studies of the Middle and Upper Miocene from the region (mainly northern Germany) and correlated with the Danish Hodde and Gram Formations (e.g. Herngreen, 1987; Daniels et al., 1990; Strauss et al., 2001; Rusbült and Strauss, 1992; Strauss and Lund, 1992). Furthermore, Powell (1992) adopted the four zones defined by Piasecki (1980) in his “Stratigraphic Index of Dinoflagellate Cysts” for the British area.

The dinocyst zonation of the Paleogene and the Miocene in NW Europe, proposed by Costa and Manum (1988), was partly based on unpublished data contributed by members of the Palynology Subgroup of the International Geological Correlation Programme Project no. 124 (“The Northwest European Tertiary Basin”). Claus Heilmann-Clausen (University of Aarhus) and Stefan Piasecki (The Geological Survey of Greenland, now GEUS) both contributed to a short review of the Tertiary dinocyst biostratigraphy of Denmark. Five dinocyst zones, D 16 to D 20, were defined for the Miocene. Unpublished studies of Danish sections provided data used for defining zone D 16, and the Danish Hodde and Gram Formations were reference sections for zones D 17 to D 20.

In a note from 1991 Strauss summarises his results from a study of the Middle Miocene succession following a transect from Jylland (Denmark) over Southwest Mecklenburg to Mittel- and Southeast Brandenburg (northeast Germany). The transect comprised 20 localities including the Danish Gram-2 well. Strauss presented a number of dinocyst biozones, although they were not defined in this note, and correlated with the zonation of Piasecki (1980). A scheme with interregional useful first occurrences, last occurrences and acmes were presented. He further showed a correlation of microfossil and macrofossil zonations and lithostratigraphic units based on the dinocyst datings. Results from this study was included and published together with data from the Ochtenhausen research drilling in northern Germany (Strauss et al., 2001).

In 1998 Heilmann-Clausen analysed the dinocysts in the Neogene succession in the Mona-1 well located in the Danish North Sea Basin. The study was a part of a multidisciplinary study aiming to establish a sequencestratigraphic subdivision of the Cenozoic deposits in the eastern North Sea (Michelsen et al., 1998). The same year Laursen et al. (1998) presented some preliminary results from a study aiming to correlate the local North German Miocene stages with the international stages, based on a combination of dinocysts, foraminifers and molluscs in the Lille Tønde borehole located in the southern part of Jylland.

From year 1999, a national drinkingwater program focused on mapping Miocene aquifers in mid- and southern Jylland. This promoted an integrated sedimentological, palynological and geophysical study of the Miocene succession based on all accessible outcrops (especially along the eastcoast of Jylland) and on more than 50 boreholes throughout the region. These studies has resulted in a detailed geological model of the Miocene succession in Jylland (Dybkjær and Rasmussen, 2000; Rasmussen, 2004a, b; Dybkjær, 2004a, 2004b; Rasmussen et al., 2004; Piasecki, 2005; Rasmussen, 2005; Rasmussen and Dybkjær, 2005; Rasmussen, Dybkjær and Piasecki, 2006; Dybkjær and Rasmussen, 2007) based on comprehensive studies of the Miocene dinocyst stratigraphy. The present dinocyst zonation is mainly based on the data achieved in connection with this program. A brief summary of the zonation presented herein was published in Dybkjær and Piasecki 2008).

Other recent investigations of Danish Neogene dinocyst assemblages include the study by Schiøler (2005) on the Oligocene – Miocene succession in the Alma-1 well in the North Sea and the studies by Piasecki (2001, 2003) on the Lower Pliocene dinocysts in the Utsira Formation in the Viking Graben and on the Neogene dinocysts in the Qulleq-1 well offshore West Greenland, respectively.

Dinocyst zonation

A Neogene dinocyst zonation for the Danish region is presented with a total of nineteen dinocyst zones; most of these are new and some are redefined (Fig. 6). The zonation is valid for both the on- and offshore regions even though some dinocyst species are most common in inner neritic settings, while others are more common in open marine settings. However, the younger Neogene strata are not present onshore and therefore, we present a twofold zonation for on- and offshore, respectively, to make the distinction between on- and offshore data clear.

Material and methods

The biozonation follows the nomenclature of the “North American Stratigraphic Code” (North American Commission on Stratigraphic Nomenclature 2005). The zones are defined as interval biozones and concurrent-range biozones. The zones are correlated both with previous published dinocyst zonations within the North Sea Basin (Köthe, 2003, 2005a; Köthe and Andruleit, 2007; Munsterman and Brinkhuis, 2004), with the North Atlantic zonation by de Verteuil and Norris (1996) and with the revised Northwest European zonation by Powell and Brinkhuis (2004) (Fig. 6). Furthermore, the new Danish dinocyst zonation is correlated with the North Sea foraminifer zonations of King (1989) and of Laursen and Kristoffersen (1999) and with the nannoplankton zonation of Martini (1971) (Fig. 7).

Unfortunately, only a minor part of the Neogene succession is represented by outcrops in Denmark. Therefore, the designated reference sections for the zones are selected from outcrops, when possible (e.g. Dykær) or from cored boreholes with the material stored at GEUS (e.g. Sdr. Vium). However, boreholes and wells from which data have been published (e.g. Gram-2 and Frida-1) as well as boreholes comprising strata not represented onshore (e.g. Lone-1 and Tove -1) has also been nominated as reference sections. The location of the reference sections are shown in ure 1. The successions in wells Frida-1, Lone-1 and Tove-1 are represented by ditch cuttings samples. However, casings immediately above the studied successions seem to have been very efficient in preventing caving, and these data has therefore been treated with confidence and even first occurrences were used from these wells.

The taxonomy of the dinocysts follows “The Lentin & Williams Index” (Fensome and Williams, 2004).

Zones

Deflandrea phosphoritica Zone (new)

Definition

The zone is defined from the last occurrence of *Distatodinium biffii* Brinkhuis et al., 1992 to the last occurrence of common to abundant *Deflandrea phosphoritica* Eisenack, 1938.

Diagnostic events

None.

General assemblage

In the Frida-1 well, located in the basinal parts of the eastern North Sea Basin (Fig. 1), the dinocyst assemblage is rich and diverse, reflecting a fully marine depositional environment. The assemblage is dominated by *Cleistosphaeridium placacanthum*, *Homotryblium plectilum*, *Reticulatosphaera actinocoronata* and *Spiniferites* spp. In the upper part of the zone, the abundance of *Deflandrea phosphoritica* increases from sporadic to common/abundant. A mutual occurrence of on one hand the outer neritic to oceanic taxa *Impletosphaeridium* and *Nematosphaeropsis* and on the other hand the inner neritic taxa *Homotryblium* spp., *Glaphyrocysta* spp. and *Deflandrea phosphoritica* was by Dybkjær and Rasmussen (2007) explained by an oceanic depositional environment with turbidites bringing material from inner neritic settings out in the more central parts of the basin.

In inner neritic settings, represented by outcrops and boreholes onshore Jylland, the dinocyst assemblage is strongly dominated by *Homotryblium plectilum* and *Spiniferites* spp. Here the same increase in abundance of *D. phosphoritica* in the upper part of the zone is found. This increase is followed by a less distinct increase in *Homotryblium plectilum* (Dybkjær, 2004a; Rasmussen and Dybkjær, 2005). An acme of *Apteodinium australiense* was found in the outcrop at Dykær at 1.20 m (Dybkjær, 2004a; Rasmussen and Dybkjær, 2005).

Reference- and boundary sections

The reference section is in the Frida-1 well from 1620 m to 1480 m (Fig. 5 in Dybkjær and Rasmussen, 2007). An additional reference section is in the onshore Harre-1 borehole (60.75 m to 26.25 m), where the zone is represented as an expanded section, compared to other onshore successions. The upper part and the upper boundary of this zone are well developed in the Dykær outcrop section (0 m to 1.60 m) (Rasmussen and Dybkjær, 2005).

Lithostratigraphy

In the Frida-1 well, representing offshore areas, this zone occurs in the Freja Member of the Lark Formation (Schiøler et al., 2007) (see Fig. 5 in Dybkjær and Rasmussen, 2007). In other offshore areas, where Freja Member (deposited as turdibite sands) is not represented, the zone correlates with a part of the Lark Formation (Knox and Holloway, 1992). In boreholes and outcrops onshore Jylland this zone occurs in the Brejning Formation (Larsen and Dinesen, 1959; Rasmussen et al., in prep.).

Sequencestratigraphy

The zone correlates with Sequence A in the Frida-1 well, as well as in boreholes and outcrops onshore Jylland (Dybkjær, 2004a; Rasmussen, 2004b; Rasmussen and Dybkjær, 2005; Dybkjær and Rasmussen, 2007).

Correlation with other dinocyst zonations

The *Deflandrea phosphoritica* Zone correlates with the lower part of DN1 *Chiropteridium galea* Zone defined in the eastern U.S.A. (de Verteuil and Norris, 1996) (Fig. 6). In the North Sea region, the *Deflandrea phosphoritica* Zone correlates with the lower part of Zone SNSM1 (Munsterman and Brinkhuis, 2004) and the upper part of D15/lower part of DN1 (Köthe, 2003, 2005a). It further correlates with the lower part or all of Zone D16a (Powell and Brinkhuis, 2004).

Biostratigraphic correlation

The last occurrence of *D. biffii* occur 9 m below the Oligocene–Miocene boundary in the Italian Stratotype Section, within the Calcareous Nannofossil Zone NP25c of Martini (1971) (Zevenboom,1996; Aubry and Villa, 1996). A correlation of this event with NP25 in the northern Hemisphere was confirmed by e.g. Müller and Köthe (1988) and Köthe (2005a) for northern Germany and by de Verteuil and Norris (1996) for Maryland and Virginia, USA.

In the Danish onshore borehole Harre-1, the *Deflandrea phosphoritica* Zone (60.75 m to 26.25 m) correlates directly with the North Sea bentonic Foraminifer Subzone NSB 8c of King (1989). The lower part of this interval was further referred to Subzone NSP 9c, while no stratigraphic significant planktonic calcareous microfossils was found in the upper part of the interval (King 1994). In the offshore Frida-1 well, the interval from 1630 m to 1590 m (the lower part of the *Deflandrea phosphoritica* Zone) was referred to NSB 8 of King (1989) (Emma Sheldon, GEUS, pers. comm., 2008).

Age

Latest late Oligocene, Late Chattian, 24.4 Ma to 23.03 Ma.

The suggested age of the lower boundary of the zone (24.40 Ma) is based on the age of the defining event, the last occurrence of *D. biffii*, as indicated by de Verteuil and Norris (1996, Fig. 3) for the New Jersey area, and by Brinkhuis et al. (1992) (referred in Powell and Brinkhuis, 2004).

The top of this zone, coinciding with the boundary between sequences A and B of Rasmussen (2004b), correlates with the Mi-1 glaciation event of Miller et al. (1987; 1991) and thus with the Oligocene–Miocene boundary (Rasmussen, 2004a,b; Rasmussen and Dybkjær, 2005; Dybkjær and Rasmussen, 2007). The age of this boundary is 23.03 Ma according to Gradstein et al. (2004). The duration of the zone is then approximately 1.4 My.

Comments

Although this paper should deal with the Neogene succession, it was decided to include this zone, dated as latest Late Oligocene, as the last occurrence of *Distatodinium biffii* is a widely used markerfor the uppermost Oligocene.

***Chiropteridium galea* Zone (de Verteuil and Norris, 1996) revised**

Definition

The zone is defined from the last occurrence of common to abundant *Deflandrea phosphoritica* Eisenack, 1938 to the last occurrence of *Chiropteridium galea* (Maier, 1959) Sarjeant, 1983.

Diagnostic events

None.

General assemblage

In basinal depositional settings, represented by Frida-1, the dinocyst assemblage is rich and diverse, reflecting a fully marine depositional environment. The assemblage is dominated by *Cleistosphaeridium placacanthum*, *Dapsilidinium pseudocolligerum*, *Homotryblium plectilum*, *H*. *tenuispinosum*, *Hystrichokolpoma rigaudiae*, and *Spiniferites* spp. In contrast to the previous zone *Deflandrea phosphoritica* is rare. Co-occurrence of the outer neritic to oceanic taxa *Nematosphaeropsis* and the inner neritic taxa *Homotryblium* spp., *Glaphyrocysta* spp. and *Deflandrea phosphoritica* was found in this zone (as in the previous) and interpreted to reflect that materials from inner neritic settings was transported out and deposited in the more basinal parts of the basin (Dybkjær and Rasmussen, 2007).

In nearshore depositional settings, the assemblage is less diverse, dominated by *Dapsilidinium pseudocolligerum*, *Distatodinium paradoxum*, *Homotryblium plectilum*, *H. tenuispinosum* and *Spiniferites* spp. *Homotryblium additense* dominates in the Addit Mark borehole (Dybkjær, 2004a, b). Strong dominance of *Homotryblium* spp. was suggested to reflect a brackish water depositional environment (Dybkjær, 2004b). *Homotryblium additense* and *H. plectilum* are most abundant in the proximal parts of the study area, while *H. tenuispinosum* is most abundant in the more distal areas. This distribution of *Homotryblium* species is interpreted to reflect a gradual increase in salinity away from the larger freshwater sources/river mouths (Dybkjær, 2004b).

Reference- and boundary sections

The reference section is in the Frida-1 well from 1480 m to 1360 m (Fig. 5 in Dybkjær and Rasmussen, 2007). The lower boundary of this zone is well developed in the Dykær outcrop section from 1.70 m to 1.40 m (Rasmussen and Dybkjær, 2005) and in the onshore Harre-1 borehole from 26.25 m to 22.25 m.

Lithostratigraphy

Offshore, the *Chiropteridium galea* Zone occurs in part of the Lark Formation, in the Frida-1 well it directly overlies the Freja Member (Knox and Holloway, 1992; Schiøler et al., 2007). Onshore Denmark, the zone occurs in the Vejle Fjord and Billund formations (Larsen and Dinesen, 1959; Rasmussen et al., in prep.). In the southern part of Jylland the zone occurs in the upper part of the Brejning Formation - the upper boundary of this formation thus seems to be diachroneous.

Sequencestratigraphy

The *Chiropteridium galea* zone correlates with the lower part of Sequence B in the Frida-1 well, as well as in boreholes and outcrops onshore Jylland (Dybkjær, 2004a; Rasmussen, 2004b; Rasmussen and Dybkjær, 2005; Dybkjær and Rasmussen, 2007).

Correlation with other dinocyst zonations

The *Chiropteridium galea* Zone, as defined/revised here, correlates with the upper part of DN1 *Chiropteridium galea* Zone defined in the eastern U.S.A (de Verteuil and Norris, 1996) (see comments) (Fig. 6). In the North Sea region it correlates with the uppermost part of D15/upper part of DN1 of Köthe (2003, 2005a) and with the upper part of Zone SNSM1 (Munsterman and Brinkhuis, 2004). It further correlates with a part of Zone D16, possibly the upper part of D16a and the lower part of D16b, of Powell and Brinkhuis (2004).

Biostratigraphic correlation

The last occurrence of *Chiropteridium galea* correlates with the lower part of the Calcareous Nannoplankton Zone NN2 of Martini (1971) (de Verteuil and Norris, 1996; Hardenbol et al., 1998; Powell and Brinkhuis, 2004). Köthe (2005a) shows correlation with NN1–2.

The foraminifer fauna from a sample at 23.75 to 24.0 m in the Harre-1 borehole, referred to the *Chiropteridium galea* Zone, was studied by King (1994). He referred it to the upper part of the North Sea bentonic Foraminifer Zone NSB 8, probably Subzone NSB 8c of King (1989). No stratigraphic significant planktonic calcareous microfossils were found in this sample and the interval above was barren of foraminifera, probably due to superficial leaching (decalcification).

Age

Early Aquitanian (earliest Early Miocene), 23.03 to 22.36 Ma.

The age of the base of this zone is discussed for the previous zone. The age of the last occurrence of *C. galea*, defining the top of the zone, was indicated as 22.2 Ma by de Verteuil and Norris (1996, Fig. 3), while Williams et al. (2004) suggested an age of 22.36 Ma for the northern hemisphere. The latter suggestion is adopted here. New Sr-isotope datings of a mollusc-shell from a sample from the northern part of Jylland (Salling), referred to the *C. galea* Zone, indicated an age within the range of 23.3 to 22.8 Ma, which is in good accordance with the suggested age-range of the zone. The duration of the zone is approximately 0.6 My.

Comments

De Verteuil & Norris defined their *Chiropteridium galea* Zone from the last occurrence of *Distatodinium biffii* to the last occurrence of *Chiropteridium galea*. The zone is here revised (narrowed) to encompass the strata between the last occurrence of common to abundant *Deflandrea phosphoritica* to the last occurrence of *Chiropteridium galea* and correlates with the upper part of their zone. The strata between the last occurrence of *Distatodinium biffii* and the last occurrence of common to abundant *Deflandrea phosphoritica* is encompassed in the previous/underlying zone, the *Deflandrea phosphoritica* Zone.

***Homotryblium* spp. Zone (new)**

Definition

The zone is defined from the last occurrence of *Chiropteridium galea* (Maier, 1959) Sarjeant, 1983 to the last occurrence of abundant *Homotryblium* spp. Davey and Williams, 1966.

Diagnostic events

Ectosphaeropsis burdigalensis appear for the first time within this zone, close to the upper boundary. This species occur however sporadic and has only been recorded in the offshore Frida-1 well and in the onshore Vandel Mark-1 borehole (DGU no. 115.1371) (Dybkjær, 2004a).

