

Organic-walled dinoflagellate cyst stratigraphy in an expanded Oligocene–Miocene boundary section in the eastern North Sea Basin (Frida-1 Well, Denmark) and correlation from basinal to marginal areas

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ABSTRACT – The organic-walled dinoflagellate cyst (dinocyst) assemblages in an unusually thick (>800m) Oligocene–Miocene boundary succession from the eastern North Sea Basin (the Frida-1 Well) were studied. Six successive dinocyst assemblages are described: the *Wetzeliella gochtii* Assemblage (early Chattian), the *Distatodinium biffii* Assemblage (Chattian), the *Deflandrea phosphoritica* Assemblage (latest Chattian), the *Homotryblum* spp. Assemblage (early Aquitanian), the *Caligodinium amiculum* Assemblage (Aquitanian) and the *Cordosphaeridium cantharellus* Assemblage (latest Aquitanian to early Burdigalian). The dinocyst assemblages are compared with informal dinocyst zonations proposed for the southern North Sea Basin (Germany, Belgium and the Netherlands).

A correlation of the expanded basinal succession in Frida-1 with the marginal marine succession found onshore Jylland, based on the dinocyst stratigraphy combined with well logs and seismic data, is proposed. This correlation confirms earlier proposed datings of the onshore deposits and the presence of several hiati. Furthermore, the correlation made it possible to subdivide the succession in Frida-1 into the sequences A–C, as defined onshore. The Mi-1 glaciation event and thus the Oligocene–Miocene boundary are proposed to correlate to the boundary between sequences A and B. *J. Micropalaeontol.* 26(1): 1–17, April 2007.

KEYWORDS: *North Sea, Oligocene–Miocene, organic-walled dinoflagellate cysts, sequence stratigraphy, Mi-1 glaciation event*

INTRODUCTION

The Global Stratotype Section and Point (GSSP) for the base of the Neogene System, and thus for the Oligocene–Miocene boundary, is defined in the Lemme–Carrosio section in northern Italy (Steininger *et al.*, 1997). The final ratification of the GSSP in 1996 initiated a series of studies (e.g. Flower *et al.*, 1997; Zachos *et al.*, 1997, 2001a; Paul *et al.*, 2000; Shackleton *et al.*, 2000) aimed at locating the boundary in other parts of the world, and testing the existence of a global climatic change near the Oligocene–Miocene boundary, the Mi-1 glaciation event, as proposed by Miller *et al.* (1987, 1991).

The understanding of the Upper Oligocene–Lower Miocene succession onshore Denmark, in Jylland (Fig. 1) has improved considerably during the last couple of years due to a series of new boreholes, new seismic data and studies of outcrops. The new interest in these deposits is related to the presence of large and relatively shallow sandbodies, comprising aquifers for groundwater. The succession represents the marginal parts of the eastern North Sea Basin and the sediments were deposited in alternating back-barrier, deltaic and inner- and outer-shelf environments (Larsen & Dinesen, 1959; Friis *et al.*, 1998; Rasmussen & Dybkjær, 2005). A sequence stratigraphic model (Dybkjær, 2004a; Rasmussen, 2004a; Rasmussen & Dybkjær, 2005) has been built up by correlating a number of boreholes and outcrops, using a combination of organic-walled dinoflagellate cyst (dinocyst) stratigraphy, log correlations and a few seismic lines. The model indicates the presence of several minor and major hiati and the dating of the stratigraphically incomplete succession is somewhat problematic in places.

The amount of data from the Oligocene–Miocene succession in the Danish North Sea sector has also improved during the last

decade, as a number of new wells have been drilled and large amounts of new seismic data have been generated (e.g. Michelsen *et al.*, 1998; Rasmussen, 2004b). However, as the targets for the seismic study and the wells have been deeper lying, possible hydrocarbon-bearing successions, the Oligocene–Miocene succession has been ignored and most data from this interval have never been published. The geology of this part of the North Sea succession is, therefore, presently not very well known. Palynological data of varying quality can be found in unpublished reports, while published palynological information from the Oligocene–Miocene succession in the North Sea area is very limited (see below).

The Danish North Sea well Frida-1 (Fig. 1) comprises a remarkably thick and presumably complete Upper Oligocene–Lower Miocene marine succession. The purpose of the present study is: (1) to document the dinocyst assemblages in an expanded Upper Oligocene–Lower Miocene succession in the eastern North Sea Basin, exemplified by the Frida-1 Well; (2) to testify the age of the sequences defined onshore and the proposed hiati by correlating the onshore succession with the stratigraphically more complete succession in Frida-1; (3) to subdivide the succession in Frida-1 using the sequence stratigraphic model defined onshore; and (4) to try to locate the Mi-1 glaciation event and the Oligocene–Miocene boundary within the succession in the Danish North Sea sector.

REGIONAL GEOLOGICAL SETTING

The North Sea Basin was formed as a failed rift basin in Jurassic times (Ziegler, 1982; Vejbæk, 1992). The sea was at its maximum extent during the Late Cretaceous when chalk and limestone

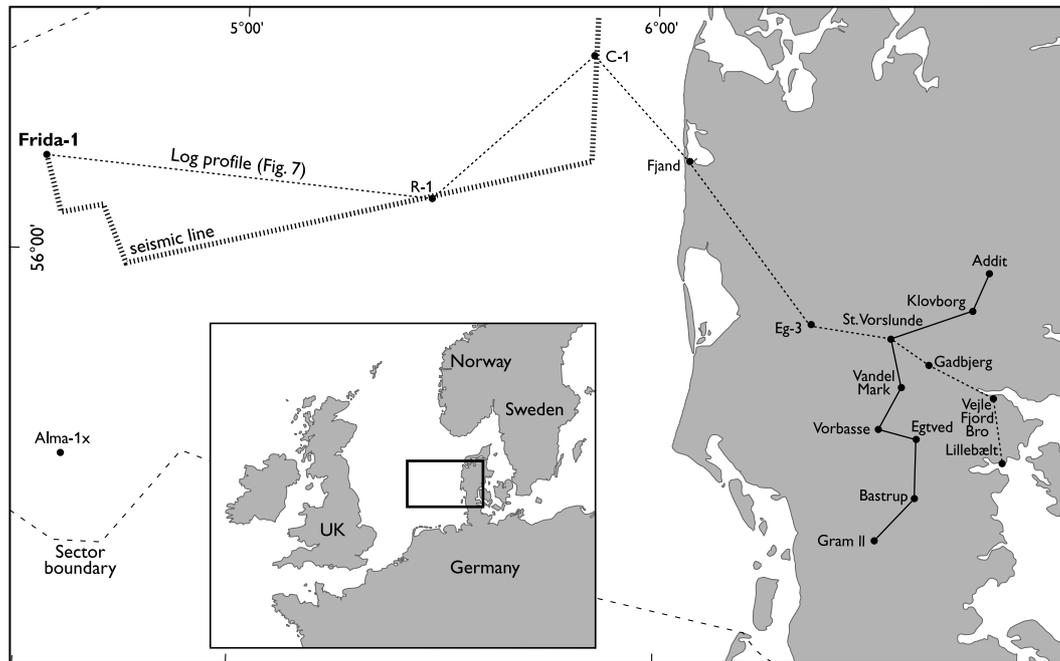


Fig. 1. Location of the Frida-1 Well and of the boreholes onshore Jylland studied by Dybkjær (2004a, b). The locations of the seismic section shown in Figure 6 and of the log-panel shown in Figure 7, respectively, are also indicated.

were deposited. Large palaeogeographical changes in the Paleocene, reflecting the Alpine orogenesis and the initial opening of the North Atlantic, resulted in distinct changes in the depositional pattern in the southern North Sea area. The sedimentation changed from the chalk-dominated biogenic deposits of the Late Cretaceous and Early Paleocene to siliciclastic deposits, at times interlayered with ash-layers during the Late Paleocene (Heilmann-Clausen, 1995a).

During the Paleocene, Eocene and most of the Oligocene, initial tectonic inversion of the western parts of the Fennoscandian Shield resulted in a marked southward progradation of the coastline. Coarse-grained, marginal marine sediments were deposited south of Norway (Jordt *et al.*, 1995) while the deposits in the Danish area consisted of basal marine clays.

In the latest Oligocene the Palaeogene progradation had reached the present-day Danish North Sea area and the palaeo-shoreline was located in the Danish area, orientated WNW–ESE. In the most marginal parts of the basin (e.g. onshore Jylland) an inner-shelf environment existed, as described by Larsen & Dinesen (1959), Friis *et al.* (1998), Rasmussen (2004a) and Rasmussen & Dybkjær (2005). In the deeper parts of the basin, outer-shelf and slope environments prevailed (Michelsen *et al.*, 1998; Rasmussen, 2004b). The height of the clinoforms seen in seismic sections (this study) indicate water depths exceeding 500 m and a succession of gravity deposits, interfingering with deep marine clay, was deposited.

In the earliest Miocene (the early Aquitanian) the environment changed to contourite deposition along the shelf slope (Hansen *et al.*, 2004). In the marginal marine areas, spit-systems, deltas and lagoons prevailed (Larsen & Dinesen, 1959; Friis *et al.*, 1998; Rasmussen, 2004a; Rasmussen & Dybkjær, 2005). Probably as a result of a major sea-level fall, a major hiatus represents the upper Aquitanian–lowermost Burdigalian in large

parts of Jylland, while a major delta was deposited in the southeastern part of Jylland (Rasmussen, 1996, 2004a; Dybkjær & Rasmussen, 2000; Dybkjær, 2004a). In the basinal areas contouritic clays were deposited continuously. The lower to mid-Burdigalian succession onshore is represented by lagoonal and inner-shelf deposits, while marine-shelf sediments were deposited in the basinal areas.

A series of sea-level changes resulted in several hiatus developing in the marginal parts of the basin and influenced the location of the coastline and the depositional environment (Dybkjær & Rasmussen, 2000; Rasmussen, 2004a, b; Dybkjær, 2004a; Rasmussen & Dybkjær, 2005). Tectonism also influenced the depositional setting. The Salian tectonic event in the mid-Oligocene initiated salt movement and reactivation of older fault segments, e.g. the Brande Trough. The Betic event, in the late Early Miocene, also affected the eastern North Sea Basin, as indicated by reactivation of salt structures and increased influx of siliciclastic sediments (Rasmussen, 2004b). The climate in the Late Oligocene–Early Miocene was humid, varying between cold temperate to subtropical (Sorgenfrei, 1958; Lotsch, 1968; Radwanski *et al.*, 1975; Buchardt, 1978).

ONSHORE STRATIGRAPHY

A sequence stratigraphic model for the uppermost Oligocene–Miocene succession in the central and southern parts of Jylland was proposed by Rasmussen (2004a). The uppermost Oligocene–Lower Miocene part of the succession was subdivided into three sequences, A–C (Fig. 2). Dybkjær (2004a, b) presented the variations in the dinocyst assemblages in a series of boreholes onshore Jylland (Fig. 1) and the ages of the sequences were discussed. This is summarized in the following sections.

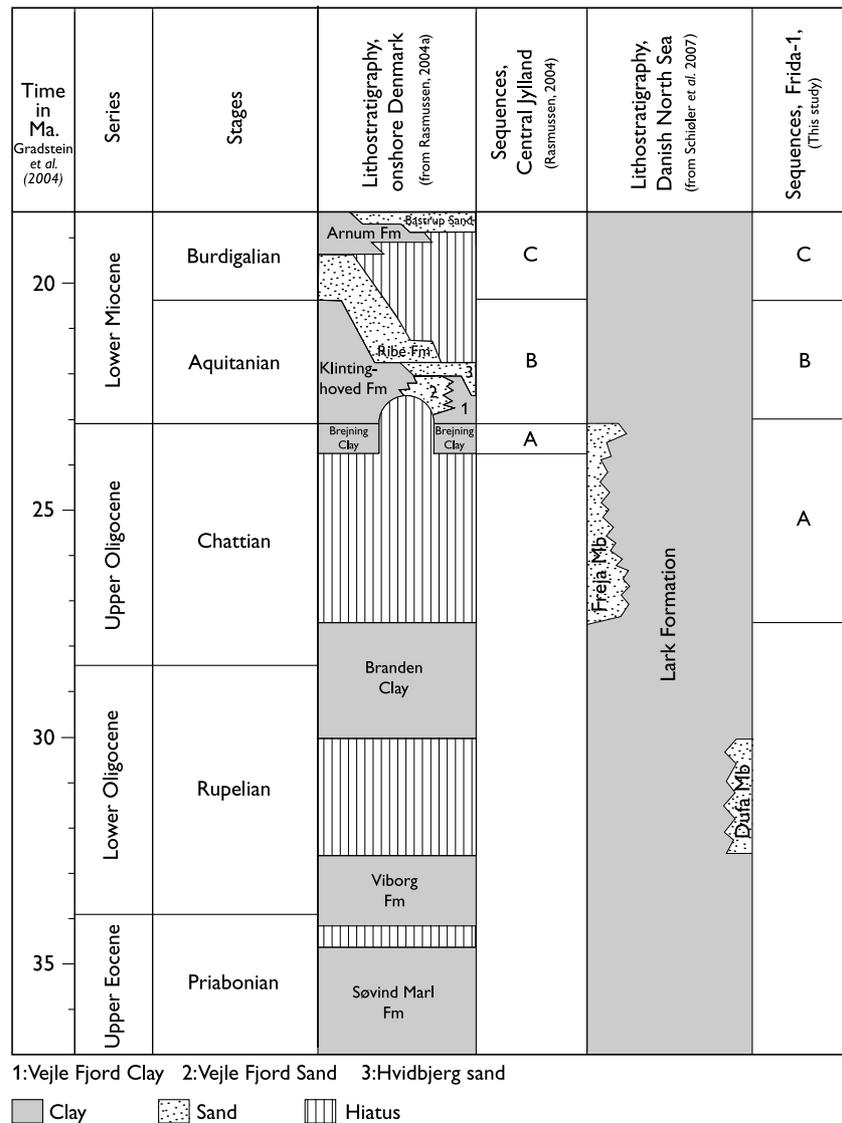


Fig. 2. Chronostratigraphy, lithostratigraphy and sequence stratigraphy onshore Jylland (Rasmussen, 2004a), lithostratigraphy in the Danish North Sea area (Schioler *et al.*, in press) and sequence stratigraphy in Frida-1. Time-scale from Gradstein *et al.* (2004).

Sequence A (latest Chattian)

In the area studied by Rasmussen (2004a) and Dybkjær (2004a) a large hiatus occurs at the basal boundary of Sequence A. Marls of Middle to Late Eocene age (the Søvind Marl) are overlain by organic-rich clayey inner-shelf deposits, referred to the Brejning Clay Member – the lowest member of the Vejle Fjord Formation (Larsen & Dinesen, 1959) (Fig. 2).

The dinocyst assemblage of Sequence A is characterized by a common occurrence of *Distatodinium paradoxum*, *Hystriocholpoma rigaudiae* and *Operculodinium centrocarpum* in the transgressive systems tract (TST), while the relative abundances of *Chiropteridium galea*, *Deflandrea phosphoritica* and *Homotryblidium plectilum* increase in the highstand systems tract (HST), towards the upper sequence boundary (Dybkjær, 2004a, b).

There is general agreement for a Late Oligocene (Chattian) age assignment for the Brejning Clay (and thus for Sequence A), but a more exact limitation within the Chattian is not clear. Molluscs in the lower part indicate a Late Oligocene age,

Chattian B (Schnetler & Beyer, 1987, 1990). Foraminifera from the same part also indicate a Late Oligocene age (King, 1983; Ulleberg, 1987), for example in the Danish Harre-1 borehole, King (1994) dated it as latest Chattian. The absence of the dinocyst species *Distatodinium biffii* made Dybkjær (2004a) suggest that Sequence A should be referred to the uppermost Chattian. According to Powell & Brinkhuis (2004a) the last occurrence of *D. biffii* is at 24.4 Ma (Fig. 3).

Sequence B (early Aquitanian)

Sequence B comprises a succession deposited in a marginal, partly restricted marine environment. The organic-rich clay is referred to the Vejle Fjord Clay (Larsen & Dinesen, 1959); in addition the sequence includes several sand units of different origin, e.g. the Vejle Fjord Sand (storm sand) (Larsen & Dinesen, 1959), the informal Hvidbjerg sand (spit system sand) and the informal Billund sand (deltaic) (see Rasmussen, 2004a).

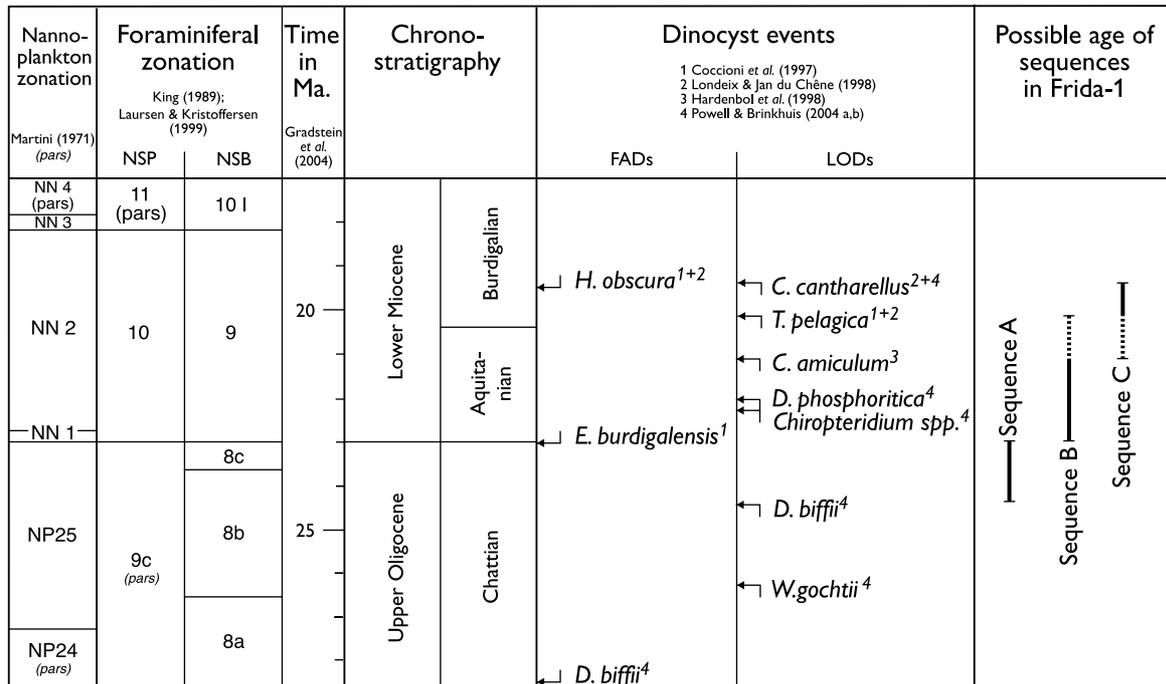


Fig. 3. Stratigraphically important dinocyst events correlated with chronostratigraphy according to the literature (Coccioni *et al.*, 1997; Hardenbol *et al.*, 1998; Londeix & Jan du Chêne, 1998; Powell & Brinkhuis, 2004a, b). The dinocyst events are correlated to nannoplankton zonation (Martini, 1971), foraminiferal zonation (King, 1989; Laursen & Kristoffersen, 1999), absolute age and chronostratigraphy. The possible age of the sequences in Frida-1 is shown. Time-scale from Gradstein *et al.* (2004).