General assemblage

In basinal depositional settings, here represented by the Frida-1 well, the dinocyst assemblage in this zone is closely comparable to the assemblage in the previous zone, reflecting a fully marine depositional environment. The assemblage is dominated by *Cleistosphaeridium placacanthum*, *Dapsilidinium pseudocolligerum*, *Homotryblium plectilum*, *H. tenuispinosum*, *Operculodinium centrocarpum* and *Spiniferites* spp. Co-occurrence of the outer neritic to oceanic taxa *Nematosphaeropsis* and the inner neritic taxa *Homotryblium* spp. and *Glaphyrocysta* spp. was found in this zone (as in the two previous). This was interpreted to reflect that material from inner neritic settings was transported out and deposited in the more basinal parts of the basin (Dybkjær and Rasmussen, 2007).

In nearshore depositional settings, the dinocyst assemblage is dominated by *Dapsilidinium pseudocolligerum*, *Homotryblium plectilum*, *H. tenuispinosum* and *Spiniferites* spp., while *Homotryblium additense* occur commonly in the Addit Mark borehole within this zone (Dybkjær, 2004a, b). The strong dominance of *Homotryblium* spp. in the onshore outcrops and boreholes in the succession here referred to the upper part of the *Deflandrea phosphoritica* Zone, the *Chiropteridium galea* Zone and the *Homotryblium* spp. Zone was suggested to reflect a brackish water depositional environment (Dybkjær, 2004a, b). A distinct trend in the distribution of different *Homotryblium* species, with *H. additense* and *H. plectilum* being most abundant in the proximal parts of the study area and *H. tenuispinosum* dominating in the more distal parts, is interpreted to reflect a gradual increase in salinity away from the larger freshwater sources/river mouths Dybkjær (2004b).

Reference- and boundary sections

The reference section is in the Frida-1 well from 1360 m to 1300 m (Fig. 5 in Dybkjær and Rasmussen, 2007). The lower boundary and the lower part of the *Homotryblium* spp. Zone is well developed in the Dykær outcrop section (4.05 m to 17.80 m, top of the outcrop; Figs. 5 and 7 in Rasmussen and Dybkjær, 2005).

Lithostratigraphy

Offshore, the *Homotryblium* spp. Zone occurs in part of the Lark Formation (Knox and Holloway, 1992). Onshore, the zone occurs in the Vejle Fjord and Billund formations (Larsen and Dinesen, 1959; Rasmussen et al., in prep.).

Sequencestratigraphy

The *Homotryblium* spp. Zone occurs in the upper part of Sequence B (Rasmussen, 2004b; Dybkjær, 2004a).

Correlation with other dinocyst zonations

De Verteuil and Norris (1996) did not report abundance of *Homotryblium* above the last occurrence of *Chiropteridium galea* and it is thus not possible to correlate the *Homotryblium* spp. Zone with their zonation, defined for the eastern U.S.A.

In the North Sea Basin, Köthe (2003, 2005a) did not find abundance of *Homotryblium* within her Zone DN2, while the *Homotryblium* spp. Zone probably correlates with part or all of the SNSM2 Zone of Munsterman and Brinkhuis (2004) (Fig. 6). They mention *Homotryblium floripes*/*plectilum* as one of the taxa that are “quantitavely well-represented” within the zone, but don´t inform if this only counts for a part of the zone or for all of the zone. The upper boundary of their SNSM2 Zone, defined by the last occurrence of *Membranilarnacia*? *picena*, is not recognizable in the Danish area as only a few sporadic specimens clearly referable to *Membranilarnacia*? *picena* have been recorded in Denmark. The *Homotryblium* spp. Zone correlates with the upper part of zone D16b and probably with the lower part of zone D16c of Powell and Brinkhuis (2004).

Biostratigraphic correlation

According to de Verteuil and Norris (1996) and Powell and Brinkhuis (2004, Figs. 21.1 and 21.2) the last occurrence of *Chiropteridium galea* correlates with the lowermost part of the Calcareous Nannoplankton Zone NN2 of Martini (1971). The *Homotryblium* Zone thus probably correlates with the lower part of the Calcareous Nannoplankton Zone NN2 of Martini (1971) (de Verteuil and Norris, 1996).

In the Høruphav borehole (DGU no. 170.381) the interval referred to the *Homotryblium* spp. Zone (76.80 m to 64.05 m) correlates with the North Sea benthic Foraminifer Zones NSB 8c and the lower part of NSB 9 and with the planktic Foraminifer Zone NSP 10 of Laursen and Kristoffersen (1999). This corresponds to the NSB 8c and NSP 9 zones of King (1989).

Age

Early Aquitanian (earliest Early Miocene), 22.36 Ma to ?21.6 Ma.

The occurrence of *Chiropteridium galea*, defining the base of the zone, was dated as 22.36 Ma for the northern hemisphere by Williams et al. (2004). See further discussion for the previous zone. The dating of the upper boundary of this zone as ?21.6 Ma is arbitrary. It must, however, be inbetween the last occurrence of *C. galea* and the last occurrence of *Caligodinium amiculum*. The age of the latter event was indicated as 21.10 Ma by Hardenbol et al. (1998) for the Mediterranean and the North Atlantic. No data exists from the North Sea Basin. The duration of the zones is then approximately 0.8 My.

Comments

Ectosphaeropsis burdigalensis appears just below the upper boundary of this zone in the Frida-1 well. In the type section for the Oligocene–Miocene boundary this species appears a few metres below the Oligocene–Miocene boundary. It is, however, reasonable to expect it to appear somewhat later in the North Sea Basin, due to higher latitude and the brackish water conditions that probably prevailed in the latest Oligocene and earliest Miocene. According to Williams et al. (2004) it has a diachronous appearance from the Southern Hemisphere mid-latitudes (26.4 Ma) to the Equatorial (23.7 Ma) of no less than 2.7 My.

Abundant occurrence of *Homotryblium* is a consistent characteristic for the uppermost Oligocene and the lowermost Miocene deposits in the Danish area and probably in large parts of the North Sea Basin, see e.g. Köthe (1990), Gradstein et al. (1992) and Munsterman and Brinkhuis (2004). The top of this abundant occurrence of *Homotryblium*, used here for defining the upper boundary of the present zone, seems to be an important regional marker horizon.

Caligodinium amiculum Zone (new)

Definition

The zone is defined from the last occurrence of abundant *Homotryblium* spp. to the last occurrence of *Caligodinium amiculum* Drugg, 1970.

Diagnostic events

Offshore, in the Frida-1 well, *Deflandrea phosphoritica*, *Ectosphaeropsis burdigalensis* and *Membranosphaeridium aspinatum* all have last occurrences within the *Caligodinium amiculum* Zone, while *Thalassiphora rota* has first occurrence. Onshore no diagnostic events were recorded from this zone.

General assemblage

In the offshore Frida-1 well, the dinocyst assemblage within the *Caligodinium amiculum* Zone reflects a fully marine depositional environment. The dinocyst assemblage is dominated by *Cleistosphaeridium placacanthum*, *Dapsilidinium pseudocolligerum*, *Hystrichokolpoma rigaudiae*, *Operculodinium centrocarpum* and *Spiniferites* spp. The deposits referred to this zone from onshore boreholes hitherto, are interpreted as valley fill and is dominated by *Cleistosphaeridium placacanthum*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum* and *Spiniferites* spp. The interval is further characterised by a common occurrence of *L. multivirgatum* and *Membranilarnacia* cf. *picena* group. In the contrary to the previous zones *Homotryblium* occurs sporadically.

Reference- and boundary sections

The reference section is in the Frida-1 well from 1300 m to 1060 m (Fig. 5 in Dybkjær and Rasmussen, 2007).

This zone was previously not found onshore (see Dybkjær and Piasecki, 2008), but recent studies have shown that it is present in the westernmost part of Jylland, and is well-developed in the Sunds borehole (DGU nr. 85.2452) from 196 m to 183 m.

Lithostratigraphy

Offshore, the *Caligodinium amiculum* Zone occurs in part of Lark Formation (Knox and Holloway, 1992). Onshore the zone occurs in the Klintinghoved Formation, in the Kolding Fjord Member.

Sequencestratigraphy

In the study by Rasmussen and Dybkjær (2007) the interval here referred to the *Caligodinium amiculum* Zone was referred to Sequence B. However, recent studies indicate that it rather should be referred to the lowermost part of Sequence C (Rasmussen pers. comm., 2009).

Correlation with other dinocyst zonations

The *Caligodinium amiculum* Zone probably correlates with the lower part of DN2 of de Verteuil and Norris (1996), defined in the eastern U.S.A. (Fig. 6). In the North Sea Basin it correlates with the lower part of DN2 of Köthe (2003, 2005a). Furthermore, it probably correlates with part of the SNSM2 and /or SNSM3 Zone of Munsterman and Brinkhuis (2004). Due to very sporadic and questionable occurrences of *Membranilarnacia*? *picena* in the Danish area, the boundary between Zones SNSM2 and SNSM3 cannot be pointed out here. The *Caligodinium amiculum* Zone correlates further with part of Zone D16 of Powell and Brinkhuis (2004), probably the lower part of Zone D16c.

Biostratigraphic correlation

The *Caligodinium amiculum* Zone correlates with part of the Calcareous Nannoplankton Zone NN2 of Martini (1971) (de Verteuil and Norris, 1996). A study of the foraminifera in the offshore well Frida-1, resulted in a direct correlation to the North Sea benthic Foraminifer Zone NSB 9 (King, 1989) (pers. com. Emma Sheldon, GEUS, 2008). According to Laursen and Kristoffersen (1999), the Nannoplankton Zone NN2 correlates with their benthic zone NSB 9 and their planktic zone NSP 10, corresponding to the upper part of NSB 8c – 9 and the upper part of NSP 9 – 10 of King (1989).

Age

Late Aquitanian (early Early Miocene), ?21.6 Ma to 21.10 Ma.
The dating of the lower boundary of this zone as ?21.6 Ma is arbitrary (see discussion for the previous zone). The upper boundary, defined as the last occur-

rence of *Caligodinium amiculum*, is dated as 21.10 Ma according to Hardenbol et al. (1998), for the Mediterranean and the North Atlantic. In lack of data from the North Sea Basin this age is adopted here. In the study by de Verteuil and Norris (1996) the last occurrence of *Caligodinium amiculum* occurred together with the first occurrence of *Exochosphaeridium insigne* at about 20.4 Ma. The latter event occurs higher in the succession studied here. The duration of the *C. amiculum* Zone is approximately 0.5 My.

Comments

In the outcrops and boreholes onshore Jylland, the last occurrence of *Caligodinium amiculum* often falls either within the former zone, the *Homotryblium* spp. Zone (e.g. Vandel Mark, Egtved Skov, Bastrup, Dykær), or even within the *Chiropteridium galea* Zone (Addit Mark, St. Vorslunde, Vorbasse) (Dybkjær, 2004a). Its generally sporadic occurrence and variable last occurrence is probably due to the inner neritic facies and because the *C. amiculum* Zone is present in a geographically very restricted area.

Thalassiphora pelagica Zone (new)

Definition

The zone is defined from the last occurrence of *Caligodinium amiculum* Drugg, 1970 to the last occurrence of *Thalassiphora pelagica* (Eisenack, 1954) Eisenack and Gocht, 1960, emended Benedek and Gocht, 1981.

Diagnostic events

None.

General assemblage

The dinocyst assemblage was deposited in a fully marine environment with variating input of terrestrial organic matter. In basinal depositional settings, here represented by the Frida-1 well, the dinocyst assemblage is dominated by *Apteodinium australiense*, *Cleistosphaeridium placacanthum*, *Operculodinium centrocarpum* and *Spiniferites* spp. Onshore, in more proximal settings, *Impletosphaeridium insolitum* also occur abundantly, see e.g. Bastrup-1 (DGU no. 133.1298)(139 to 134 m) (Dybkjær, 2004a, Fig. 10), while *Apteodinium australiense* only occur sporadically.

Reference- and boundary sections

The reference section is in the Frida-1 well from 1060 m to 1040 m (Fig. 5 in Dybkjær and Rasmussen, 2007). The *Thalassiphora pelagica* Zone is further well-represented in the boreholes Vorbasse (DGU no. 123.1167) (213 to 165 m) and Bastrup (DGU no. 133.1298) (154 m to 133 m) (Dybkjær, 2004a, Figs. 8 and 10) and in the outcrops at Hagenør and Rønshoved (Dybkjær and Rasmussen, 2000; Rasmussen and Dybkjær, 2005, Fig. 5).

Lithostratigraphy

Offshore, the *Thalassiphora pelagica* Zone occurs in part of the Lark Formation (Knox and Holloway, 1992). Onshore, this zone occurs in the Klintinghoved and Kolding Fjord formations (Sorgenfrei, 1958; Rasmussen, et al., in prep.).

Sequencestratigraphy

The *Thalassiphora pelagica* Zone occur in the lowermost part of Sequence C, in the transgressive systems tract (Rasmussen, 2004b; Dybkjær and Rasmussen, 2007, Fig. 5).

Correlation with other dinocyst zonations

The *Thalassiphora pelagica* Zone probably correlates with the middle part of Zone DN2 of de Verteuil and Norris (1996), defined in the eastern U.S.A. (Fig. 6). Within the North Sea Basin it correlates with the revised Zone DN2 of Köthe (2003, 2005a) and with SNSM2 and/or SNSM3 of Munsterman and Brinkhuis (2004). As mentioned previously the boundary between the latter two Zones cannot be pointed out in the Danish area. The *Thalassiphora pelagica* Zone further correlates with the lower part of Zone D16c of Powell and Brinkhuis (2004, Fig. 21.2).

Biostratigraphic correlation

The *Thalassiphora pelagica* Zone correlates with the lower to middle part of the Calcareous Nannoplankton Zone NN2 of Martini (1971) (de Verteuil and Norris, 1996). In the Høruphav borehole (DGU no. 170.381), the *T. pelagica* Zone correlates with the North Sea benthic Foraminifer Zones NSB 9–10I and with the planktic Foraminifer Zone NSP 10–11 (Laursen and Kristoffersen, 1999), corresponding to NSB 9 and NSP 10 of King (1989). A study of the foraminifera in the offshore well Frida-1, resulted in a direct correlation to the North Sea benthic Foraminifer Zone NSB 9 (King, 1989) (pers. com. Emma Sheldon, GEUS, 2008).

Age
Early Burdigalian (late Early Miocene), 21.10 Ma to 20.0 Ma. The last occurrence of *Caligodinium amiculum*, is 21.10 Ma according to Hardenbol et al. (1998), for the Mediterranean and the North Atlantic. This age is adopted here in lack of data from the North Sea Basin.

An absolute age of the last occurrence of *T. pelagica* is not given in any references known to the authors. In Powell and Brinkhuis (2004, Fig. 21.2) it is shown as near 20.6 Ma, which is in the latest Aquitanian. An Aquitanian age for this event is, however, in contradiction to the study by Londoix and Jan Du Chêne (1998) from the Burdigalian type area in France, where this species is found to occur consistently in the lower part of the Burdigalian succession. Coccioni et al. (1997) also reported the last occurrence of *T. pelagica* in the lower Burdigalian from the section at Santa Croce di Arcevia, in Italy.

New Sr-isotope datings on a mollusc shell from the core from the Danish Sdr. Vium borehole estimated an age of 20.0 Ma. As this is within the early Burdigalian, and also in between the absolute datings of the events below and above: the last occurrence of *Caligodinium amiculum* at 21.10 Ma according to Hardenbol et al. (1998) and the first occurrence of *Exochosphaeridium insigne*, this is adopted here. The duration of the zone is then approximately 1.1 My.

Comments
The boundary between the *Thalassiphora pelagica* Zone and the underlying *Calgodinium amiculum* Zone are not recorded in onshore successions, and the lower boundary of the *T. pelagica* Zone is therefore recorded on top of the *Homotryblium* spp. Zone, due to a significant hiatus in the succesion. Onshore as well as offshore, in the wells Frida-1 and Alma-1, this zone is very thin. In the onshore successions this zone is interpreted to have been deposited in a more open marine depositional environment than the underlying *Homotryblium* spp. Zone (Dybkjær, 2004a; Rasmussen and Dybkjær, 2005).

Sumatradinium hamulatum Zone (new)

Definition
The *Sumatradinium hamulatum* Zone is defined from the last occurrence of *Thalassiphora pelagica* (Eisenack, 1954) Eisenack and Gocht, 1960, emended Benedek and Gocht, 1981 to the first occurrence of *Exocosphaeridium insigne* de Verteuil and Norris, 1996.

Diagnostic events

Sumatradinium hamulatum has first occurrences within this zone, while *Thalassiphora rota* has last occurrence.

General assemblage

The dinocyst assemblage is diverse and reflects a fully marine depositional environment with variating input of terrestrial organic matter. The assemblage within the *Sumatradinium hamulatum* Zone is dominated by *Apteodinium australiense*, *Cleistosphaeridium placacanthum*, *Dapsilidinium pseudocolligerum*, *Impletosphaeridium insolitum*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum* and *Spiniferites* spp.