Palynologically, the boundary between sequences A and B is characterized by a distinct decrease in relative abundance of *Deflandrea phosphoritica* and *Chiropteridium galea*. In Sequence B these species occur only sporadically. Otherwise, the sparse dinocyst assemblage of Sequence B is characterized by common to abundant occurrence of *Homotryblum* spp. and the sporadic occurrence of *Caligodinium amiculum* and *Glaphyrocysta cf. vicina* (Dybkjær, 2004a, b).

Sequence B is dated as latest Chattian and/or early Aquitanian based on the sporadic occurrences of *Chiropteridium galea*, *Deflandrea phosphoritica* and *Caligodinium amiculum* throughout the sequence (Hardenbol *et al.*, 1998; Dybkjær, 2004a; Powell & Brinkhuis, 2004b) (Fig. 3). The index taxon *Ectosphaeropsis burdigalensis* appears in the upper part of the sequence (Dybkjær, 2004a). This species appears immediately below the Oligocene/Miocene boundary in the Italian type section (Coccioni *et al.*, 1997) and in the stratotype area for the Rupelian–Chattian it was found to appear in the upper part of the Chattian (Van Simaey *et al.*, 2004). Its appearance in Sequence B onshore Jylland may have been delayed due to the restricted marine depositional environment (Dybkjær, 2004a). According to Brinkhuis (pers. comm. 2006), the indication of this event in the earliest Aquitanian in Williams *et al.* (2004) is an error.

Correlation with eustatic sea-level curves (Prentice & Matthews, 1988; Zachos *et al.*, 2001b) indicates that the Oligocene–Miocene boundary is located at the boundary between sequences A and B, and that Sequence B is, thus, of early Aquitanian age (Dybkjær, 2004a; Rasmussen, 2004b).

Sequence C (early Burdigalian)

In large parts of Jylland there is a hiatus between sequences B and C, spanning the late Aquitanian–earliest Burdigalian (Dybkjær & Rasmussen, 2000; Dybkjær, 2004 a, b; Rasmussen, 2004a; Rasmussen & Dybkjær, 2005). Sequence C clearly consists of more open-marine deposits than Sequence B (Dybkjær, 2004a; Rasmussen & Dybkjær, 2005). The marine clays of Sequence C are referred to the Arnum Formation (Sorgenfrei, 1958), while the more coarse-grained, fluvio-deltaic deposits are referred to the informal Bastrup sand (Rasmussen, 2004a).

The dinocyst assemblage shows a distinct change across the boundary between the sequences B and C, from a low-diversity *Homotryblum*-dominated assemblage to a higher-diversity assemblage dominated by *Impletosphaeridium insolitum*, *Operculodinium centrocarpum*, *Spiniferites* spp. and *Cleistosphaeridium placacanthum*. *Homotryblum* spp. occurs only sporadically.

The last occurrence of *Thalassiphora pelagica* and the first occurrence of *Hystrichosphaeropsis obscura* in the lower part of Sequence C indicate an early Burdigalian age (Coccioni *et al.*, 1997; Hardenbol *et al.*, 1998; Londeix & Jan du Chêne, 1998; Powell & Brinkhuis, 2004b) (Fig. 3). The last occurrence of *Cordosphaeridium cantharellus* in the sequence above indicates an age not younger than early Burdigalian (Londeix & Jan du Chêne 1998; Powell & Brinkhuis, 2004b). An early Burdigalian age for the lower part of the Arnum Formation is supported by earlier studies of dinocysts (Dybkjær & Rasmussen, 2000; Dybkjær, 2004a) and of foraminifera (Laursen & Kristoffersen, 1999).

PREVIOUS PALYNOSTRATIGRAPHIC STUDIES OF THE UPPER OLIGOCENE–LOWER MIOCENE IN THE NORTH SEA AREA

Palynological data from the Upper Oligocene–Lower Miocene succession in the Danish area comprise the studies of the two North Sea wells Mona-1 (Michelsen *et al.*, 1998) and Alma-1 (Schjølter, 2005), and the studies of onshore boreholes and outcrops by Dybkjær & Rasmussen (2000), Dybkjær (2004a, b), Rasmussen & Dybkjær (2005) and Rasmussen *et al.* (2006).

Several studies have also been made from Germany, e.g. Maier (1959), Gerlach (1961), Benedek (1972), Benedek & Müller (1974), Heilmann-Clausen & Costa (1989), Köthe (1990, 1996, 2000, 2003a, b, 2004, 2005), Köthe *et al.* (2002), Lund *et al.* (1993), Lund & Heilmann-Clausen (2001) and Strauss *et al.* (2001).

More recently Van Simaey *et al.* (2004) presented the results of a study on the Rupelian and Chattian in their type regions in Belgium and Germany and Van Simaey *et al.* (2005) presented a zonation for the Oligocene in the southern North Sea Basin. Before that, data from Belgium were presented by Louwye & Laga (1998) and Louwye *et al.* (1999, 2000).

Herngreen (1983, 1987) has published papers on Miocene dinocyst stratigraphy from the Netherlands and recently Munsterman & Brinkhuis (2004) published an informal zonation for the Miocene succession in the southern North Sea Basin, based on data from the Netherlands. Powell (1992) presented an informal zonation for the British offshore area.

Very little information about Upper Oligocene–Lower Miocene palynology from the central and northern North Sea area is available at present. From the northern North Sea there is an abstract by Costa (1980) and from the central North Sea area there is the overall zonation by Gradstein *et al.* (1992).

MATERIAL AND METHODS

The Frida-1 Well is located in the basinal part of the Danish North Sea area (Fig. 1). The studied succession comprises the interval from 980–1740 m. Borehole casing placed around 970 m reduced caving of younger sediments below that level (the samples above that level were contaminated strongly by caved material). The cuttings samples used in the present study are thus of high quality and allow, with caution, the use of first appearances (last downhole occurrences) and percentage variations of specific species for stratigraphic purposes. Lithostratigraphically, the studied succession is referred to the Lark Formation (Knox & Holloway, 1992); the sandy interval from 1486–1622 m is referred to the Freja Member (Schjølter *et al.*, in press) (Fig. 2).

A total of 37 ditch cuttings samples and four conventional core samples were studied (Figs 4, 5). The ditch cuttings samples represent intervals of 5 m or 10 m (980–1390 m: 10 m interval; 1390–1740 m: 5 m interval). The depths for the ditch cuttings samples shown in Figures 4 and 5 are the base depths of the interval represented by each sample. The depths indicated as base or top of a dinocyst assemblage correspond to the depth in between the base depths of the ditch cuttings sample from which the dinocyst event defining the boundary was encountered and the sample above (Figs 4, 5).

The sample material was processed using standard palynological preparatory methods including treatment with HF and

HCl to dissolve silicates and heavy liquid separation to remove the undissolved mineral matter. The residue was sieved using an 11 µm mesh, and mild oxidation with dilute nitric acid was carried out. One slide for kerogen studies was produced, by mounting the organic residue in glycerine jelly. Following sieving through a 20 µm mesh to concentrate the dinocysts, two additional slides were produced. The material was studied using a normal light microscope.

A minimum of 200 dinocysts was counted in each sample. Fresh-water algae and acritarchs recorded during this process were also counted. Additionally, two full slides were inspected in order to register rare species. The slides are stored at the Geological Survey of Denmark and Greenland (GEUS). A number of stratigraphically important species are shown in Plate 1. The LVR numbers refer to file numbers in the image database of GEUS from where further information about the illustrated species can be extracted.

RESULTS

The results from the palynological study in Frida-1 are presented in Figure 4. Based on the variations in the occurrence of dinocysts, six dinocyst assemblages are defined and described in the following, starting with the oldest assemblage.

The *Wetzelialla gochtiil* Assemblage

Occurrence in Frida-1: 1740–1685 m (Fig. 5).

Base: Not defined here.

Top: The last occurrence of the *Wetzelialla gochtiil*/*W. symmetrica* group.

General characteristics: This assemblage is characterized by the co-existence of the *Wetzelialla gochtiil*/*W. symmetrica* group and *Distatodinium biffii*. *Spiniferites* spp. dominate the assemblage.

Important events within the zone: Last occurrences of *Areoligera semicirculata*, *Rhombodinium draco* and *Svalbardella cooksoniae* at 1720 m (Fig. 5).

Age: Early Chattian. The occurrence of *Distatodinium biffii* at 1740 m indicates an age not older than the Chattian (Powell & Brinkhuis, 2004a) (Fig. 3). Sporadic occurrences of specimens very much like *D. biffii* in an Eocene section in Denmark (Heilmann-Clausen & Van Simaey, 2005) indicate, however, that the first occurrence of this species may be older than hitherto thought. The last occurrence of the *Wetzelialla gochtiil*/*W. symmetrica* group at 1700 m indicates an age not younger than the early Chattian (Powell & Brinkhuis, 2004a) (Fig. 3).

The *Distatodinium biffii* Assemblage

Occurrence in Frida-1: 1685–1620 m (Fig. 5).

Base: The last occurrence of the *Wetzelialla gochtiil*/*W. symmetrica* group.

Top: The last occurrence of *Distatodinium biffii*.

General characteristics: *Distatodinium biffii* occurs consistently. The assemblage is dominated by *Spiniferites* spp. and *Cleistosphaeridium placacanthum*.

Important events within the zone: None.

Age: Chattian. The last occurrence of the *Wetzelialla gochtiil*/*W. symmetrica* group at 1700 m indicates an early Chattian age for the assemblage below, while the last occurrence of

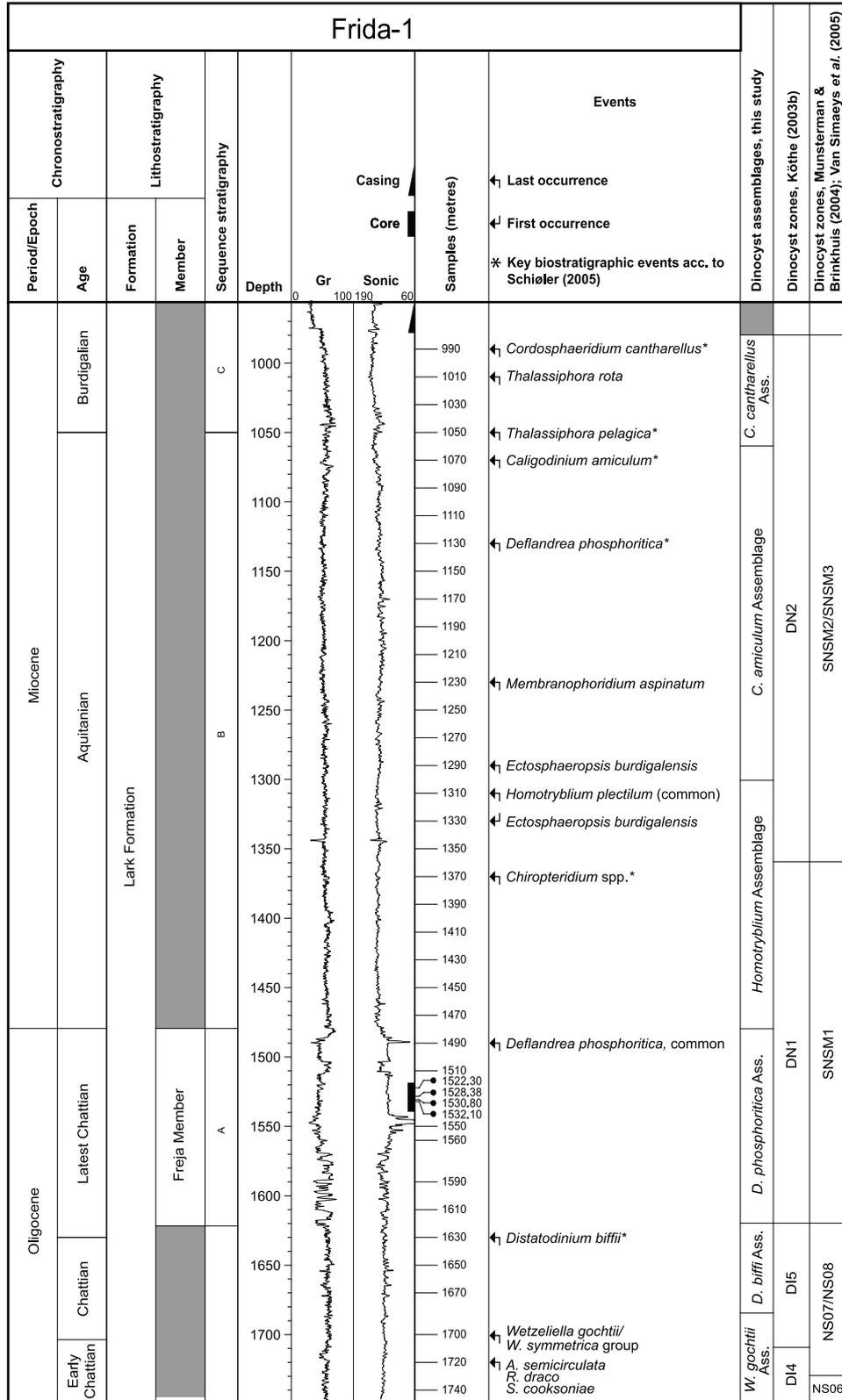


Fig. 5. Chrono-, litho- and sequence stratigraphy of the studied succession in Frida-1. The location of samples, the cored interval and the casing is shown. The location of the stratigraphically important events (Schjølter, 2005) are also indicated and the dinocyst assemblages of the present study are compared with previously defined zonations (Köthe, 2003b; Munsterman & Brinkhuis, 2004; Van Simaey *et al.*, 2005) for the southern North Sea area.

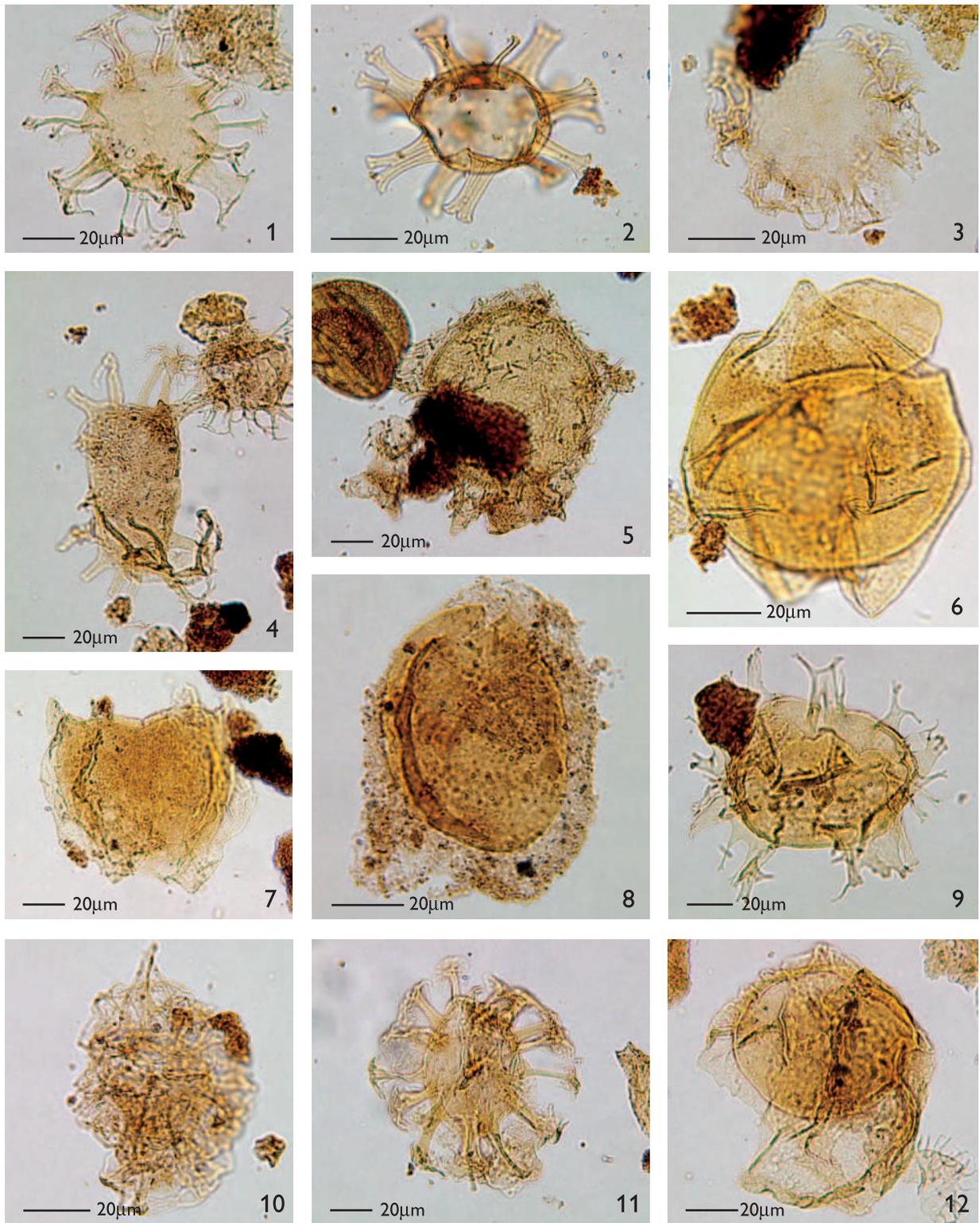


Plate 1.