Reference- and boundary sections

The reference section for the *Sumatradinium hamulatum* Zone is in the Sdr. Vium borehole (DGU no. 102.948) from 246.98 m to 143.48 m. The zone is also well-developed in the Egtved Skov borehole (DGU no. 124.1159) (109m to 73 m) (Dybkjær, 2004a, Figs. 3 and 9). Offshore, only ditch cuttings samples exists from the Neogene succession in the Danish area at present and caving is generally a major problem. The upper boundary of the *Sumatradinium hamulatum* Zone, defined as the first occurrence of *Exochosphaeridium insigne*, has therefore not been pointed out yet. In the Frida-1 well no *E. insigne* have been recorded from the studied interval (Dybkjær and Rasmussen, 2007), and in Alma-1 the lowest recordings of *E. insigne* is here interpreted as being due to caving (Schiøler, 2005).

Lithostratigraphy

Offshore, the *Sumatradinium hamulatum* Zone occurs in part of the Lark Formation (Knox and Holloway, 1992) and onshore it occurs in the Klintinghoved Formation (Sorgenfrei, 1958; Rasmussen et al., in prep.) and part of the Bastrup Formation (Rasmussen et al., in prep.).

Sequencestratigraphy

The *Sumatradinium hamulatum* Zone occurs in Sequence C (Rasmussen, 2004b; Dybkjær, 2004a; Rasmussen and Dybkjær, 2005; Dybkjær and Rasmussen, 2007, Fig. 5).

Correlation with other dinocyst zonations

The *Sumatradinium hamulatum* Zone probably correlates with the middle part of Zone DN2 of de Verteuil and Norris (1996), defined in the eastern U.S.A. (Fig.

6). In the North Sea Basin it correlates with the revised Zone DN2 of Köthe (2003, 2005a) and with Zone SNSM2 and/or SNSM3 of Munsterman and Brinkhuis (2004). As mentioned previously the boundary between the latter two zones cannot be pointed out in the Danish area. Furthermore, it correlates with the upper part of Zone D16c in the zonation of Powell and Brinkhuis (2004, Fig. 21.2). The *Cordosphaeridium cantharellus* Assemblage defined in Frida-1 (Dybkjær and Rasmussen, 2007) probably correlates with the lower part of the *Sumatradinium hamulatum* Zone.

Biostratigraphic correlation

The *Sumatradinium hamulatum* Zone correlates with the middle to upper part of the Calcareous Nannoplankton Zone NN2 of Martini (1971) (de Verteuil and Norris, 1996). The upper part of NN2 further correlates with the upper part of the benthic Foraminifera Zone NSB 9–10I and the upper part of the North Sea planktonic Foraminifera Zone NSP 10–11 (Laursen and Kristoffersen, 1999), corresponding to NSB 9 and NSP 10 of King (1989).

Age

Early Burdigalian (late Early Miocene), 20.0 Ma to 19.0 Ma. The absolute age of the base of the zone is estimated as 20.0 Ma, based on new Sr-isotope datings, see the comments for the previous zone.

According to de Verteuil (1997) the absolute age of the first occurrence of *Exochosphaeridium insigne* for the New Jersey coastal plain is about 20.0 Ma and this age was adopted by Köthe (2005a, Fig. 2) for the German area. The indicated absolute age (19.0 Ma) of the top of the zone herein is based on new Sr-isotope data from the cored Danish Sdr. Vium borehole, suggesting an age for the first occurrence of *Exochosphaeridium insigne* between 18.7 Ma and 20 Ma, closest to 18.7 Ma. The duration of the zone is then 1 My.

Comments

Thalassiphora rota has only been recorded offshore, in the wells Alma-1 and Frida-1 (Schiøler, 2005; Dybkjær and Rasmussen, 2007). In Alma-1 caving prevents identification of the first occurrence of *Exochosphaeridium insigne*. In Frida-1 the last occurrece of *T. rota* was recorded close to the top of the studied succession, while no *E. insigne* was recorded, probably because the studied succession does not reach up into the stratigraphic interval comprising this species.

Cordosphaeridium cantharellus Zone (new)

Definition

The *Cordosphaeridium cantharellus* Zone is defined from the first occurrence of *Exocosphaeridium insigne* de Verteuil and Norris, 1996 to the last occurrence of *Cordosphaeridium cantharellus* (Brosius, 1963) Gocht, 1969.

Diagnostic events

None.

General assemblage

The dinocyst assemblage was deposited in a fully marine environment with variating input of terrestrial organic matter. The dinocyst assemblage within the *Cordosphaeridium cantharellus* Zone is dominated by *Apteodinium australiense*, *Cleistosphaeridium placacanthum*, *Dapsilidinium pseudocolligerum*, *Impletosphaeridium insolitum*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum* and *Spiniferites* spp.

Reference- and boundary sections

The reference section is in the Sdr. Vium borehole (DGU no. 102.948) from 143.48 m to 111.54 m.

Lithostratigraphy

Offshore, the *Cordosphaeridium cantharellus* Zone occurs in part of the Lark Formation (Knox and Holloway, 1992). Onshore it occurs in the upper part of the Klintinghoved Formation (Sorgenfrei, 1958; Rasmussen et al., in prep.), in the Bastrup Formation (Rasmussen et al., in prep.) and in the lower part of the Arnum Formation (Sorgenfrei, 1958; Rasmussen et al., in prep.).

Sequencestratigraphy

The *Cordosphaeridium cantharellus* Zone occurs in Sequences C and D (Rasmussen, 2004b).

Correlation with other dinocyst zonations

The *Cordosphaeridium cantharellus* Zone probably correlates with the upper part of Zone DN2 of de Verteuil and Norris (1996), defined in the eastern U.S.A. (Fig. 6). It further correlates with the revised Zone DN2 of Köthe (2003, 2005a) and with SNSM2 and/or SNSM3 of Munsterman and Brinkhuis (2004), both defined within the North Sea Basin. As mentioned previously the boundary between the latter two zones cannot be pointed out in the Danish area. Furthermore, it correlates with the upper part of Zone D16c in the zonation of Powell and Brinkhuis (2004, Fig. 21.2).

Biostratigraphic correlation

The *Cordosphaeridium cantharellus* Zone correlates with the upper part of the Calcareous Nannoplankton Zone NN2 of Martini (1971) (de Verteuil and Norris, 1996). The upper part of NN2 further correlates with the upper part of the benthic Foraminifera Zone NSB 9–10I and the upper part of the North Sea planktonic Foraminifera Zone NSP 10–11 (Laursen and Kristoffersen, 1999), corresponding to NSB 9 and NSP 10 of King (1989).

Age

Early Burdigalian (late Early Miocene), 19.0 Ma to 18.4 Ma. The indicated absolute age of the base of the zone is based on new Sr-isotope analysis, see discussion above. The absolute age of the top of the zone (defined by the last occurrence of *Cordosphaeridium cantharellus*) seems to be problematic. Hardenbol et al. (1998) suggested an age of 17.95 Ma for this event for the Mediterranean and North Atlantic, while the studies by de Verteuil and Norris (1996) and de Verteuil (1997) from New Jersey, U.S.A. indicated an age of about 19.4-19.5 Ma. Based on the latter studies, an age of 19.5 Ma was suggested by Williams et al. (2004) for the northern Hemisphere, mid-latitude, while Powell and Brinkhuis (2004) and Köthe (2005a) indicate an age of 19.4 Ma for this event. Jiménez-Moreno et al. (2006) found *C. cantharellus* in deposits referred to the middle Ottnangian – mid Burdigalian – in Austria. These deposits were referred to nannofossil zone NN3. The Ottnangian stage is limited by SB Bur 3 (18.7 Ma) and Bur 4 (17.3 Ma) according to the chart of Vakarcs et al. (1998). New Sr-isotope datings from mollusc shells from the cored Danish Sdr. Vium borehole estimated an age of the last occurrence of *C. cantharellus* inbetween 18.2 and 18.7 Ma. An age of 18.4 Ma for this event is therefore suggested here. The duration of the zone is then approximately 0.6 My.

Comments

None.

Exochosphaeridium insigne Zone (new)

Definition

The *Exochosphaeridium insigne* Zone is defined from the last occurrence of *Cordosphaeridium cantharellus* (Brosius, 1963) Gocht, 1969 to the first occurrence of *Cousteaudinium aubryae* de Verteuil and Norris, 1996.

Diagnostic events

Exochosphaeridium insigne occurs for the last time within this zone.

General assemblage

The dinocyst assemblage was deposited in a fully marine environment with minor input of terrestrial organic matter. The assemblage within the *Exochosphaeridium insigne* Zone is dominated by *Apteodinium australiense*, *Cleistosphaeridium placacanthum*, *Dapsilidinium pseudocolligerum*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum* and *Spiniferites* spp.

Reference- and boundary sections

The reference section for the *Exochosphaeridium insigne* Zone is in the Sdr. Vium borehole (DGU no. 102.948) from 111.54 m to 89.68 m. It is further well-developed in the boreholes Estrup (DGU no. 132.1838) (117 to 105 m) and Føvling (DGU no. 132.1835 (129 to 120 m). The *Exochosphaeridium insigne* Zone is not identified in the studied offshore wells Alma-1 and R-1 due to much caving.

Lithostratigraphy

Offshore, the *Exochosphaeridium insigne* Zone occurs in part of Lark Formation (Knox and Holloway, 1992). Onshore, it occurs in the Arnum Formation (Sorgenfrei, 1958; Rasmussen et al., in prep.) and the lower part of the Odderup Formation (Rasmussen, 1961; Rasmussen et al., in prep.).

Sequencestratigraphy

The *Exochosphaeridium insigne* Zone occurs within Sequence D (Rasmussen, 2004b).

Correlation with other dinocyst zonations

De Verteuil and Norris (1996) report the the first occurrence of *C. aubryae* much lower (in the middle Aquitanian) in their succession from the eastern U.S.A. than recorded from the Danish area. However, they record the two other important events of the *Exochosphaeridium insigne* Zone, the last occurrence of *Cordosphaeridium cantharellus* in the uppermost part of their zone DN2 and the last occurrence of *Exochosphaeridium insigne* defining the upper boundary of DN2. Therefore, the *Exochosphaeridium insigne* Zone may be correlated with the uppermost part of DN2 of de Verteuil and Norris (1996) (Fig. 6).

In northern Germany, in the research borehole Wursterheide, Köthe (2005b) recorded the first occurrence of *C. aubryae* in the upper part of the interval referred to Dinocyst Zone DN3, in the middle part of the Burdigalian. This DN3 Zone is defined to represent the interval between the last occurrence of *C. cantharellus* and the first occurrence of *Labyrinthodinium truncatum*. It thus seems that the first occurrence of *C. aubryae* in both Denmark and Germany occur distinctly later than in the area studied by de Verteuil and Norris (1996) and that the *Exochosphaeridium insigne* Zone correlates with the lower to middle part of Zone DN3 of Köthe (2003, 2005a). Furthermore, it may correlate with the lower part of the SNSM4 Zone of Munsterman and Brinkhuis (2004), defined by the same events as Köthes Zone DN3.

The *Exochosphaeridium insigne* Zone may also correlate with the uppermost part of Zone D16c in the zonation of Powell and Brinkhuis (2004, Fig. 21.2), although they do not indicate the first occurrence of *C. aubryae*. The uppermost part of Zone D16c represents the interval between the last occurrence of *C. cantharellus* and the last occurrence of *E*. *insigne*.

Biostratigraphic correlation

According to de Verteuil and Norris (1996) the interval between the last occurrence of *Cordosphaeridium cantharellus* and the last occurrence of *Exochosphaeridium insigne* correlates with the uppermost part of the Calcareous Nannoplankton Zone NN2 of Martini (1971). In the Wursterheide research borehole from Germany, the interval between the last occurrence of *Cordosphaeridium cantharellus* and the last occurrence of *Exochosphaeridium insigne*, defining the *Exochosphaeridium insigne* Zone in the present study, correlates with the lower to middle part of the Calcareous Nannoplankton Zone NN3 (Köthe, 2005b).

The uppermost part of NN2 correlates with the uppermost part of the benthic Foraminifera Zone NSB 9–10I and the uppermost part of the North Sea planktonic Foraminifera Zone NSP 10–11, while NN3 correlates with the lowermost part of NSB10I and the lowermost part of NSP 11 (Laursen and Kristoffersen, 1999). These zones further correlates with the upper part of NSB – lower part of NSB10 and the upper part of NSP 10 – lower part of NSP 11 of King (1989).

Age

Burdigalian (late Early Miocene), 18.4 Ma to 17.8 Ma. The age of the last occurrence of *Cordosphaeridium cantharellus* was here suggested to be 18.4 Ma, based on new Sr-isotope analysis, see further discussed above.

The age of the first occurrence of *Cousteaudinium aubryae* is 16.95 Ma according to Hardenbol et al. (1998) for the Mediterranean and North Atlantic areas and was also adopted by Williams et al. (2004) for the Mediterranean area. This dating seems further to be in good correspondence with the results from the Wursterheide borehole (Köthe, 2005b). In the contrary, the dating of this event shown by Williams et al. (2004) for the northern hemisphere, based on the study by de Verteuil and Norris (1996), is 22.1 Ma, and thus in the early Aquitanian. In the study by de Verteuil (1997) the first occurrence of *C. aubryae* was found indeposits referred to the Burdigalian; in the Atlantic City borehole in deposits dated as 17.8 Ma, and in the Cape May borehole in deposits dated as 19.9 Ma.

New Sr-isotope analysis on mollusc fragments from the cored Danish Sdr. Vium borehole estimated ages of 17.8 and 18.86 Ma, respectively, for the first occurrence of *C. aubryae*. The latter result suggests, however, an age older than the ages found for several analysed samples below this event and is therefore interpreted as due to either reworking of the mollusc material or an analytical error. An age of 17.8 Ma is therefore suggested here. The duration of the zone is then approximately 0.6 My.

Comments

In the Sdr. Vium borehole the last occurrence of *Exochosphaeridium insigne* occur at the base of this zone. The zone is here only represented by two samples, a sample at the base with the last occurrence of *C. cantharellus*, and a sample at the top with the first occurrence of *Cousteaudinium aubryae*. In the boreholes Estrup (DGU no. 132.1838) and Føvling (DGU no. 132.1835) *E. insigne* occurs consistently throughout the zone and further up in the succession above.

Cousteaudinium aubryae Zone (new)

Definition

The zone is defined from the first occurrence of *Cousteaudinium aubryae* de Verteuil and Norris, 1996 to the first occurrence of *Labyrinthodinium truncatum* Piasecki, 1980.

Diagnostic events

Achomosphaera alcicornu and Sumatradinium soucouyantiae appear at the base of the zone. *Cerebrocysta poulsenii* appear within the zone and *Apteodinium spiridoides* occur for the last time within the zone. Acmes of *Apteodinium tectatum* and *Polysphaeridium zoharyi* is recorded within the zone.

General assemblage

The dinocyst assemblage was deposited in a fully marine environment with minor input of terrestrial organic matter. The assemblage is dominated by *Apteodinium australiense*, *A. tectatum*, *Cleistosphaeridium placacanthum*, *Dapsilidinium pastielsii*, *Hystrichokolpoma rigaudiae*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum*, *Polysphaeridium zoharyi* and *Spiniferites* spp.

Reference- and boundary sections

The reference section of the *Cousteaudinium aubryae* Zone is located in the Sdr. Vium borehole (DGU no. 84.2602) from 89.68 m to 59.48 m.

Lithostratigraphy

Offshore, the *Cousteaudinium aubryae* Zone occurs in part of Lark Formation (Knox and Holloway, 1992; Schiøler et al., 2007). Onshore, it occurs in the Arnum Formation (Sorgenfrei, 1958; Rasmussen et al., in prep.) and the Odderup Formation (Rasmussen, 1961; Rasmussen et al., in prep.).

Sequencestratigraphy

The *Cousteaudinium aubryae* Zone occurs in Sequence D (Rasmussen, 2004b).

Correlation with other dinocyst zonations

The *Cousteaudinium aubryae* Zone may be correlated with the upper part of Zone DN3 of de Verteuil and Norris (1996) based on the stratigraphy of species that we consider stratigraphic significant and which de Verteuil and Norris also report associated with the zonal boundaries. However, the appearance of the zonal species *C. aubryae* is significantly higher in the Danish area than the eastern U.S.A. (Fig. 6). See further the discussion for the previous zone. In the North Sea Basin, the *Cousteaudinium aubryae* Zone clearly correlates with the upper part of Zone DN3 of Köthe (2003, 2005a) and it may correlate with the upper part of the SNSM4 Zone of Munsterman and Brinkhuis (2004), defined as the interval from the last occurrence of *C. cantharellus* to the first occurrence of *Labyrinthodinium truncatum*.

The *C. aubryae* ssp. *gonoperforata* Interval Zone (Cgo Zone; Strauss et al., 2001) in Germany was defined from the first apperance of *C. aubryae* to the first occurrence of *Palaeocystodinum miocaenicum* and correlates with the new *C. aubryae* Zone except for missing the uppermost part to the first occurrence of *L. truncatum*.

The *Cousteaudinium aubryae* zone may also correlate with the uppermost part of Zone D17a in the zonation of Powell and Brinkhuis (2004, Fig. 21.2), although they do not indicate the first occurrence of *C. aubryae*.

Biostratigraphic correlation

According to de Verteuil and Norris (1996) the interval between the last occurrence of *Exochosphaeridium insigne* and the first occurrence of *Labyrinthodinium truncatum* correlates with the Calcareous Nannoplankton Zone NN3 and the lower part of NN4 of Martini (1971). According to Köthe (2003; 2005a,b) the interval between the last occurrence of *C. cantharellus* and the first occurrence of *Labyrinthodinium truncatum* correlates with the Calcareous Nannoplankton Zone NN3 to NN4. The *C. aubryae* ssp. *gonoperforata* Interval Zone (Strauss et al., 2001) in Germany is correlated to NN4.

The NN3 Zone correlates with the lowermost part of the North Sea bentonic Foraminifera Zone NSB10I and the lowermost part of the planktonic Foraminifera Zone NSP 11, while the NN4 Zone correlates with NSB 10I–10II and NSP 11 (Laursen and Kristoffersen, 1999). The NN3 Zone further correlates with the upper part of NSB 9 to the lower part of NSB 10 and the upper part of NSP 10 and the lower part of NSP 11 of King (1989), while the NN4 Zone correlates with NSB 10 and NSP 11.

Age

Late Burdigalian (latest Early Miocene), 17.8 Ma to 15.97 Ma. The age of the first occurrence of *Cousteaudinium aubryae* is based on new Sr-isotope analysis, see further discussion for the previous zone.

According to Williams et al. (2004), the first occurrence of *Labyrinthodinium truncatum* correlates with the Burdigalian–Langhian boundary. The age of this boundary is 15.97 Ma according to Powell and Brinkhuis (2004). New Sr-isotope datings from the cored Danish Sdr. Vium borehole indicates that the age of the first occurrence of *L. truncatum* is slightly younger than 16.6 Ma, and thus support the age suggested by Powell and Brinkhuis (2004). The duration of the zone is approximately 1.8 My.

Comments
None.

Labyrinthodinium truncatum Zone (Piasecki, 1980)

Definition
The zone is defined from the first occurrence of *Labyrinthodinium truncatum* Piasecki, 1980 to the first occurrence of *Unipontidinium aquaeductus* (Piasecki, 1980) Wrenn, 1988.

Diagnostic events
Cousteaudinium aubryae occurs for the last time in this this zone. A significant acme of *Polyshaeridium zoharyi* is recorded near the base of the zone followed by an acme of *Palaeocystodinium miocaenicum* near the top of the zone.

General assemblage
The dinocyst assemblage is rich and diverse reflecting marine depositional environment in front of a prograding shoreline followed by transgression of the sea. The assemblage is dominated of *Hystrichokolpoma rigaudiae*, *Operculodinium centrocarpum*, *Spiniferites* spp., *Cleistosphaeridium placacanthum*. *Apteodinium spiridoides/tectatum* and *Heteraulacysta campanula* dominate locally.

Reference- and boundary sections
The *Labyrinthodinium truncatum* Zone is defined in the boring DGU no. 141.423 at Gram claypit from 42.0 m – 36.0 m below surface (Piasecki, 1980). The zone is also recorded from 59.45 m – 49.08 m in the cored well at Sønder Vium (DGU no. 84.2602).

Lithostratigraphy

Offshore the Labyrinthodinium truncatum Zone occurs in the uppermost Lark Formation (Knox and Holloway, 1992) and in the lowermost Nordland Group (Deegan and Scull, 1977). Onshore the zone occurs in the Arnum Formation (Sorgenfrei, 1958; Rasmussen et al., in prep.) and in the lower part of the Hodde Formation (Rasmussen, 1961; Rasmussen et al., in prep.).

Sequencestratigraphy

The *Labyrinthodinium truncatum* Zone occurs in the highstand systemstract of Sequence D and in the transgressive system tract of Sequence E (Rasmussen, 2004b).

Correlation with other dinocyst zonations

Labyrinthodinium truncatum Zone correlates with DN4 *Distatodinium paradoxum* Zone (eastern U.S.A.; de Verteuil and Norris, 1996)(Fig. 6). The upper boundary of DN4 is defined by the last occurrence of *Distatodinium paradoxum* near the first occurrence of *U. aquaeductum* but the *D. paradoxum* event is not clearly demarked in the Danish material, though it is recognised in some successions. DN4 is also used by (Köthe, 2003) in northern Germany.

M5 Zone of the southern North Sea (Munsterman and Brinkhuis, 2004) and the D17b subzone (NW-Europe; Powel and Brinkhuis, 2004) is defined on the same events as the *Labyrinthodinium truncatum* Zone and consequently they correlate.

Biostratigraphic correlation

DN4 is correlated with nannoplankton zones NN4–5 (de Verteuil and Norris, 1996; Köthe, 2003). In the Gram I–II wells, the *Labyrinthodinium truncatum* Zone correlates directely with mid North Sea benthonic Foraminifer Zone NSB 11(I–II) and mid planktonic Foraminifer Zone NSP 12 (I–II) (Laursen and Kristoffersen, 1999). This is equivalent to NSB12a and NSP13 of King (1989). The lower part of the zone correlate with the Shell bed I mollusc Assemblage Zone of Rasmussen (1966).

Age

Langhian (Middle Miocene), 15.97 Ma to 14.8 Ma. The first occurrence of *L. truncatum* is correlated with the Burdigalian–Langhian boundary, which is dated as 15.97 Ma (Lourens et al., 2004). The first occurrence of *U. aquaeductum* is correlated with mid-Langhian and dated as 14.8 Ma in Powell and Brinkhuis

(2004). The duration of the zone is approximately 1.2 My. New Sr-isotope datings from the lowermost part of the zone indicate an age of 16.6 My.

Comments

L. truncatum Zone is considered a zone, not a subzone (D17b) as suggested by Powell and Brinkhuis (2004), due to the consistent and precise occurrence all over the North Atlantic region.

Unipontidinium aquaeductus Zone (Piasecki, 1980)

Definition

The zone is defined from the first occurrence of *Unipontidinium aquaeductus* (Piasecki, 1980) Wrenn, 1988 to the first occurrence of *Achomosphaera andalousiensis* Jan du Chéne, 1977 and is equivalent to the stratigraphic range of *U. aquaeductus*.

Diagnostic events

A significant acme of *Palaeocystodinium miocaenicum* occurs near the base of the zone and abundant *Cleistosphaeridium placacanthum* occurs at the top of the zone.

General assemblage

The dinocyst assemblage is rich and diverse reflecting a fully marine depositional environment in a transgressive marine facies. The assemblage is dominated of Hystrichokolpoma *rigaudiae*, *Operculodinium centrocarpum*, *Lingulodinium machaerophorum*, *Spiniferites* spp., *Cleistosphaeridium placacanthum*. However, *Apteodinium* spp., *Labyrinthodinium truncatum*, *Dapsiliodinium pastielsii* and *Paleocystodinium miocaenicum* are locally abundant.

Reference- and boundary sections

The *Unipontidinium aquaeductus* Zone occurs in the boring at Gram claypit (DGU no. 141.423), from 36.0 m to 29.0 m below surface. The *U. aquaeductus* Zone occurs more condensed from 49.08 m to 47.48 m in the cored well at Sønder Vium (DGU no. 84.2602).

Lithostratigraphy

Offshore, the *Unipontidinium aquaeductus* Zone occurs in the basal Nordland Group (Deegan and Scull, 1977). Onshore it occurs in the upper part of the Hodde Formation (Rasmussen, 1966; Rasmussen et al., in prep.). The upper boundary of the zone is coincident with the boundary of the Hodde and Gram Formations (Piasecki, 2005).

Sequencestratigraphy

The *Unipontidinium aquaeductus* Zone correlates with the upper part of Sequence E (Rasmussen, 2004b).

Correlation with other dinocyst zonations

The *Unipontidinium aquaeductum* Zone correlates with dinocyst zonation D18a of Powell and Brinkhuis (2004) (Fig. 6) and with the *Batiacasphaera spherica* Zone, DN5 (de Verteuil and Norris, 1996). The upper boundary of DN5 is defined by the last occurrence of *Cleistosphaeridium placacanthum* contemporaneous with the last occurrence of *U. aquaeductum*. In Denmark, *Cleistosphaeridium placacanthum* occurs higher in the succession associated with *Cannosphaeropsis passio* and *Achomosphaera andalousiensis*. The last occurrence of *C. placacanthum* is not distinct but fades out over several metres. However, the presence of abundant *C. placacanthum* is not recovered above the *Unipontidinium aquaeductum* Zone. In Germany Köthe (2003, 2005a) follows the definition of the zone and extends the upper boundary of DN5 above the last occurrence of *U. aquaeductum*. The *U. aquaeductum* Zone correlates in part with M6 Zone (Munsterman and Brinkhuis, 2004) in the southern North Sea; the upper boundary is not recognised in the Danish material but uppermost M6 Zone is presumably equivalent to our *Achomosphaera andalousiensis* Zone. The *U. aquaeductum* Zone correlates in part with the Naq Zone in Germany (Strauss et al., 2001) which also include lower part of our overlying *Achomosphaera andalusiense* Zone.

Biostratigraphic correlation

The dinocyst zone D18a by Powell and Brinkhuis (2004) correlates with nannoplankton zonation NN5–6. The *Batiacasphaera spherica* Zone, DN5 in eastern USA is correlated with nannoplankton zones NN5–6 (Verteuil and Norris, 1996) and the corresponding DN5 zone in Germany is correlated with NN5–6 (Köthe, 2005a). There seems to be agreement about this correlation in the North Atlantic region.

In the Gram II well, the *U. aquaeductum* Zone correlates directly in part with bentonic foraminifer zone NSB 11II and planktonic foraminifer zones NSP 12II and 13 (Laursen, 1995; Laursen and Kristoffersen, 1999). This corresponds approximately to NSB 12a-c and NSP 13 (and 14a) by King (1989). The *U. aquaeductum* Zone also correlates with the Hodde mollusc Assemblage Zone (Rasmussen, 1966).

Age

Early Langhian to early Serravallian (Middle Miocene), 14.8 Ma to 13.2 Ma. The first occurrence of *U. aquaeductus* is dated as 14.8 Ma and the last occurrence is dated as 13.2 Ma by Powell and Brinkhuis (2004) equivalent to a total duration of 1.4 My.

Comments

The *Unipontidinium aquaeductus* Zone is generally condensed in distal depositional settings e.g. in the central North Sea, and therefore rarely recorded in more than one sample due to the 30 feet spacing of samples. The *U. aquaeductus* Zone is considered a zone, not a subzone, due to its consistent and precise occurrence all over the North Atlantic region. The zone was defined in Denmark by S. Piasecki (1980) and the eponymous species is widely used as a stratigraphic marker in the North Atlantic region, e.g. eastern USA (de Verteuil and Norris, 1996), West Greenland (Head et al., 1989; Piasecki, 2003), Rockall Plateau (Edwards, 1984), Mediterranean region (Zevenboom, 1995), North Sea (Powell, 1992; Louwye et al., 2000; Strauss et al., 2001; Köthe, 2003) and Norwegian Sea (Manum, 1976).

Achomosphaera andalousiensis Zone (Piasecki, 1980) revised

Definition

The zone is defined from the first occurrence of common *Achomosphaera andalousiensis* Jan du Chéne, 1977 to the first occurrence of *Gramocysta verricula* (Piasecki, 1980) Lund and Lund-Christensen, 1990.

Diagnostic events

The range of *Cannosphaeropsis passio* occurs within this zone and *Cerebrocysta poulsenii* and *Cleistosphaeridium placacanthum* occur for the last time at the top of the zone and may be used as alternative markers for demarcation of the upper limit of the zone in offshore settings where *G. verricula* is absent.

General assemblage

The dinocyst assemblage is deposited in a fully marine environment with very little terrestrial organic matter (Piasecki, 2005). The dominating species are *Hystrichokolpoma rigaudiae*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum* and *Spiniferites* spp. *Spiniferites pseudofurcatus*, *Dapsiliodinium pastielsii*, *Filisphaera filifera*, *Labyrinthodinium truncatum* and *Pentadinium laticinctum* are locally abundant.

Reference- and boundary sections

The reference section for the *Achomosphaera andalousiensis* Zone occurs in the Gram II borehole (DGU no. 141.423) from 28.5 m to 26.5 m below surface.

Lithostratigraphy

In offshore settings, the *Achomosphaera andalousiensis* Zone occurs in the lower Nordland Group (Deegan and Scull, 1977). Onshore, the *Achomosphaera andalousiensis* Zone occurs in the Ørnhøj Formation (Rasmussen et al., in prep.).

Sequencestratigraphy

The *Achomosphaera andalousiensis* Zone correlates with the maximum flooding of Sequence E (Rasmussen, 2004b).

Correlation with other dinocyst zonations

The *Achomosphaera andalousiensis* Zone correlates with dinocyst subzone D18b of Powell and Brinkhuis (2004) (Fig. 6). This zone also correlates with DN6 and 7 in Germany (Köthe, 2005a) and DN6 and 7 in eastern USA (de Verteuil and Norris, 1996). The upper part of *Achomosphaera andalousiensis* Zone correlates in with the Cpa and San Zones in Germany (Strauss et al., 2001). In the southern North Sea, the uppermost M6 Zone (Munsterman and Brinkhuis, 2004) correlates with the *Achomosphaera andalousiensis* Zone.

Biostratigraphic correlation

Powell (1992) and Powell and Brinkhuis (2004) correlate the zone with a narrow interval of calcareous nannoplankton zone NN6, whereas the DN zones from eastern USA and Germany (de Verteuil and Norris, 1996; Köthe, 2005a) are correlated with NN6, NN7 and NN8. The *A. andalousiensis* Zone in the Gram II well occurs within an interval barren of forminifers but the zone may correlate in part with the bentonic foraminifer zonation NSB 12a–b transition and the mid of planktonic zone NSP 13 (Laursen and Kristoffersen, 1999). The NSB 12a–b transition (the barren interval) correlates with uppermost NN6 nannoplankton zonation. In the North Sea foraminifer zonation of King (1989) this corresponds to the NSB 12c–13a transition and the NSP 14a-b transition, also equivalent to uppermost NN6. Molluscs are absent in this part of the succession (Rasmussen, 1966).

Age

Early to mid-Serravallian (Middle Miocene), 13.2 Ma to 12.8 Ma. The first occurrence of *Achomosphaera andalousiensis* is estimated to 13.2 Ma and the first occurrence of *Gramocysta verricula* is dated as 12.8 Ma (Powell and Brinkhuis, 2004). The duration of the zone is then approximately 0.4 My.

Comments

The first occurrence of *Achomosphara andalousiensis* is indicate by relatively few specimens and some authors prefer therefore to use a stratigraphic level slightly higher where *A. andalousiensis* becomes abundant (e.g. Köthe, 2005a). The *Achomosphaera andalousiensis* Zone was defined in the Gram II borehole (Piasecki, 1980). The stratigraphical range in the reference section is corrected here. Powell (1992) applied the zone for the North Sea and the eponymous species is used as stratigraphic marker all over the North Atlantic region (see refs. under *U. aquaeductus*).

***Gramocysta verricula* Zone (Piasecki, 1980; Powell, 1992)**

Definition

The zone is defined from the first occurrence of *Gramocysta verricula* (Piasecki, 1980) Lund and Lund-Christensen, 1990 to the first occurrence of *Amiculosphaera umbraculum* Harland, 1979.

Diagnostic events

Gramocysta verricula appears for the first time at the basis of this zone.

Paleocystodinium miocaenicum occurs for the last time at the upper boundary of the zone and may be used to identify the upper limit of the zone as an alternative to the first occurrence of *Amiculosphaera umbraculum* which tend to be absent in proximal depositional settings.

General assemblage

The dinocyst assemblage is deposited in a fully marine environment with very little terrestrial organic matter (Piasecki, 2005). Foraminifers and molluscs are rare to absent (Rasmussen, 1961, 1966; Laursen and Kristoffersen, 1999). The dominating species are *Dapsiliodinium pastielsii*, *Hystrichokolpoma rigaudiae*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum*, *Spiniferites* spp. However, *Labyrinthodinium truncatum* and *Operculodinium giganteum* are locally abundant.

Reference- and boundary sections

The *Gramocysta verricula* Zone occurs in the Gram II borehole (DGU no. 141.423) from 26 m below surface. The upper boundary of the zone has not been identified in onshore succession due to the absence of *Amiculosphaera umbraculum* but is indirectly identified by the last occurrence of *Paleocystodinium miocaenicum* in 25 m below topographic surface.

Lithostratigraphy

Offshore, the *Gramocysta verricula* Zone occurs in the lowermost Nordland Group (Deegan and Scull, 1977) e.g. in Tove-1, 4010-4040'. Onshore it occurs in the Ørnhøj Formation (Rasmussen et al., in prep.).

Sequencestratigraphy

The *Gramocysta verricula* Zone correlates with part of Sequence E of Rasmussen (2004b).

Correlation with other dinocyst zonations

The *Gramocysta verriculum* Zone correlates with revised Northwest European dinocyst zones D18c (Powell and Brinkhuis, 2004) (Fig. 6). Together, *Gramocysta verricula* and the overlying *Amiculosphaera umbraculum* Zones correlate with dinocyst zone DN8 in Germany and eastern U.S.A. (de Verteuil and Norris, 1996; Köthe, 2003). The *Gramocysta verriculum* Zone correlates indirectly with the Gve Zone in Germany (Strauss et al., 2001) but not with the M7 Zone in Belgium (Munsterman and Brinkhuis, 2004) due to deviating distribution of the associated marker species.

Biostratigraphic correlation

Powell (1992) and Powell and Brinkhuis (2004) correlate the D18c Subzone with calcareous nannoplankton zones NN7–8 (Martini, 1971). Strauss et al. (2001) indirectly correlates the Gve Zone with "NN8–9" via foraminifer stratigraphy. The *Gramocysta verricula* Zone in the Gram II well falls within an interval barren of forminifers but the zone correlates within the “bentonic” zonation NSB 12a-b and the “planktonic” zonation NSP 13 (Laursen, 1995) equivalent to NSB 12c – lowermost 13a and NSP 14a–b of King (1989) in both cases equivalent to NN6–7. Molluscs are also absent in this interval (Rasmussen, 1966).