Explanation of Plate 1. Stratigraphically important dinocyst species from the Frida 1 Well. Magnification is shown by the 20 µm bar on each figure. **fig. 1.** *Areoligera semicirculata* (Morgenroth, 1966) Stover & Evitt, 1978. LVR 27680. **fig. 2.** *Homotryblium plectilum* Drugg & Loeblich, 1967. LVR 27672. **fig. 3.** *Glaphyrocysta* spp. LVR 27659. **fig. 4.** *Distatodinium biffii* Brinkhuis *et al.*, 1992. LVR 27653. **fig. 5.** *Wetzeliella gochtii* Costa & Downie, 1976. LVR 22779. **fig. 6.** *Deflandrea phosphoritica* Eisenack 1938. LVR 27622. **fig. 7.** *Membranophoridium aspinatum* Gerlach, 1961. LVR 27629. **fig. 8.** *Caligodinium amiculum* Drugg 1970. LVR 27684. **fig. 9.** *Chiropteridium galea* (Maier, 1959) Sarjeant, 1983. LVR 27647. **fig. 10.** *Ectosphaeropsis burdigalensis* Londeix & Jan du Chêne, 1988. LVR 27637. **fig. 11.** *Cordosphaeridium cantharellus* (Brosius, 1963) Sarjeant, 1981. LVR 27600. **fig. 12.** *Thalassiphora pelagica* (Eisenack, 1954) Eisenack & Gocht, 1960. LVR 27608.

Distatodinium biffii at 1630 m indicates a latest Chattian age for this assemblage (Powell & Brinkhuis, 2004a) (Fig. 3). In the Italian type section, the last occurrence of *Distatodinium biffii* occurs closely below (9 m below) the Oligocene–Miocene boundary (Zevenboom, 1996). In studies by Munsterman & Brinkhuis (2004) on Dutch material and by Van Simaëys *et al.* (2005) on material from Belgium, northern Germany and the Netherlands, the last occurrence of *D. biffii* was also recorded in the upper part of the Chattian.

The *Deflandrea phosphoritica* Assemblage

Occurrence in Frida-1: 1620–1480 m (Fig. 5).

Base: The last occurrence of *Distatodinium biffii*.

Top: The last occurrence of common *Deflandrea phosphoritica*.

General characteristics: Dominated by *Homotryblium plectilum* and *Spiniferites* spp. *Deflandrea phosphoritica*, *Chiropteridium* spp. and *Membranophoridium aspinatum* occur consistently. In the upper part of the interval the relative abundances of *D. phosphoritica* and *Homotryblium* spp. increase. The acritarch species *Cyclopsiella elliptica* and *Paralecaniella indentata* occur abundantly at 1530.80 m (core) and 1528.38 m (core).

Important events within the zone: None.

Age: Latest Chattian. The last occurrence of *D. biffii* at the base of the zone indicates an age not older than the latest Chattian (Coccioni *et al.*, 1997; Van Simaëys *et al.*, 2004; Powell & Brinkhuis, 2004a) (Fig. 3). The last occurrence of *Chiropteridium* spp. at 1370 m, in the assemblage above, indicates an earliest Aquitanian age (Powell & Brinkhuis, 2004a), while the first occurrence of *Ectosphaeropsis burdigalensis* at 1330 m indicates a very latest Chattian age (Coccioni *et al.*, 1997) (Fig. 3).

The *Homotryblium* Assemblage

Occurrence in Frida-1: 1480–1300 m (Fig. 5).

Base: The last occurrence of common *Deflandrea phosphoritica*.

Top: The last occurrence of common *Homotryblium* spp.

General characteristics: Dominated by *Homotryblium plectilum*, *H. tenuispinosum* and *Spiniferites* spp. Sporadic occurrences of *Chiropteridium* spp., *Membranophoridium aspinatum* and *Deflandrea phosphoritica*. *Ectosphaeropsis burdigalensis* occurs in a narrow interval in the uppermost part. The relative abundance of *Homotryblium plectilum* decreases gradually upwards.

Important events within the zone: Last occurrence of *Chiropteridium* spp. at 1370 m, *Homotryblium plectilum* at 1310 m and *Glaphyrocysta* spp. at 1330 m. First occurrence of *Ectosphaeropsis burdigalensis* at 1330 m and last occurrence at 1290 m.

Age: Early Aquitanian. The last occurrence of *Distatodinium biffii* in the succession below indicates an age not older than the latest Chattian (Coccioni *et al.*, 1997; Powell & Brinkhuis, 2004a) (Fig. 3). The first occurrence of *Ectosphaeropsis burdigalensis* at 1330 m indicates a latest Chattian age (Coccioni *et al.*, 1997) (Fig. 3). The occurrence of *Chiropteridium* spp. up to 1370 m indicates an age not younger than the early Aquitanian (Powell & Brinkhuis, 2004a).

The *Caligodinium amiculum* Assemblage

Occurrence in Frida-1: 1300–1060 m (Fig. 5).

Base: The last occurrence of common *Homotryblium* spp.

Top: The last occurrence of *Caligodinium amiculum*.

General characteristics: Dominated by *Spiniferites* spp. and *Cleistosphaeridium placacanthum*. *Hystriocholpoma rigaudiae* and *Operculodinium centrocarpum* are common to dominant.

Sporadic occurrences of *Caligodinium amiculum*, *Deflandrea phosphoritica*, *Homotryblium* spp., *Membranophoridium aspinatum*, *Operculodinium piaseckii* and *Thalassiphora pelagica*.

Important events within the zone: The last occurrence of *Membranophoridium aspinatum* at 1230 m and *Deflandrea phosphoritica* at 1130 m. The first occurrence of *Operculodinium piaseckii* at 1270 m may also be important. The freshwater dinocyst species *Pseudokomewuia* aff. *granulata* (Batten *et al.*, 1999) appears at the base of this interval.

Age: Aquitanian. The occurrence of *Ectosphaeropsis burdigalensis* in the succession below strongly indicates an age not older than the Aquitanian (Coccioni *et al.*, 1997) (Fig. 3). The last occurrence of *Deflandrea phosphoritica* at 1130 m and *Caligodinium amiculum* at 1070 m indicates an age not younger than the Aquitanian (Hardenbol *et al.*, 1998; Powell & Brinkhuis, 2004a).

The *Cordosphaeridium cantharellus* Assemblage

Occurrence in Frida-1: 1060–?980 m (Fig. 5).

Base: The last occurrence of *Caligodinium amiculum*.

Top: The last occurrence of *Cordosphaeridium cantharellus*. This species was not recorded in samples above 990 m, but, as the samples immediately above 980 m are full of caved dinocysts (and the *in situ* assemblage thus diluted), the ‘true’ last occurrence of *C. cantharellus* may be higher up-section.

General characteristics: Dominated by *Operculodinium centrocarpum*, *Spiniferites* spp. and *Cleistosphaeridium placacanthum*. Consistent occurrence of *Operculodinium piaseckii*. *Homotryblium tenuispinosum* is dominant at 990 m.

Important events within the zone: The last occurrence of *Thalassiphora pelagica* at 1050 m and *Thalassiphora rota* at 1010 m (Fig. 5).

Age: Early Miocene (latest Aquitanian to early Burdigalian). The last occurrence of *Caligodinium amiculum* at 1070 m indicates an age not older than the latest Aquitanian (Hardenbol *et al.*, 1998) (Fig. 3). The last occurrence of *Thalassiphora pelagica* at 1050 m and *Thalassiphora rota* at 1010 m indicates an earliest Burdigalian age (Coccioni *et al.*, 1997; Londeix & Jan du Chêne, 1998; Schiøler, 2005). The occurrence of *Cordosphaeridium cantharellus* at 990 m indicates an age not younger than early Burdigalian (Londeix & Jan du Chêne, 1998; Powell & Brinkhuis, 2004a).

CORRELATION WITH ZONATIONS AND KEY BIOSTRATIGRAPHIC EVENTS DEFINED IN NEARBY AREAS

The dinocyst assemblages defined in the present study are correlated easily with the zonation proposed by Köthe (2003b) based on data from Germany (Fig. 5). The index markers (first and last occurrences of dinocyst species) used by Köthe for defining her zonation in the Upper Oligocene–Lower Miocene were also recorded in the present study. The zonations proposed by Van Simaëys *et al.* (2005) (for the Oligocene in the southern

North Sea) and by Munsterman & Brinkhuis (2004) (for the Miocene in the southern North Sea) are also illustrated for comparison in Figure 5.

The *Wetzeliiella gochtii* Assemblage

In the Linde-1 borehole onshore Jylland the co-existence of *Distatodinium biffii* and *Wetzeliiella gochtii* has been recorded from the interval referred to the middle part of the Branden Clay (Heilmann-Clausen, 1995b). The *W. gochtii* Assemblage correlates to the lower part of Dinocyst Zone D14 of Köthe (2003b) and to parts of the Dinocyst Zones NSO6-7 of Van Simaey *et al.* (2005) (Fig. 5).

The *Distatodinium biffii* Assemblage

This interval probably corresponds to the upper part of the Branden Clay onshore Jylland (Heilmann-Clausen, 1995b). The *D. biffii* Assemblage correlates to Dinocyst Zone D15 of Köthe (2003b) and parts of the Dinocyst Zones NSO7 and NSO8 of Van Simaey *et al.* (2005) (Fig. 5).

The *Deflandrea phosphoritica* Assemblage

The consistent occurrence of *Chiropteridium* spp. and *Membranophoridium aspinatum* and the increase in relative abundance of *Deflandrea phosphoritica* and *Homotryblium plectilum* in the upper part is closely comparable to Dinocyst Assemblage 1 as described in Rasmussen & Dybkjær (2005) from outcrops referred to the Brejning Clay of latest Chattian age, and to the dinocyst assemblage described from Sequence A onshore Jylland (Dybkjær, 2004a; Rasmussen, 2004a).

The *D. phosphoritica* Assemblage correlates to the lower part of Dinocyst Zone DN1 of Köthe (2003b) and the lower part of Dinocyst Zone SNSM1 of Munsterman & Brinkhuis (2004) (Fig. 5).

The *Homotryblium* Assemblage

The abundance of *Homotryblium plectilum* and *H. tenuispinosum*, the sporadic occurrences of *Chiropteridium* spp., *Deflandrea phosphoritica* and *Caligodinium amiculum* and the occurrence (in a narrow interval) of *Ectosphaeropsis burdigalensis* compare closely to the dinocyst assemblage in Sequence B described in Dybkjær (2004a, b) and to Assemblage 2 (Rasmussen & Dybkjær, 2005) from outcrops referred to the Vejle Fjord Clay, Vejle Fjord Sand, Hvidbjerg sand and Billund sand.

The lower part of the *Homotryblium* Assemblage correlates to the upper part of Dinocyst Zone DN1 of Köthe (2003b) and the upper part of SNSM1 of Munsterman & Brinkhuis (2004). The upper part (above the last occurrence of the index marker *Chiropteridium* spp.) correlates to the lower part of Dinocyst Zone DN2 (Köthe, 2003b) and to the lower part of SNSM2 of Munsterman & Brinkhuis (2004).

The *Caligodinium amiculum* Assemblage

This assemblage is presently not comparable to any assemblage recorded onshore Jylland, possibly due to different facies or to a missing onshore section. A large hiatus, representing approximately 3.5 Ma, is present onshore between sequences B and C in the eastern and central parts of Jylland (Dybkjær & Rasmussen, 2000; Dybkjær, 2004a), while a large delta (Ribe Formation) existed in the southern and western parts. The succession

referred to the *C. amiculum* Assemblage in Frida-1 possibly represents the marine facies corresponding to the hiatus and the delta.

The *C. amiculum* Assemblage correlates to the middle part of the Dinocyst Zone DN2 of Köthe (2003b) and to the upper part of Dinocyst Zone SNSM2 and the lower part of SNSM3 of Munsterman & Brinkhuis (2004) (Fig. 5). Unfortunately, *Membranilarnacia? picena*, the last occurrence of which is used for defining the base of zone SNSM3 in the latter zonation, was not recorded in Frida-1.

The *Cordosphaeridium cantharellus* Assemblage

The last occurrence of *T. pelagica* in the lower part of the interval, and the last(?) occurrence of *C. cantharellus* in the upper part, indicate a correlation with Sequence C onshore (the lower part of the Arnum Formation and the Bastrup sand) (Dybkjær, 2004a; Rasmussen, 2004a).

Severe caving in Frida-1 down to the casing at 970 m hinders a trustworthy comparison of the dinocyst assemblages above this level with assemblages from onshore sections. The *C. cantharellus* Assemblage correlates to the upper part of the Dinocyst Zone DN2 of Köthe (2003b) and the Dinocyst Zone SNSM3 of Munsterman & Brinkhuis (2004).

Comparison of the Alma-1 and Frida-1 wells

Schiøler (2005) pointed out a number of ‘key biostratigraphic events’ in the Alma-1 Well located in the southern part of the Danish North Sea Sector (see location of Alma-1 in Fig. 1). In general these events correspond very well with those used for stratigraphic purposes in the present study. However, not all of the dinocyst species used by Schiøler (2005) as key events were recorded in Frida-1 (especially in the interval from the last occurrence of *Thalassiphora pelagica* and upwards). Key events used by Schiøler (2005) which were not recorded in Frida-1 include: *Tectatodinium* sp. 1 of Chateauneuf (1980), *Brigantedinium?* spp., *Leptodinium italicum* and *Hystrichokolpoma ‘reductum’* of Zevenboom & Santarelli in Zevenboom (1995).

The interval from the last occurrence of *Distatodinium biffii* to the last occurrence of *Thalassiphora pelagica* is expanded in Frida-1 when compared to Alma-1 and, within that interval, some important events and abundance variations were found only in Frida-1. Notable events include an increase in abundance of *Deflandrea phosphoritica* in the uppermost Chattian and the last occurrences of *Chiropteridium* spp., *Deflandrea phosphoritica*, *Membranophoridium aspinatum* and *Ectosphaeropsis burdigalensis* (in Alma-1 the last occurrences of the former three species are condensed within a single sample). Furthermore, the first occurrence of *Ectosphaeropsis burdigalensis* was used in Frida-1, as the casing around 970 m allows the use of first occurrences with caution in the studied interval.

BASIN-MARGIN CORRELATION

In order to support the dinocyst-based correlation between the basinal succession in Frida-1 and the marginal marine deposits onshore Jylland, a seismic section, running from Frida-1 to the Danish west coast, was included in the study (Fig. 6). In addition, a correlation panel of offshore wells and onshore boreholes and outcrops was established (Fig. 7). Due to the

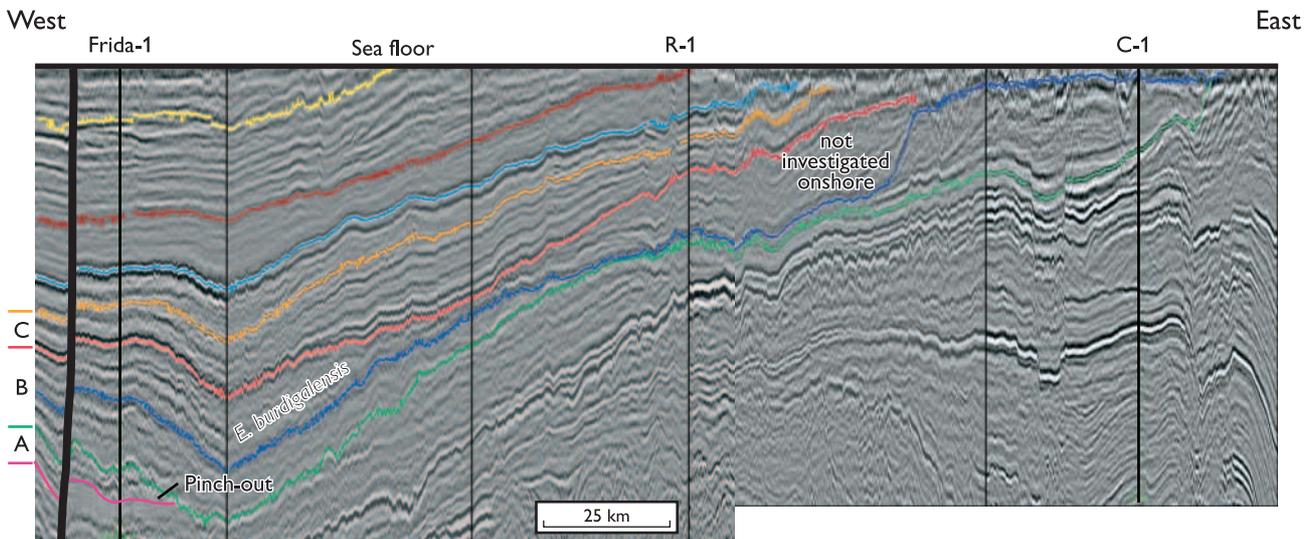


Fig. 6. East–west-striking seismic section through the offshore wells Frida-1, R-1 and C-1 (see location in Fig. 1). The sequences A to C are shown and the succession containing *Ectosphaeropsis burdigalensis* is indicated. Note that Sequence A is thinning towards the west. The succession containing *Ectosphaeropsis burdigalensis* is also pinching out towards the C-1 Well. Seismic courtesy Danpec, TGS-Nopec and Fugro.

lobal nature of the studied succession, the resulting pinch-out of delta lobes hinders direct correlation. However, the re-appearance of the pinched-out parts of the succession, as illustrated both by the seismic data and the log panel, confirms the results of the biostratigraphic study.

Correlation based on dinocysts strongly indicates that the interval corresponding to the *Wetzeliaella gochtii* and the *Distatodinium biffii* Assemblages correlates with the Branden Clay onshore (Heilmann-Clausen, 1995b). This informal clay unit is preserved only in a few locations onshore, in the central and northern Jylland (Heilmann-Clausen, 1995a). This is confirmed by the seismic section (Fig. 6) and the log panel (Fig. 7) where a pinch-out of this interval can be seen just west of the Frida-1 Well (the lower part of the interval between the red and the green seismic markers).