Age

Serravallian to Tortonian (Middle to Late Miocene), 12.8 Ma to 11.4 Ma. The first occurrence of *Gramocysta verricula* is indicated to approximately 12.8 Ma and the first occurrence of *Amiculosphaera umbraculum* is indicated to approximately 11.4 Ma by Powell and Brinkhuis (2004) suggesting a duration of 1.4 My.

Comments

Amiculosphaera umbraculum is not recorded in Danish onshore successions and therefore, the top of the *Gramocysta verricula* Zone cannot be distinguished from the overlying *Amiculosphaera umbraculum* Zone on the basis of this species in proximal settings. In contrast *Gramocysta verricula* is rare in offshore settings, and therefore the zone is difficult to distinguish from the underlying *Achomosphaera andalousiensis* Zone. The zone was defined by (Piasecki, 1980) with no upper boundary. Powell (1992) defined the Hve Zone with the upper boundary at the first occurrence of *Amiculosphaera umbraculum*. Strauss et al. (2001) used this zone (as Gve Zone) in northern Germany.

***Amiculosphaera umbraculum* Zone (Powell, 1992) revised**

Definition

The zone is defined from the first occurrence of *Amiculosphaera umbraculum* Harland, 1979 to the first occurrence of *Barssidinium evangelineae* Lentin et al., 1994.

Diagnostic events

The last occurrence of *Paleocystodinium miocaenicum* occurs at the base of the zone, and the last occurrence of “*Cordosphaeridium” minimum*, *Palaeocystodinium* spp. and *Cleistosphaeridium placacanthum* coincide with the upper boundary of the zone.

General assemblage
The dinocyst assemblage is deposited in a marine environment with input of terrestrial organic matter from the prograding coast-line (Piasecki, 2005). The dominating species are *Lingulodinium machaerophorum*, *Operculodinium centrocarpum* and *Spiniferites* spp., whereas *Gramocysta verricula* and *Homotryblium tenuispinosum* dominates especially in the upper zone. In contrast, *Labyrinthodinium truncatum* and *Operculodinium giganteum* are abundant in the lower zone.

Reference- and boundary sections
The reference section is in the offshore well Lone-1 from 4680´ to 4350´. In the onshore Gram II borehole (DGU no. 141.423), the corresponding succession is identified by accessory marker species from 24 to 16 m.

Lithostratigraphy
The *Amiculosphaera umbraculum* Zone occurs offshore in strata of the Nordland Group (Deegan and Scull, 1977) and onshore in the Gram Formation (Rasmussen, 1961, 1966; Rasmussen et al., in prep.).

Sequencestratigraphy
The *Amiculosphaera umbraculum* Zone occurs in part of the highstand systemstract of sequence F (Rasmussen, 1996, 2004b).

Correlation with other dinocyst zonations
The *Amiculosphaera umbraculum* Zone corresponds to revised Northwest European dinocyst subzone D19a of Powell and Brinkhuis (2004) and to the upper part of DN8 *Palaeocystodinium golzowense* Zone in eastern USA and in Germany (de Verteuil and Norris, 1996; Köthe, 2003) (Fig. 6). The upper limit of M13 in the Netherlands (Munsterman and Brinkhuis, 2004) as well as the upper boundary of the Pal Subzone in Germany (Strauss et al., 2001) coincides with the upper boundary of the *Amiculosphaera umbraculum* Zone.

Biostratigraphic correlation
The equivalent dinocyst zone D19a (Powell and Brinkhuis, 2004) correlates with calcareous nannoplankton zones mid-NN7 – mid-NN10 of Martini (1971) all in lower Tortonian. The dinocyst Zone DN8 in eastern USA (de Verteuil and Norris, 1996) and northern Germany (Köthe, 2005a) was earlier correlated precisely with NN9 and 10 (i.e. the same time interval, early Tortonian) whereas

the DN7 zone were refered to the uppermost Serravallian. Köthe and Andruleit (2007) revised the correlation of DN8 in Germany to mid-NN7 – mid-NN10.

In the Gram II borehole, the succession equivalent to the *Amiculosphaera umbraculum* Zone correlates with the North Sea, bentonic foraminifer zones NSB 12b–c, and planktonic foraminifer zones NSP 13–14b (Laursen and Kristoffersen, 1999; Piasecki, 2005) i.e. equivalent to NSB 13a and NSP 14b–15a of King (1989). The latter is equivalent to NN7–10. This succession also correlates with the mollusc Assemblage Zones I – IV of Rasmussen (1966) (Piasecki, 2005).

Age

Early Tortonian (Late Miocene), 11.4 Ma to 8.8 Ma. The appearance of *Gramocysta verricula* is estimated as 11.4 Ma and the appearance of *Barssidinium evangelineae* and the last occurrence of *Palaeocystodinium* spp. at 8.8 Ma by Powell and Brinkhuis (2004), indicating a duration of the zone of approximately 2.6 My.

Comments

The *Amiculosphaera umbraculum* Zone was defined by Powell (1992) from the first occurrence of *Amiculosphaera umbraculum* to the first occurrence of *Spiniferites* cf. *pseudofucatus.* The present definition limits the zone to the lowermost part of that interval. The appearance of *Barssidinium evangelineae* is a distinct stratigraphic event in offshore settings.

***Hystrichosphaeropsis obscura* Zone (de Verteuil and Norris, 1996)**

Definition

The zone is defined from the first occurrence of *Barssidinium evangelineae* Lentin et al., 1994 to the last occurrence of *Hystrichosphaeropsis obscura* Habib, 1972.

Diagnostic events

The last occurrence of Cordosphaeridium minimum, Palaeocystodinium spp. and Cleistosphaeridium placacanthum coincide with the lower boundary of the zone. The last occurrence of abundant Gramocysta verricula, Homotryblium tenuispinosum and Spiniferites pseudofurcatus occur in this zone. The last occurrence of Labyrinthodinium truncatum is close to the upper boundary. The last occurrence of Impagidinium “densiverrucosum” is also close to the upper boundary, however this species is only recorded in offshore successions.

General assemblage

The dinocyst assemblage was deposited in a marine environment with engrossing input of terrestrial organic matter from the prograding coast (Piasecki, 2005). The assemblage is dominated by *Lingulodinium machaerophorum*, *Operculodinium centrocarpum* and *Spiniferites* spp. whereas *Gramocysta verricula* and *Homotryblium tenuispinosum* dominate only in the lower part of the zone. In contrast, *Bitectatodinium*? *aborichianum*, *Hystrichokolpoma salacium*, *Polysphaeridium zoharyi* and *Spiniferites pseudofurcatus* are locally very abundant.

Reference- and boundary sections

The lower boundary of the *Hystrichosphaeropsis obscura* Zone occurs at 15 m below surface in the Gram II borehole (DGU no. 141.423) in the Gram Formation (Piasecki, 2005). The upper boundary is not definitively recorded onshore Denmark although the top of the zone appears near in the uppermost, erosionally limited Gram Formation in southern Jylland, e.g. in the wells at Sæd Toldstation (DGU no. 167.445), Tinglev (DGU no. 168.1378) and Gram brickwork (DGU no. 144.423)(Piasecki, 2001, 2005).
Offshore in the well Tove-1, the *H. obscura* Zone occurs from 3650–3890’.

Lithostratigraphy

Offshore, the *Hystrichosphaeropsis obscura* Zone occurs in the Nordland Group (Deegan and Scull, 1977). Onshore, it occurs in the upper part of the Gram Formation and in the Marbæk Formation (Rasmussen, 1961, 1966; Rasmussen et al., in prep.).

Sequencestratigraphy

The *Hystrichosphaeropsis obscura* Zone occurs in the highstand system tracts of Sequence F (Rasmussen, 1996; 2004b).

Correlation with other dinocyst zonations

The *Hystrichosphaeropsis obscura* Zone correlates with the revised North West European dinocyst zone D19b (Powell and Brinkhuis, 2004) and with the DN9 Zone of de Verteuil and Norris (1996) in eastern USA and in Germany (Köthe, 2003) based on the two events used for definition of the zone (Fig. 6). The *H. obscura* Zone also correlates with the upper Aum Zone in Germany (Strauss et al., 2001) and the M14 Zone in The Netherlands (Munsterman and Brinkhuis, 2004).

Biostratigraphic correlation

The *Hystrichosphaeropsis obscura* Zone (DN9) is correlated with lower nannoplankton zone NN11 in eastern U.S.A. (de Verteuil and Norris, 1996) and with upper NN10 – lower NN11 in Germany (Köthe and Andruleit, 2007). The latter correlation is in accordance with the age estimate below. In the onshore wells, the Gram II (DGU no. 141.423) and the Sæd Toldstation (DGU no. 167.445) wells, this zone correlates with the foraminifer zones, NSB 13a–13b and NSP 14b–15a (Laursen, 1995; Laursen and Kristoffersen, 1999; Piasecki, 2005) equivalent to NSB 13b and NSP 15b-c of King (1989). Furthermore, this correlates with NN 11 (Martini, 1971). In the Gram II and Sæd Toldstation wells, the *H. obscura* Zone correlates with mollusc Assemblage Zones IV–VI (Rasmussen, 1966; Piasecki, 2005).

Age

Late Tortonian (Late Miocene), 8.8 Ma to 7.6 Ma. The first occurrence of *Barssidinium evangelineae* and the last occurrence of *Palaeocystodinium* spp. is indicated approximately at 8.8 Ma and the last occurrence of *Hystrichosphaeropsis obscura* is indicated approximately at 7.6 Ma (Powell and Brinkhuis, 2004), suggesting a duration of the zone of 1.2 My.

Comments

None.

Selenopemphix armageddonensis Zone (de Verteuil and Norris, 1996) revised

Definition

The zone is defined from the last occurrence of *Hystrichosphaeropsis obscura* Habib, 1972 to the last occurrence of *Barssidinium evangelineae* Lentin et al., 1994.

Diagnostic events

The first occurrence of *Selenopemphix armageddonensis* coincides with the lower boundary and the range of the species is presumed to approximate the range of the zone. The last occurrences of *Operculodinium piaseckii*, *Pentadinium laticinctum* and *Spiniferites solidago* occur in the zone.

General assemblage

Achomosphaera andalousiensis, Operculodinium spp. and Spiniferites spp. are the most abundant dinocysts, whereas Barssidinium graminosum, Barssidinium evangelineae, Invertocysta lacrymosa, Melitasphaeridium choanophorum and Operculodinium antwerpense are common to locally abundant. The Selenopemphix armageddonensis Zone is recorded in offshore wells in sediments deposited in marine settings. However, abundance of terrestrial, organic material probably reflects continuous progradation of the coast from the East.

Reference- and boundary sections

Offshore, the *Selenopemphix armageddonensis* Zone is recorded in the hydrocarbon exploration wells Tove-1 from 3380–3650' and in Lone-1 from 3930–4350'. The *Selenopemphix armageddonensis* Zone is not definitively recorded onshore Denmark although the dinoflagellate flora in the uppermost, erosionally limited Gram Formation in southern Jylland indicates proximity to the lower boundary e.g. in the wells at Sæd Toldstation (DGU no. 167.445), Tinglev (DGU no. 168.1378) and Gram brickwork (DGU no. 144.423)(Piasecki, 2001, 2005). The corresponding *S. armageddonensis* Zone (the upper boundary based on the last ocurrence of *Erymnodinium delectabile*) is reported from the Wursterheide well in Germany, just south of the Danish border (Köthe, 2003).

Lithostratigraphy

Offshore, the *Selenopemphix armageddonensis* Zone occurs in the Nordland Group (Deegan and Scull, 1977). The *S. armageddonensis* Zone has not been recorded onshore.

Sequencestratigraphy

The *Selenopemphix armageddonensis* Zone occurs in the upper part of Sequence F and in Sequence G (Rasmussen et al., 2005b).

Correlation with other dinocyst zonations

The *Selenopemphix armageddonensis* Zone correlates in part with the *Achomosphaera andalousiensis* Zone (Costa and Manum, 1988; Powell, 1992) equivalent to the revised Northwest European dinocyst zone D20a (Powell and Brinkhuis, 2004) (Fig. 6). The Southern North Sea zonation (Munsterman and Brinkhuis, 2004) does not reach into the Messinian.

Biostratigraphic correlation

The last occurrence of *Hystrichosphaeropsis obscura* is reported mainly from nannoplankton zone NN11 (Powell, 1992; de Verteuil and Norris, 1996; Köthe and Andruleit, 2007). The last occurrence of *Barssidinium evangelineae* is reported close to the NN12–NN13 transition (Powell and Brinkhuis, 2004). The apparent coincident last occurrence of *Erymnodinium delectabile* is reported from NN12 in Germany (Köthe and Andruleit, 2007). The *Selenopemphix armageddonensis* Zone is therefore considered correlated with nannoplankton zones upper NN11–NN12 (Martini, 1971).

Age

Latest Tortonian to earliest Zanclean (Late Miocene – earliest Pliocene), 7.6 Ma to 5.0 Ma. The last occurrence of *H. obscura* is indicated at approximately 7.6 Ma, while the last occurrence of *Barssidinium evangelinae* is indicated at approximately 5.0 Ma, in the lowermost Pliocene (Powell and Brinkhuis, 2004). This indicates a 2.6 My duration of the zone.

Comments

The occurrence and distribution of *Selenopemphix armageddonensis* and *Erymnodinium delectabile* are not well documented in the Danish region but these species are reported from regions south and southwest of Denmark in Germany, The Netherlands and Belgium (Louwye et al., 1999; Munsterman and Brinkhuis, 2004; Köthe and Andruleit, 2007). The top of the zone is therefore defined and located by the last occurrence of *Barssidinium evangelineae* which occurs abundantly in this region. However, the zone is considered equivalent to the earlier *Selenopemphix armageddonensis* Zone (de Verteuil and Norris, 1996) and the name is therefore retained.

Melitasphaeridium choanophorum Zone (Powell, 1992) revised

Definition

The zone is defined from the last occurrence of *Barssidinium evangelineae* Lentin et al., 1994 to the last occurrence of *Melitasphaeridium choanophorum* (Deflandre and Cookson, 1955) Harland and Hill, 1979.

Diagnostic events

Reticulatosphaera actinocoronata occurs for the last time within the zone. Louwye et al. (2004) evaluate this last occurrence on the basis of North Atlantic deep sea drillings to be 4.4 Ma.

General assemblage

The dominating species are *Achomosphaera andalousiensis*, *Operculodinium* spp. and *Spiniferites* spp. and most other species occur in relative low numbers associated with abundant terrestrial organic material

Reference- and boundary sections

The reference section for the *Melitasphaeridium choanophorum* Zone is in the Lone-1 hydrocarbon exploration well in the Danish North Sea from 3390' to 3900'. Furthermore, the *M. choanophorum* Zone occurs from 2330' to 3380' in the Tove-1 well.

Sources

The *Melitasphaeridium choanophorum* Zone was defined by Powell (1992) and compared with Zone III of Harland (1979).

Lithostratigraphy

Offshore, the *Melitasphaeridium choanophorum* Zone occurs in the Nordland Group (Deegan and Scull, 1977). It has not been recorded onshore.

Sequencestratigraphy

The *Melitasphaeridium choanophorum* Zone occurs in the Sequence G (Rasmussen et al., 2005b).

Correlation with other dinocyst zonations

The *Melitasphaeridium choanophorum* Zone correlates with the revised Northwest European dinocyst subzones D20b – lower D21a of Powell and Brinkhuis (2004)(Fig. 6).

Biostratigraphic correlation

The *Melitasphaeridium choanophorum* Zone correlates with NN13–NN15 according to Powell and Brinkhuis (2004).

Age

Zanclean (Early Pliocene), 5.0 Ma to 3.6 Ma. *Barssidinium evangelineae* occur for the last time at approximately 5.0 Ma and *Melitasphaeridium choanophorum* occurs for the last time at approximately 3.6 Ma according to Powell and Brinkhuis (2004). The duration of the zone is then approximately 1.4 My.

Comments

The original definition is from the first occurrence of *Spiniferites* cf. *pseudofurcatus* to the first occurrence of *Spiniferites elongates* (Powell 1992) and is compared to Zone III of Harland (1979). The present revision introduces a much shorter and more applicable zone. The name of the zone is retained because *Melitasphaeridium choanophorum* is a prominent and easy recognisable species with in the zone, and because the upper limit of the zone is defined by this species

Barssidinium pliocenicum Zone (new)

Definition

The *Barssidinium pliocenicum* Zone is defined from the last occurrence of *Melitasphaeridium choanophorum* (Deflandre and Cookson, 1955) Harland and Hill, 1979 to the first occurrence of *Impagidinium multiplexum* Wall and Dale, 1968.

Diagnostic events

Invertocysta lacrymosa occurs for the last time in the basal part of this zone followed by the last occurrences of *Barssidinium graminosum* and *Bitectatodinium raedewaldii*. The last occurrence of *Barssidinium pliocenicum* occurs at the upper boundary of this zone.

General assemblage

The dinocysts are abundant in the lower part of the zone but much more limited in the upper part. *Achomosphaera andalousiensis* dominates the lower assemblage whereas *Spiniferites* spp. and *Operculodinium* spp. are abundant to common in most samples. Reworked dinocysts are frequent in all samples and terrestrial organic material is abundant.