The *Deflandrea phosphoritica* Assemblage comprises a c. 140m thick depositional succession (the Freja Member) mainly composed of turbiditic sands (Schjølér *et al.*, in press). Based on comparison with biostratigraphic assemblages in a marginal marine setting onshore Jylland, which show similar trends (e.g. increase in the relative abundance of *Deflandrea phosphoritica* and in *Homotryblum* spp.) (Dybkjær, 2004a, b), the succession can be correlated to a strongly condensed, glauconite-rich, clay succession onshore Jylland (the Brejning Clay; Fig. 2) which was referred to Sequence A (Rasmussen, 2004a). Due to the eastward condensed nature of Sequence A it cannot be followed directly on the seismic section (Fig. 6) or on the log correlation panel (Fig. 7). The Brejning Clay has been suggested previously to be latest Chattian in age (see Dybkjær, 2004b) and a latest Chattian age is supported strongly by the data from Frida-1, with the last occurrence of *Distatodinium biffii* recorded in the succession below and the first appearance of *Ectosphaeropsis burdigalensis* above (see Fig. 3).

The interval comprising the *Homotryblum* Assemblage is represented both onshore and offshore by a relatively thick succession (corresponding to the interval between the green and blue seismic horizon on Figs 6 and 7). The correlation panel for

a series of onshore boreholes (Fig. 8) for this interval (referred to the lower part of Sequence B) shows an early prograding deltaic section, the Billund sand which is restricted to the north and pinches out southwards. A pinch-out towards the south and west in more basinal areas is also shown in the seismic section (Fig. 6) and in the east–west correlation panel (Fig. 7), where the lower part of Sequence B is missing in the R-1 Well.

The interval comprising the *Caligodinium amiculum* Assemblage in the basinal area in Frida-1, is represented by an unconformity in the marginal areas (central parts of Jylland) spanning a time interval of up to 3.5 Ma (Dybkjær & Rasmussen, 2000; Dybkjær, 2004b). However, in the southern part of Jylland, south of the Estrup borehole, it may be represented by the deltaic deposits of the Ribe Formation (Fig. 8). In Frida-1 this upper part of Sequence B is represented by a c. 240 m thick marine succession characterized by the sporadic occurrence of *Caligodinium amiculum* and sporadic *Homotryblum tenuispinosum*. Thus, there is probably no hiatus between sequences B and C in the basinal areas represented by Frida-1.

The *Cordosphaeridium cantharellus* Assemblage represented by the interval 1060–980 m in Frida-1, corresponds strongly to the assemblages recorded from Sequence C (the lower Arnum Formation) in the marginal marine deposits onshore Jylland. A direct correlation from Frida-1 to the onshore sections is, however, hampered by the presence of a Quaternary incised valley at the location of the C-1 borehole and poor quality of the seismic data in the upper part (Figs 6, 7). Severe caving of dinocysts from younger intervals in Frida-1 down to the casing around 970 m hinders a reliable correlation of the succession above 970 m.

DEPOSITIONAL ENVIRONMENT

The occurrence of the genera *Impagidinium* and *Nematosphaeropsis* in Frida-1 indicates outer neritic to oceanic settings, according to Wall *et al.* (1977), Brinkhuis (1994) and Dale (1996). In detail, the presence of several species of *Impagidinium*

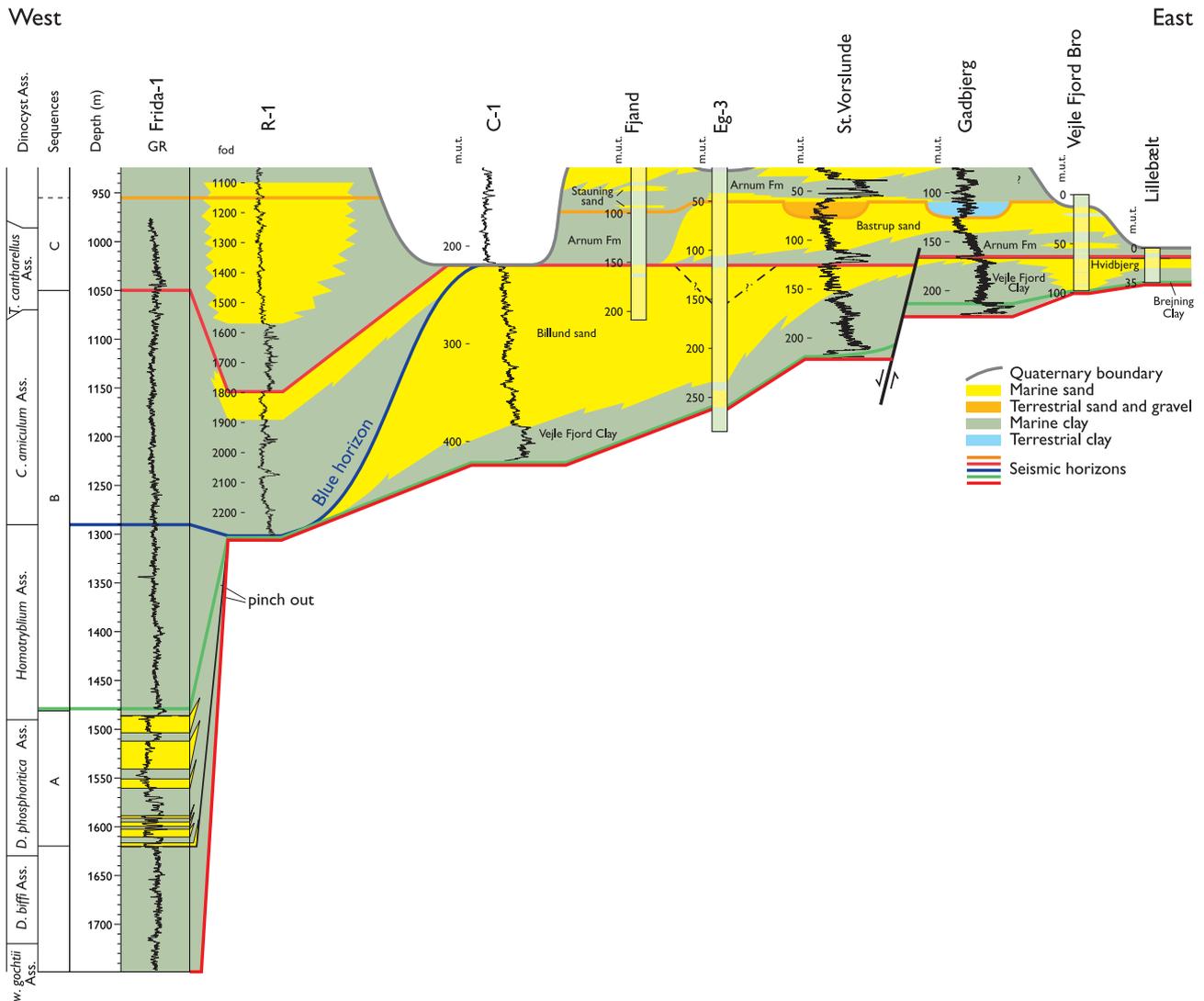


Fig. 7. Sequence stratigraphic subdivision of the Frida-1 Well and a correlation panel correlating the offshore wells Frida-1, R-1 and C-1 with the onshore boreholes Fjand, Eg-3, Store Vorslunde, Gadbjerg, Vejle Fjord Bro, and the combined borehole and outcrop section from Lillebælt. The sequence boundaries are indicated in the same colours as on the seismic section in Figure 6.

within Sequence A and the consistent occurrence of *Nematospaeropsis labyrinthus* in Sequence A and the lower part of Sequence B indicate that outer neritic to oceanic conditions prevailed during deposition of this part of the studied succession. This contradicts the contemporaneous presence of genera such as *Deflandrea*, *Glaphyrocysta* and *Homotryblum*, which are thought to prefer inner neritic settings (or with respect to the former, nutrient-rich settings such as upwelling areas or inner neritic settings) (following Downie *et al.*, 1971; Williams, 1977; Bradford & Wall, 1984; Harland, 1988; Brinkhuis *et al.*, 1992; Brinkhuis, 1994; de Verteuil & Norris, 1996; Dybkjær, 2004b). The presence of the latter genera probably resulted from turbiditic transport from inner neritic settings by currents also responsible for the deposition of sand layers in the upper part of Sequence A.

A change in the depositional setting towards a more shallow-marine environment and closer proximity to the shoreline in the lower to middle part of Sequence B is indicated by rare

Impagidinium in Sequences B and C and by the disappearance of *N. labyrinthus* in the lower to middle part of Sequence B. This interpretation also agrees with the environmental interpretations based on the log patterns and the seismic data presented below.

SEQUENCE STRATIGRAPHY OF FRIDA-1

The sequence stratigraphic subdivision of the Upper Oligocene–Lower Miocene succession in Frida-1 (Figs 2, 5) follows the sequence stratigraphic subdivision of the eastern North Sea Basin suggested by Rasmussen (2004a, b) based on onshore data. The subdivision in Frida-1 is based on the correlation of dinocyst assemblages from the basinal area with the marginal marine deposits onshore, combined with seismic data (Fig. 6) and the log correlation panel (Fig. 7). The precise location of the sequence boundaries is based on changes in the geophysical log patterns (see Fig. 5).