Reference- and boundary sections

The reference section for the *Barssidinium pliocenicum* Zone is in the Tove-1 well in the Danish North Sea from 2330–1640’. The lower boundary of the zone is recorded in the Lone-1 well in sample 3390’, the highest sample analysed.

Lithostratigraphy

Offshore, the *Barssidinium pliocenicum* Zone occurs in the Nordland Group (Deegan and Scull, 1977). It has not been recorded onshore.

Sequencestratigraphy

The *Barssidinium pliocenicum* Zone occurs in the upper Sequence G and sequences H and I (Rasmussen et al., 2005b).

Correlation with other dinocyst zonations

The *Barssidinium pliocenicum* Zone correlates with the major part of the revised Northwest European dinocyst subzone D21a by Powell and Brinkhuis (2004) (Fig. 6). Other dinocyst zonations in the North Atlantic region and especially in the North Sea region do not include Pliocene successions or embrace Pliocene and Holocene in one dinocyst zone e.g. (Costa and Manum, 1988; Powell, 1992).

Biostratigraphic correlation

The last occurrence of *Melitasphaeridium choanophorum* can be indirectely correlated with lowermost nannoplankton Zone NN16 (Powell and Brinkhuis, 2004). The first occurrence of *Impagidinium multiplexum* in the North Sea Basin can be indirectely correlated with NN17–18 based on the age of the event (Head, 1998; Gibbard and van Kolfschoten, 2004).

Age

Piacensian to earliest Gelasian (Middle Pliocene to Late Pliocene), 3.6 Ma to 2.6–2.4 Ma. *Melitasphaeridium choanophorum* occurs for the last time approximately at 3.6 Ma according to Powell and Brinkhuis (2004). *Impletosphaeridium multiplexum* appears for the first time 2.6–2.4 Ma (Head, 1998) i.e. in lowermost Gelasian. The duration of the zone is then approximately 1 to 1.2 My. Louwye et al. (2004) indicate the last occurrence of *Barssidinium pliocenicum* at 2.6 Ma in the North Sea.

Comments
Williams and Bujak (1977) used the highest occurrence of *Melitasphaeridium choanophorum* to discriminate the Pliocene offshore eastern Canada, and Powell (1992) applied the *Melitasphaeridium choanophorum* Zone in Northwest Europe considering the last occurrence of *M. choanophorum* approximately at the top of Zanclean, Lower Pliocene.

Impletosphaeridium multiplexum Zone (New)

Definition
The *Impletosphaeridium multiplexum* Zone is defined from the first occurrence of *Impletosphaeridium multiplexum* Wall and Dale, 1968 to the last occurrence of *Amiculosphaera umbraculum* Harland, 1979.

Diagnostic events
The last occurrence of *Barssidinium pliocenicum* is at the lower boundary of the zone. *Bitectatodinium tepikiense* appears in the lowermost part of the zone. Lower Pleistocene is considered highest occurrence of *Filisphaera filifera* in the North Atlantic (Mudie, 1989; de Vernal et al., 1992).

General assemblage
Operculodinium spp. and Spiniferites spp. dominate the assemblage. *Bitectatodinium tepikiense*, *Habibacysta tectata* and *Filisphaera filifera* are locally common.

Reference- and boundary sections
The *Impletosphaeridium multiplexum* Zone occurs from 1490–1340' in the Tove-1 exploration well in the Danish North Sea.

Lithostratigraphy
Offshore, the *Impletosphaeridium multiplexum* Zone occurs in the Nordland Group (Deegan and Scull, 1977). It has not been recorded onshore.

Sequencestratigraphy
The *Impletosphaeridium multiplexum* Zone is not correlated to any sequence stratigraphic subdivision at present.

Correlation with other dinocyst zonations

The *Impletosphaeridium multiplexum* Zone correlates with the lower part of the revised Northwest European dinocyst subzone D21b (Powell and Brinkhuis, 2004) (Fig. 6).

Biostratigraphic correlation

The first occurrence of *Impagidinium multiplexum* can indirectly be correlated with approximately NN17–18 in the nannoplankton zonation (Martini, 1971) based on the age of the event (Head, 1998; Gibbard and van Kolfschoten, 2004). The last occurrence of *Amiculosphaera umbraculum* is indirectly correlated with lower NN19 nannoplankton zone (Head, 1998; Gibbard and van Kolfschoten, 2004).

Age

Gelasian to the earliest Pleistocene (Late Pliocene to earliest Pleistocene), 2.6–2.4 Ma to 1.6 Ma. *Impletosphaeridium multiplexum* appears for the first time at 2.6–2.4 Ma (Head, 1998), i.e. in lowermost Gelasian. *Amiculosphaera umbraculum* is reported in the lowermost Pleistocene where it occurs for the last time at approximately 1.6 Ma (Harland, 1992; Powell, 1992; Head, 1998; Williams et al., 2004). The duration of the zone is then approximately 1.0 My.

Comments

Head (1998) demonstrates the stratigraphic distribution of the key species in the western North Sea Basin, eastern England.

Discussion

Geographical extent and thickness of the zones

The geographical extent and the thickness of the dinocyst zones defined herein, reflect the complex geological history of the study area. Detailed mapping of the extent of the single zones will not be presented here, but the overall picture will be briefly outlined in the following.

As would be expected, the presence and thicknes of the zones varies significantly both in proximal to distal and in lateral directions. Generally the succession offshore Denmark, representing the more central parts of the depositional basin in the Miocene, is much thicker and stratigraphic more complete than the onshore succession, while missing successions are generally identified in presently onshore settings. For example, in the Frida-1 well an extraordinarily (more than 800 m) thick and probably complete Upper Oligocene – Lower Miocene succession occurs (see the thickness variation from the onshore Lillebælt succession to the corresponding succession in Frida-1 in Dybkjær and Rasmussen, 2007, Fig. 7), while the late Aquitanian *Caligodinium amiculum* Zone is missing in large areas onshore.

Neogene uplift of the Fennoscandian Shield, tilting towards the southwest, and increased subsidence of the North Sea Basin in the Middle Miocene and again in the Late Miocene and Pliocene, followed by glacial erosion have resulted in a pattern where the onshore deposits comprising the oldest dinocyst zones (*D. phosphoritica* Zone, *C. galea* Zone and *Homotryblium* spp. Zone) are outcropping in the north-eastern parts of the study area along the eastcoast of Jylland, in the Lillebælt and Vejle Fjord area, while the deposits comprising the youngest dinocyst zones present onshore (the *Labyrinthodinium truncatum* to *Hystrichosphaeropsis obscura* Zones), outcrops in the southwestern parts of Jylland. The four uppermost dinocyst zones; *Selenopemphix armageddonensis*, *Melitasphaeridium choanophorum*, *Barssidinium pliocenicum* and *Impagidinium multiplexum* Zones of latest Tortonian to earlist Pleistocene age, are not preserved onshore. The tilting and the truncation of the Neogene succession are obvious on seismic sections (Fig. 4b).

Correlation with previous dinocyst zonations

A correlation of the zonation presented herein with previous zonations within the North Sea Basin (Köthe, 2003; Strauss et al., 2001; Munsterman and Brinkhuis,

2004) and to the North Atlantic (the USA Eastcoast) (de Verteuil and Norris, 1996) is presented in figure 6. Correlation to the zonation of Powell and Brinkhuis (2004) for northwest Europe, presented in the latest “Geologic Time Scale” by Gradstein et al. (2004) is also shown. In contrast to most of the previous zonations, the present zonation covers the complete Neogene succession. Furthermore, the present zonation gives a subdivision which is more detailed at the Oligocene–Miocene transition, in the Lower Miocene and in the Upper Miocene and Pliocene successions.

As we have selected diagnostic species of proven stratigraphic importance to define the dinocyst zones through the Danish Neogene, the correlation is remarkable straight forward even across the North Atlantic. This probably reflects the high quality of the studies of the Neogene dinocyst floras and the usefulness of dinocysts for biostratigraphic correlation. The Messinian – Pliocene dinocyst stratigraphy is the least studied part of the Neogene with respect to formal biostratigraphy but in contrast, the dinocyst taxonomy, stratigraphy and distribution as well as absolute dating have progressed remarkably in the last years due to the combined efforts of M. Head, S. Louwye and S. de Schepper.

Distinct changes in relative abundance used for defining zonal boundaries herein, are probably only of local use (in the Danish area, or perhaps within the North Sea Basin), e.g. the last common occurrence *Deflandrea phosphoritica* (defining the top of the *D. phosphoritica* Zone) and the last common occurrence of *Homotryblium* spp. (defining the top of the *Homotryblium* spp. Zone). These events are based on abundance-variations, which are assumed to reflect changes in the depositional environment. However, these abundance variations have been recognized all over the study area, comprising a wide variety of depositional environments, possibly due to transport/spreading of the cysts by currents. Future studies will show the extent of their use.

In the correlation scheme in figure 6, dinocyst zones defined by the same events are shown to be isochronous, although this is probably not always true. E.g. the first occurrences of *Exochosphaeridium insigne* and of *Cousteaudinium aubryae* are in the Aquitanian in the USA Eastcoast, according to de Verteuil and Norris (1996), while they in the present study appear in the early Burdigalian and in the late Burdigalian, respectively. Such apparent diachronity of some dinocyst events from outer regions and into the North Sea Basin may be due to a periodically, very narrow sea-way connection from the North Sea Basin to the North Atlantic Ocean. Differences in temperature or salinity of sea-surface water between the North Sea Basin and the North Atlantic Sea may also be responsible for diachronity of first occurrences and last occurrences. Strontium isotope datings and C-13 isotope curves may help in the future to support correlations between successions within and outside the North Sea Basin.

Correlation with other microfossil zonations

Nannoplankton

A correlation between the dinocyst zonation erected herein with the calcareous nannofossil zonation of Martini (1971) is presented in figure 6. The correlation is indirect, based on the absolute ages of the nannoplankton zones as indicated in Lourens et al. (2004), as no nannofossil-studies of the Danish Neogene succession has been published until now.

Foraminifera

Laursen and Kristoffersen (1999) worked out the foraminifer stratigraphy of the same Danish onshore sediments as studied here for dinocysts. We have even analysed a few of the same, older wells as they analysed in their study, e.g Gram-1, Borg-1 and Høruphav-1. A direct correlation between the dinocyst zonation defined herein and the foraminifer zonation of Laursen and Kristoffersen (1999), based on analyses of the successions in these three wells is presented in figure 7. Furthermore, a study of the foraminifera in the offshore well Frida-1, resulted in a direct correlation to the benthic North Sea Foraminifer Zonation of King (1989) (pers. com. Emma Sheldon, GEUS, 2008) for the *D. phosphoritica* and the *Caligodinium amiculum* Zones.

Even though such direct correlations should be straigth forward there are many problems. The conclusive foraminifer stratigraphy scheme (Laursen and Kristoffersen, 1999; Fig. 13) is deviating from the specific results in specific wells, e.g. the identified NSP (North Sea Planktonic foraminifer) zone in a specific sample and the corresponding NSB (North Sea Bentonic foraminifer) zone may suggest diffent stratigraphic levels. Furthermore, the conclusive stratigraphy and zonation are different from the central North Sea foraminifer stratigraphy (King, 1989), e.g. new ages are referred to some zones and the bethonic *versus* the planktonic zones are correlated differently. However, the best possible correlation between dinocyst and foraminifer zonations is attempted here, and even though the Danish foraminifer zonation apparently is not much applied for North Sea stratigraphy, this correlation also create a secondary correlation to the traditional, central North Sea, foraminifer stratigraphy (Fig. 7).

The foraminifer zonations was by Laursen and Kristoffersen (1999) correlated with the nannoplankton zonation of Martini (1971) (Fig. 7). This correlation should be equal to the nannoplankton zonation correlated from the dinocyst zonation (Fig. 6) if everything is worked out correctly. This is not the case; actually there are very limited stratigraphic agreement as the displacement of the stratigraphy is at least one nannoplankton zone throughout the succession. One exception is in the uppermost Gram Formation where both dinocyst and foraminifer stratigraphy correlates with nannoplankton zone NN11 (Figs. 6 and 7). The problems with the correlation of the dinocysts and the foraminifer zonations probably illustrate the stratigraphic limitation of foraminifer faunas in marginal marine settings.

Absolute datings of the zonal boundaries and the lasting of each zone

In most cases the age of the zonal boundaries given herein are based on previously published biochronostratigraphic schemes, e.g. Williams et al. (2004) and Powell and Brinkhuis (2004), which again are mostly based on the combined dinocyst stratigraphy and strontium isotope datings of de Verteuil and Norris (1996) and de Verteuil (1997).

To support these informations, especially in the light of the obvious problems with diachroneous first- and last occurrences of dinocyst species between the study areas of the previous studies and the areas studied herein, we included some new Sr-isotope datings of mollusc shells from the Sdr. Vium borehole and from a few outcrops in the present study. These new datings are concentrated on the Lower Miocene succession where the largest problems and disagreements in the previous datings seem to have been. A more comprehensive analytical program is presently carried out, and will bed presented later.

The longest lasting zone, the *Amiculospharea umbraculum* Zone, covers ca. 2.6 million years in the Late Miocene, whereas the shortest Zone, the *Achomosphaera andalousiensis* Zone, spans ca. 0.4 million years.

Conclusion

A dinocyst zonation for the complete Neogene succession in the eastern part of the North Sea Basin (Denmark) is presented. The zonation comprises nineteen dinocyst zones of which most are newly defined herein. Compared with previously published zonations from the Neogene, the presented zonation is remarkable for its detailed subdivision of the Oligocene–Miocene transition, of the Lower Miocene and of the Upper Miocene and Pliocene successions.

The zonation is correlated with other biostratigraphic subdivisions of the Neogene succession in the Danish region as well as litho- and sequencestratigraphy. Absolute ages of the new dinocyst zones are proposed based on correlation from the studied succession within the North Sea Basin with the international zonations and stratigraphic schemes. Parts of the succession have been dated by strontium isotope analysis in mollusc shells.

Neogene biostratigraphy in the North Sea Basin has been problematic due to the periodically, limited connection from the North Sea Basin to the North Atlantic Ocean, especially with respect to stratigraphy based on foraminifers and calcareous nannoplankton. Many of the stratigraphically most important taxa, e.g. those defining stratigraphic boundaries in typesections, have not been found within the North Sea Basin. This problem seems to be solved by correlation based on the new dinocyst stratigraphy, because stratigraphic significant taxa do occur in the North Sea deposits, even in marginal marine settings.

The new Neogene dinocyst stratigraphy for the Danish area has provided a stratigraphic tool with higher resolution and wider application than any previous stratigraphies. This stratigraphy gives the possibility to discriminate and correlate sedimentary units e.g. deltaic sand systems and lobes in wells and to correlate these units on seismic section in details not possible before. The integration of biostratigraphy, sedimentology, sequence stratigraphy, well logs and seimic data lead to solution of several, historical geological problems in the Danish Miocene:

The stratigraphy of the Upper Oligocene – Lower Miocene onshore strata is understood for the first time (e.g. Dybkjær and Rasmussen, 2000; Dybkjær, 2004a, 2004b; Rasmussen and Dybkjær, 2005) and strata previously believed to be mid-Miocene are now referred to the Lower Miocene Vejle Fjord Formation (e.g. Rasmussen et al., 2006). The detailed, but fragmented, onshore Upper Oligocene – Lower Miocene stratigraphy was compared with the corresponding, but more complete, strata in the North Sea well, Frida-1, and successfully correlated, and the location of the Oligocene–Miocene boundary in the

Danish area was pointed out (Rasmussen, 2004a; Rasmussen and Dybkjær, 2005; Dybkjær and Rasmussen, 2007).

The stratigraphic position and regional extent of three major delta systems in the Lower – Middle Miocene is specified on the basis of dinocyst stratigraphy and illustrates the significance of the interplay between eustatic sea-level changes, regional and local tectonics and the Ringkøbing-Fyn High in relation to the deposition of the Miocene succession in Denmark (e.g. Rasmussen, 2004a, b; Rasmussen and Dybkjær, 2005; Rasmussen et al., 2006).

The age of the Gram Formation is specified to the late Serravallian – Tortonian (late Middle Miocene to early Late Miocene) in contrast with the foraminifer stratigraphy but basically in accordance with the old mollusc stratigraphy (Piasecki, 2005). The palaeodepositional and –climatic conditions of the Hodde and Gram Formations are illucidated on the basis of the dinocyst floras and the organic content.

Dinocyst studies were extended offshore to the younger Neogene based on material from the wells Tove-1, S-1 and Lone-1 in the Danish North Sea, for mapping the strata missing onshore and to illustrate the tilting and erosion of the Neogene succession (Piasecki and Rasmussen, 2004; Rasmussen et al., 2005b).

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Figure list

Fig. 1: Map of Denmark showing the location of studied wells and exposures. The insert map shows the location of the offshore exploration wells included in this study.

Fig. 2: Paleogeographic reconstruction of the North Sea Basin and adjacent areas in the Miocene. Based on Knox et al. (in press) and Rasmussen et al. (2008).

Fig. 3a to h: Paleogeographic maps showing the changing position of the coastline, resulting from changes in eustatic sea-level and large-scale tectonic events. From Rasmussen et al. (in prep.).

Fig. 4a: Geological map of the Neogene succession subcropping the Quaternary cover. Note the progressively younger sediments towards the west. The location of the seismic line shown in Figure 4b is indicated. **b**: Seismic section trending ENE-WSW, showing the Neogene succession. Note the marked truncation of the succession towards the ENE. For location, see figure 4a. From Rasmussen et al. (2005).

Fig. 5: Lithostratigraphy of the Danish Neogene succession, from Rasmussen et al. (in prep.). The age of the succession is shown to the left and the sequence stratigraphy is indicated to the right.

Fig. 6: Dinocyst zonation scheme for the Danish Neogene succession. Note that the younger Neogene strata are not present onshore and therefore we present a twofold, on- and offshore zonation. Correlation with previous published dinocyst zonations within the North Sea Basin (Köthe, 2003, 2005a; Köthe and Andruleit, 2007; Munsterman and Brinkhuis, 2004), with the revised Northwest European zonation by Powell and Brinkhuis (2004) and with the North Atlantic zonation by de Verteuil and Norris (1996) is shown. Dashed lines indicate where the zonal fossil is absent and the zonal boundary is identified on accesory fossils. The Danish dinoflagellate stratigraphy is correlated with the standard nannofossil zonation (Martini, 1971) on the basis of published correlations and absolute ages of the dinoflagellate events.

Fig. 7: Correlation with the North Sea foraminifer zonation of King (1989) and the revised Danish North Sea foraminfer zonation of Laursen and Kristoffersen (1999). The foraminifer stratigraphies are correlted with the standard nanno-

plankton zonation (Martini, 1971). Note that the foraminfer correlation with the standard nannoplankton zonation (to the right) deviates significantly from the correlation between the dinoflagellate zonation and the nannoplankton zonation (to the left).

Fig. 8: Illustrations of the zonal dinoflagellate cyst species. Magnification x 400.
A. *Distatodinium biffii* Brinkhuis et al., 1992.
B. Deflandrea phosphoritica Eisenack, 1938.
C. *Chiropteridium galea* (Maier, 1959) Sarjeant, 1983.
D. *Exochosphaeridium insigne* de Verteuil and Norris, 1996.
E. *Thalassiphora pelagica* (Eisenack, 1954) Eisenack and Gocht, 1960, emended
Benedek and Gocht, 1981.
F. Caligodinium amiculum Drugg, 1970.
G. Membranophoridium aspinatum Gerlach, 1961.
H. *Thalassiphora rota* Schiøler, 2005.
I. *Cordosphaeridium cantharellus* (Brosius, 1963) Gocht, 1969.
J. *Sumatradinium hamulatum* de Verteuil and Norrris, 1996.
K. *Ectosphaeropsis burdigalensis* Londeix and Jan du Chêne, 1988.
L. *Homotryblium plectilum* Drugg and Loeblich, 1967.
M. *Homotryblium tenuispinosum* Davey and Williams, 1966.

Fig. 9: Illustrations of the zonal dinoflagellate cyst species. Magnification x 400.
A. Hystrichosphaeropsis obscura Habib, 1972.
B. *Paleocystodinium miocaenicum* Strauss in Strauss et al., 2001.
C. Paleocystodinium powellense Strauss et al., 2001.
D. *Cannosphaeropsis passio* de Verteuil and Norris, 1996.
E. Labyrinthodinium truncatum Piasecki, 1980.
F. Achomosphaera andalousiensis Jan du Chêne, 1977.
G. *Unipontidinium aquaeductus* (Piasecki, 1980) Wrenn, 1988.
H. *Unipontidinium aquaeductus* (Piasecki, 1980) Wrenn, 1988.
I. *Cerebrocysta poulsenii* de Verteuil and Norris, 1996.
J. *Gramocysta verricula* (Piasecki, 1980) Lund and Lund-Christensen, 1990.
K. *Cousteaudinium aubryae* de Verteuil and Norris, 1996.
L. *Cleistosphaeridium placacanthum* (Deflandre and Cookson, 1955) Eaton et al., 2001.
M. *Polysphaeridium zoharyi* (Rossignol, 1962) Bujak et al., 1980.

Fig. 10: Illustrations of the zonal dinoflagellate cyst species. Magnification x 400.
A. Amiculosphaera umbraculum Harland, 1979.

B. *Barssidinium pliocenicum* (Head, 1993) Head, 1994.

C. *Impagidinium multiplexum* (Wall and Dale, 1968) Lentin and Williams, 1981.

D. *Erymnodinium delectabile* (de Verteuil and Norris, 1992) Lentin et al., 1994.

E. Barssidinium evangelineae Lentin et al., 1994.

F. Bitectatodinium tepikiense Wilson, 1973.

G. *Reticulosphaera actinocoronata* (Benedek, 1972) Bujak and Matsuoka, 1986.

H. *Selenopemphix armageddonensis* de Verteuil and Norris, 1992.

I. *Melitasphaeridium choanophorum* (Deflandre and Cookson, 1955) Harland and Hill, 1979.

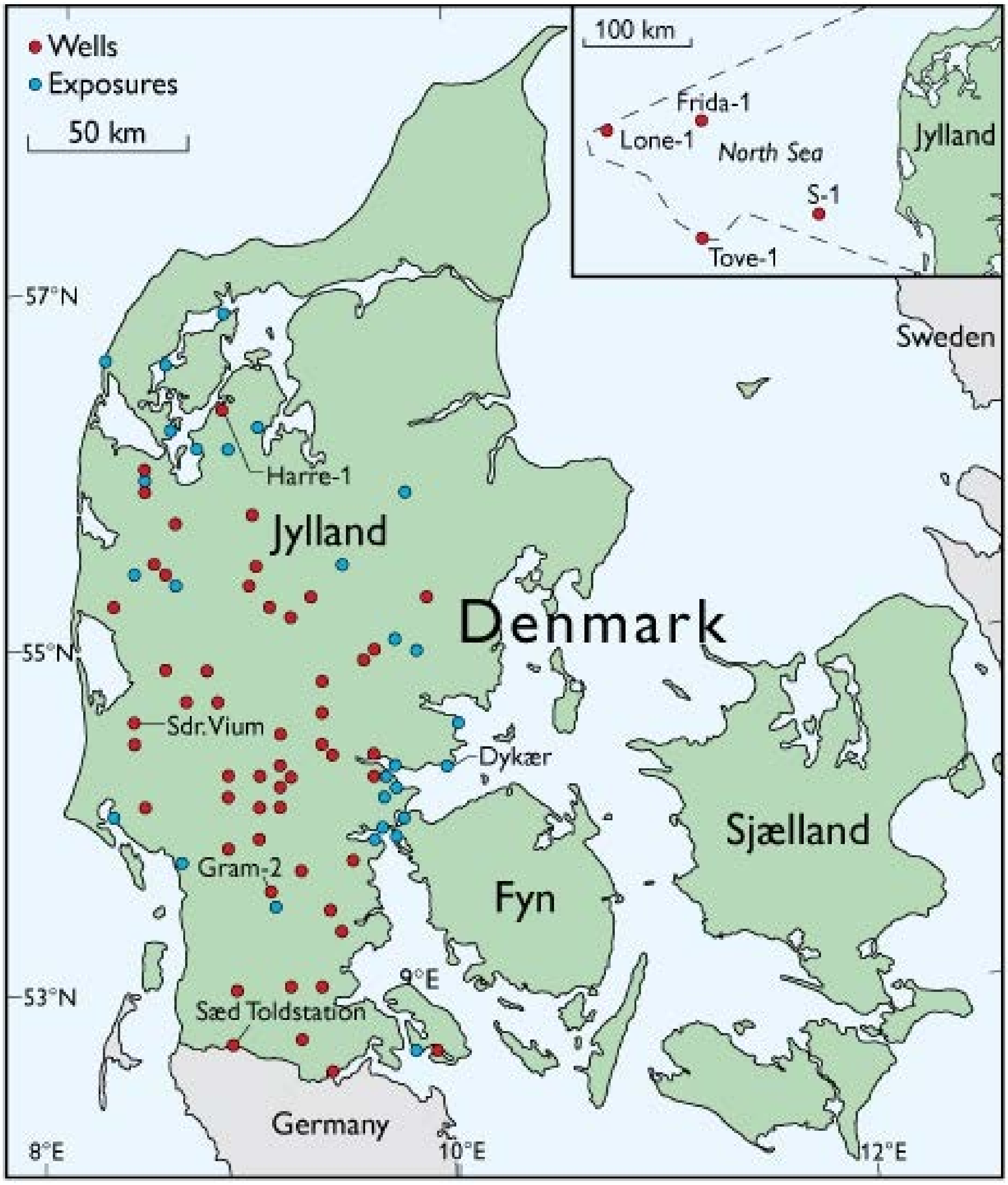

Wells
Exposures
50 km
100 km
Frida-1
Lone-1
North Sea
S-1
Tove-1
Jylland
Sweden
57°N
Harre-1
Jylland
Denmark
55°N
Sdr. Vium
Dykær
Sjælland
Gram-2
Fyn
9°E
53°N
Sæd Toldstation
Germany
8°E
10°E
12°E

Fig. 1


North Atlantic Ocean
Fennoscandian shield
North Sea Basin
Sorgenfrei-Tornquist Zone
Ringkøbing-Fyn High
Bohemian massif
Rhenish massif
500 km

Fig. 2

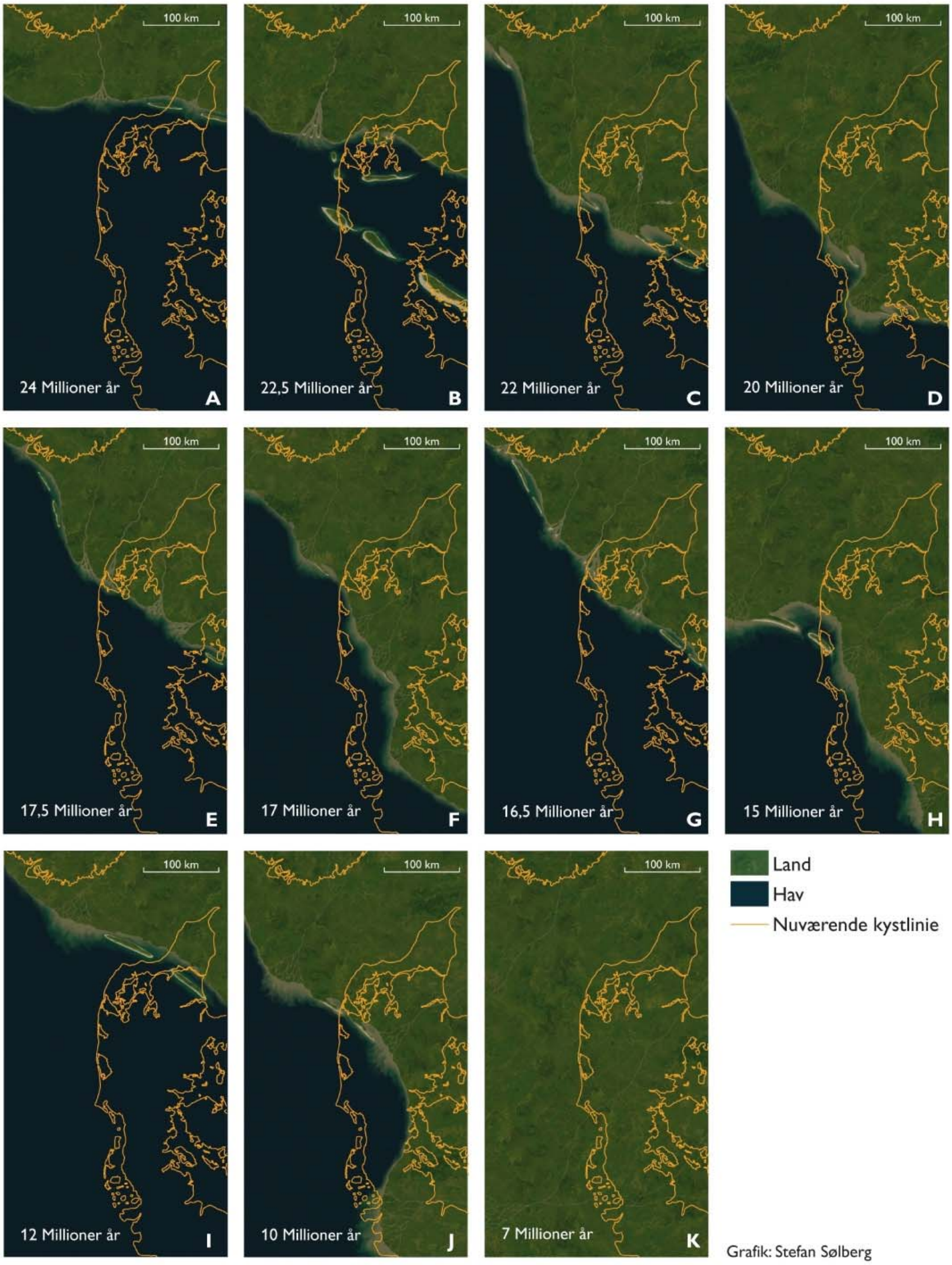
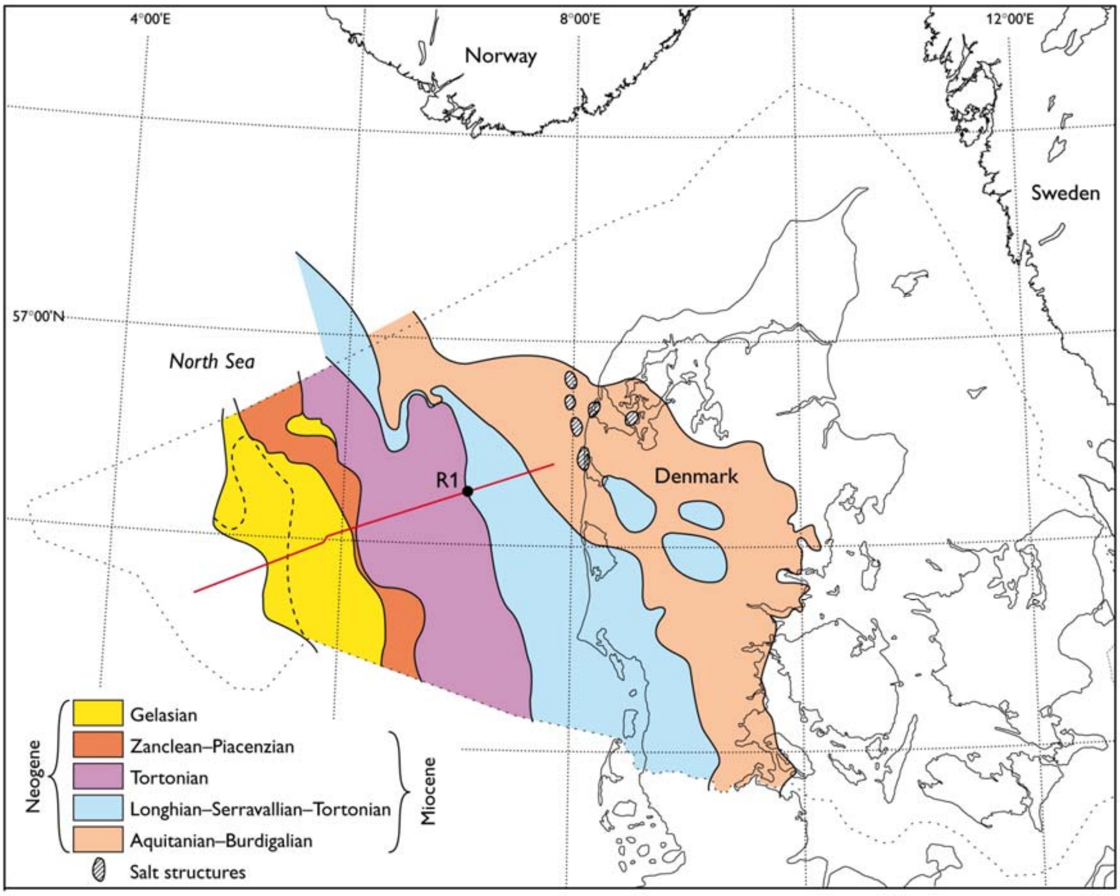
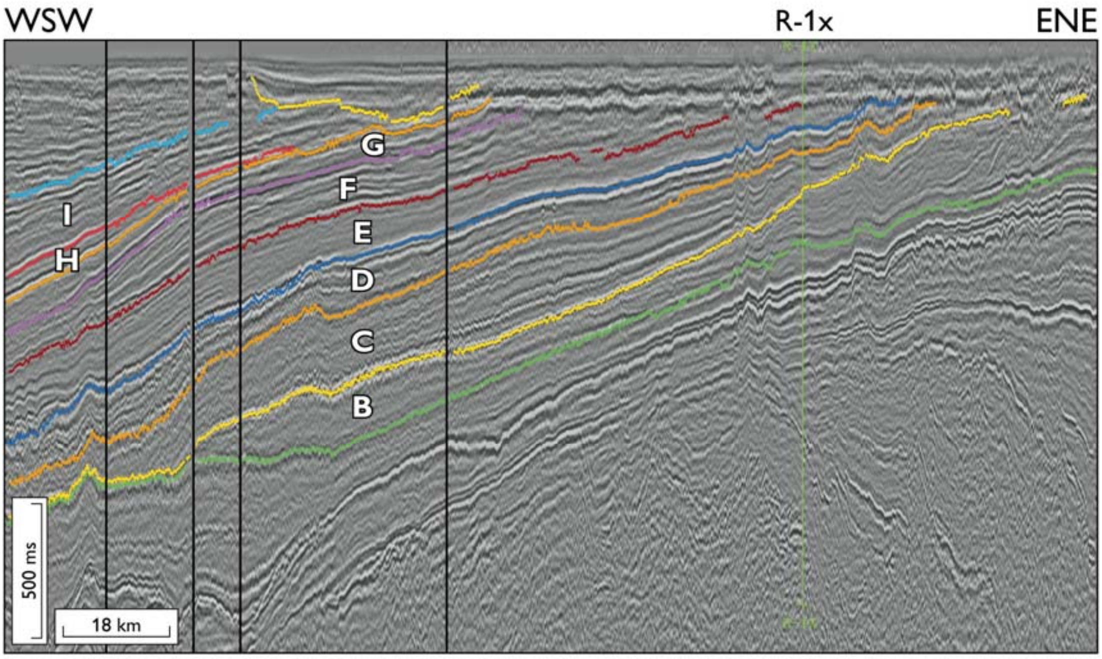

100 km
24 Millioner år
A
22,5 Millioner år
B
22 Millioner år
C
20 Millioner år
D
17,5 Millioner år
E
17 Millioner år
F
16,5 Millioner år
G
15 Millioner år
H
12 Millioner år
I
10 Millioner år
J
7 Millioner år
K
Land
Hav
Nuværende kystlinie
Grafik: Stefan Sølberg

Fig. 3



4°00'E
8°00'E
12°00'E
Norway
Sweden
57°00'N
North Sea
R1
Denmark
Gelasian
Zanclean–Piacenzian
Tortonian
Longhian–Serravallian–Tortonian
Aquitanian–Burdigalian
Salt structures
Neogene
Miocene

Fig. 4A



WSW
R-1x
ENE
G
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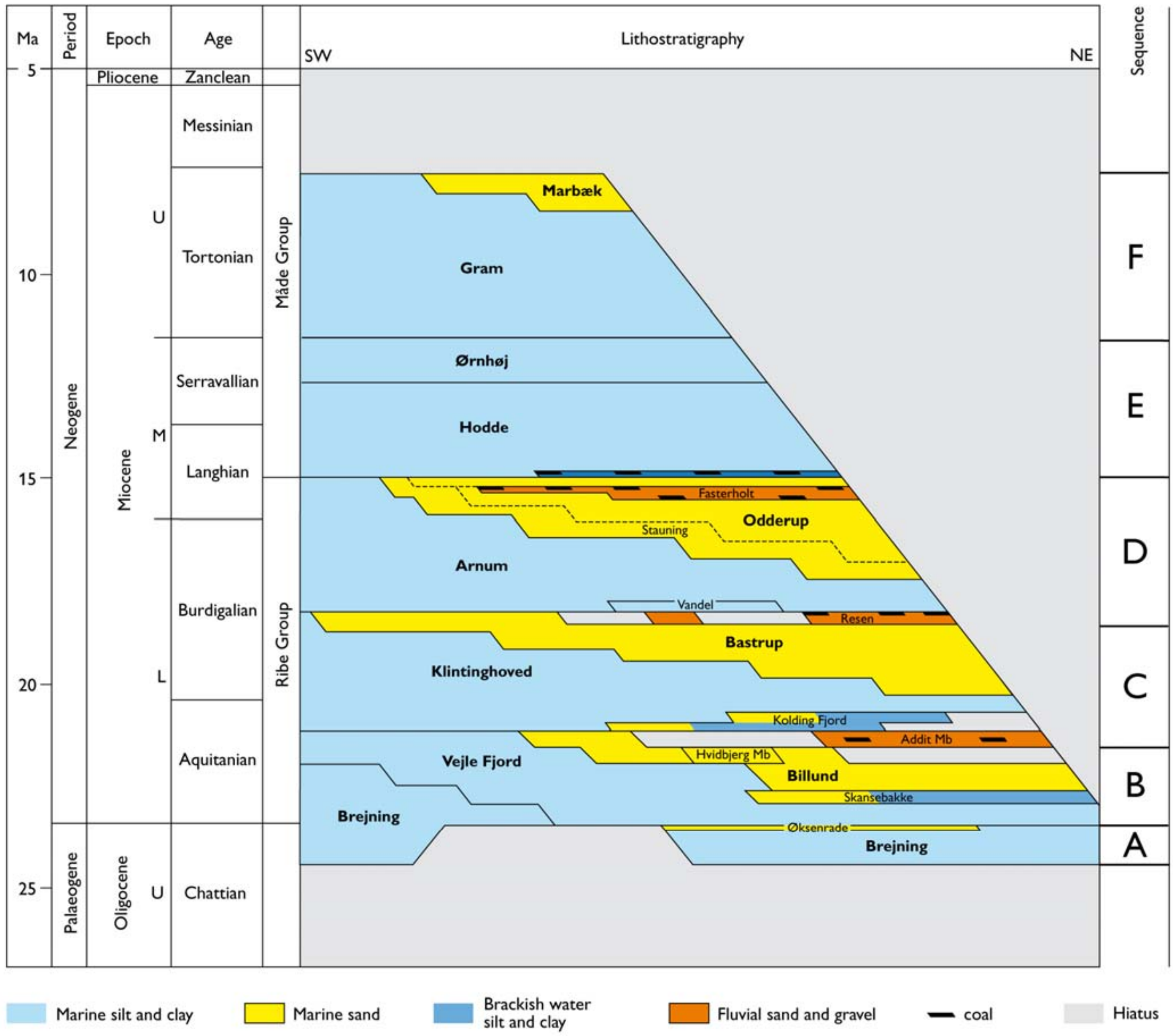
D
C
B
I
H
500 ms
18 km

Fig. 4B


Ma
Period
Epoch
Age
Lithostratigraphy
SW
NE
Sequence
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10
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25
Neogene
Palaeogene
Pliocene
Miocene
Oligocene
U
M
L
U
Zanclean
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
Måde Group
Ribe Group
Marbæk
Gram
Ørnhøj
Hodde
Fasterholt
Stauning
Odderup
Arnum
Vandel
Resen
Bastrup
Klintinghoved
Kolding Fjord
Addit Mb
Hvidbjerg Mb
Vejle Fjord
Billund
Skansebakke
Brejning
Øksenrade
Brejning
F
E
D
C
B
A
Marine silt and clay
Marine sand
Brackish water silt and clay
Fluvial sand and gravel
coal
Hiatus

Fig. 5

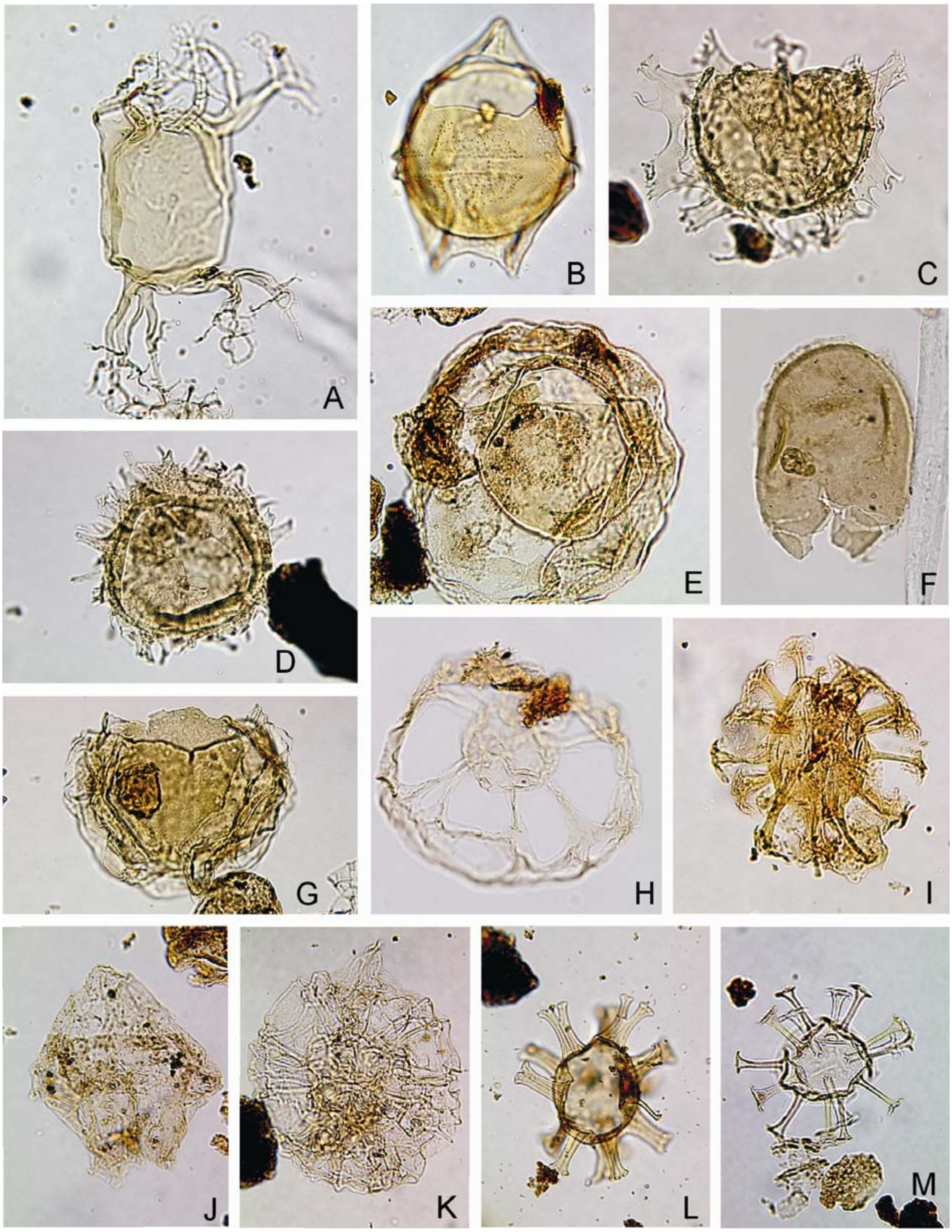

Fig. 8

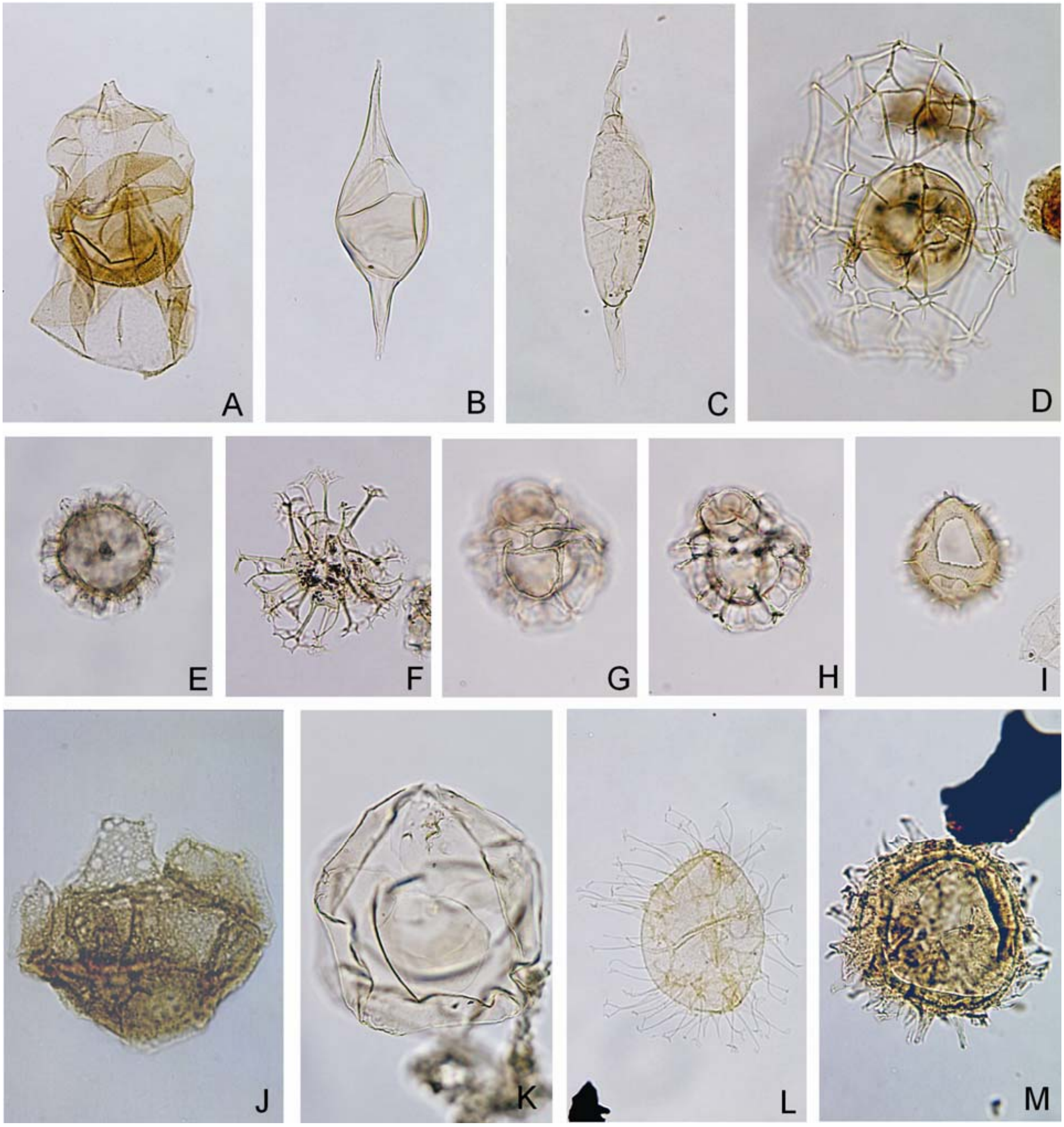

Fig. 9

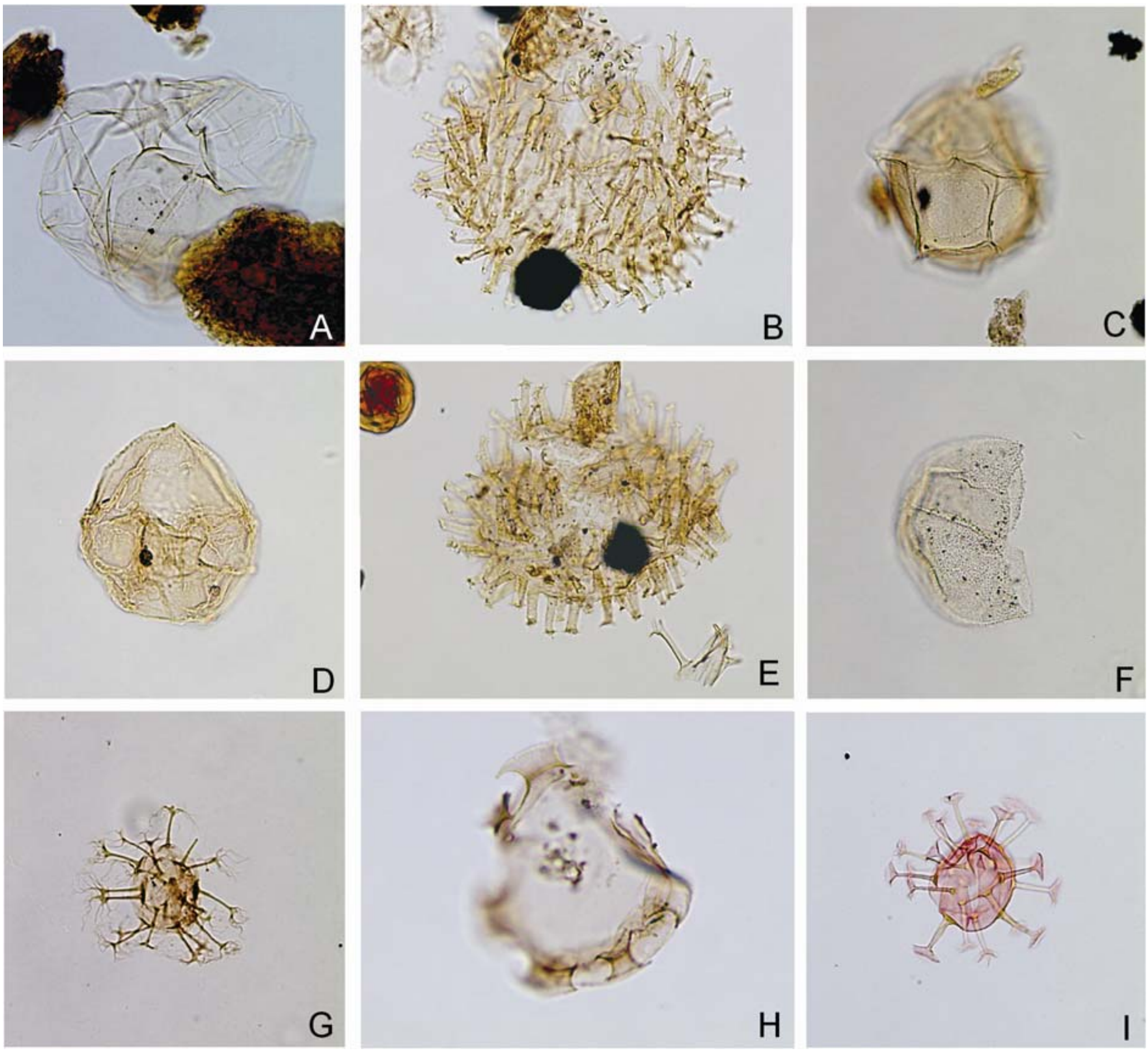

Fig. 10