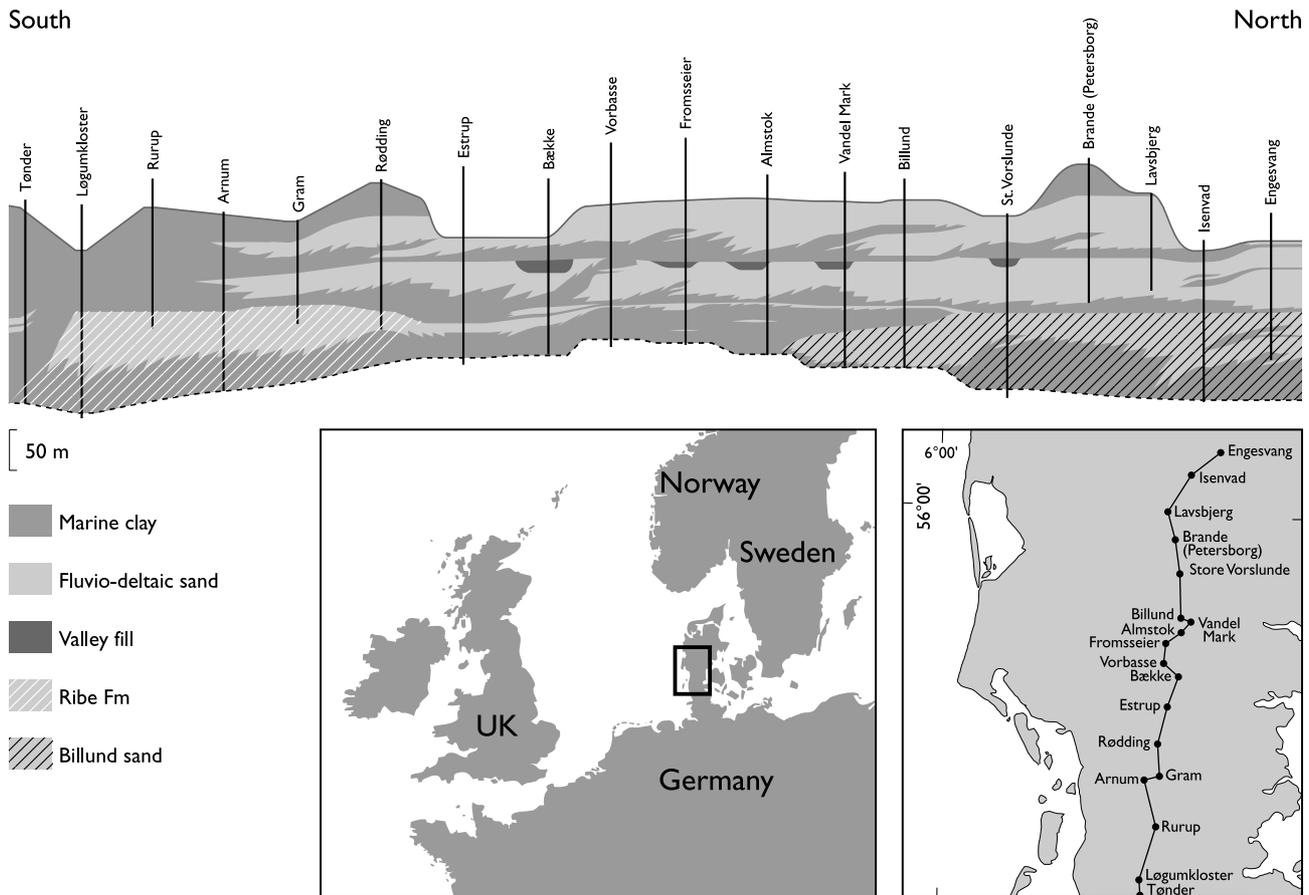


Fig. 8. Log correlation panel showing a series of boreholes from north to south in the central Jylland. Pinching out from north to south of the deltaic Billund sand is evident and the deltaic Ribe Formation is also shown. The location of the correlated boreholes is shown.

Sequence A (1620–1478 m)

The lower boundary of Sequence A should probably be placed in the interval between 1610 m and 1630 m in Frida-1, as the last occurrence of *D. biffii* at 1630 m probably correlates to the top of the Branden Clay onshore. The Branden Clay occurs only in the northern and central parts of Jylland due to erosion in most of Jylland. This pattern indicates that a period with distinct lowered sea-level existed during part of the Oligocene, in the time between deposition of the Branden Clay and the Brejning Clay (Michelsen *et al.*, 1998). The gamma-low at 1620 m in Frida-1 (Fig. 5) suggests that the sequence boundary should be located here, at the base of the lowest turbidite sandstone of the Freja Member. The succession comprising the dinocyst assemblages *W. gochtii* and *D. biffii* thus probably represents a sequence older than Sequence A. Sequence A comprises a series of gravity deposits referred to the Freja Member (Schjøler *et al.*, in press).

Sequence B (1478–1050 m)

In marginal marine areas the lower boundary of Sequence B is often marked by a gravel layer (Rasmussen, 2004a). The boundary occurs at the top of an acme of *Deflandrea phosphoritica* (Dybkjær, 2004a). In Frida-1, although representing a more basal setting, a corresponding increase in abundance of *D. phosphoritica* was found. The uppermost sample with high

abundances of *D. phosphoritica* is at 1490 m. The lower boundary of Sequence B is therefore located at a minor gamma low at 1478 m (Fig. 5). The boundary can be seen as a regional seismic marker with downlap and onlap, locally with erosional features, and with conformal strata in basal areas (Michelsen *et al.*, 1998). The succession consists of brownish, clayey siltstone with mica interpreted as contouritic clays (Hansen *et al.*, 2004).

Sequence C (1050–955 m)

There is probably no hiatus between sequences B and C in Frida-1, while this sequence boundary in some marginal marine areas in Central Jylland represents a hiatus of up to 3.5 Ma. (Dybkjær & Rasmussen, 2000; Dybkjær, 2004a; Rasmussen & Dybkjær, 2005). In the southwestern parts of Jylland the deltaic Ribe Formation was probably deposited at that time. The basal-marginal marine correlation is further supported by the regional seismic study (Rasmussen, 2004b) and the log correlation panel (Fig. 7).

Onshore the lower boundary of Sequence C is located between the last occurrence of *Caligodinium amicum* and the last occurrence of *Thalassiphora pelagica* and this is followed here, where the boundary is located at 1050 m, at the top of an interval with an aggradational gamma log pattern. Above the boundary the gamma log shows an abrupt increase concurrent with an increase in the sonic log and a distinct peak on the

density log, probably representing a flooding surface. On the seismic section (Fig. 6) the sequence boundary constitutes a regionally mappable marker horizon with onlap, but conformable in basal areas. The succession consists of brownish clayey siltstones to fine-grained sandstones with mica, interpreted as marine-shelf deposits.

Severe caving in Frida-1 down to the casing around 970 m, combined with a poor log pattern, hinders a reliable identification of the upper boundary of Sequence C, but the dinocyst assemblage in the interval from 1060 m to 980 m in Frida-1 corresponds strongly to the assemblages recorded from Sequence C onshore. A correlation is further supported by the regional seismic study (Rasmussen, 2004b) (Fig. 6).

LOCATION OF THE MI-1 GLACIATION EVENT AND THE OLIGOCENE–MIOCENE BOUNDARY

Although correlation between the uppermost Oligocene–Lower Miocene dinocyst assemblages in the Danish onshore area and the type profile in northern Italy is not totally straightforward (see discussion in Dybkjær, 2004a), it was suggested by Rasmussen (2004b) and Rasmussen & Dybkjær (2005) that the boundary between sequences A and B correlate to the Mi-1 glaciation event of Miller *et al.* (1987; 1991). It was accordingly proposed that the Oligocene–Miocene boundary be located at the sequence boundary. In addition, the boundary between sequences B and C was proposed to correlate to the Mi-1a event of Miller *et al.* (1991).

The results from the present study of the stratigraphically more complete succession in Frida-1 strongly support the previous datings of sequences A to C and the proposed existence of a hiatus between sequence B and C onshore (Dybkjær & Rasmussen, 2000; Dybkjær, 2004a). The recorded last occurrence of *Distatodinium biffii* near the base of sequence A strongly supports a latest Chattian age for sequence A, while the last occurrences of *Chiropteridium* spp., *Deflandrea phosphoritica* and *Caligodinium amiculum* within sequence B strongly indicate an Aquitanian age for this sequence (Fig. 3).

A correlation between the Mi-1 glaciation event and the boundary between sequences A and B is thus supported by the present study. The location of the Oligocene–Miocene boundary in Frida-1 is likewise proposed to be located at or very near this boundary.

CONCLUSION

The Frida-1 Well, located in the basal parts of the eastern North Sea Basin, penetrates an unusually thick (>800 m) and probably complete succession spanning the Upper Oligocene–Lower Miocene, comprising marine sediments deposited in a basinal setting.

Six dinocyst assemblages are described: the *Wetzeliella gochti* Assemblage (early Chattian), the *Distatodinium biffii* Assemblage (Chattian), the *Deflandrea phosphoritica* Assemblage (latest Chattian), the *Homotryblium* spp. Assemblage (latest Chattian and/or early Aquitanian), the *Caligodinium amiculum* Assemblage (Aquitanian) and the *Cordosphaeridium cantharellus* Assemblage (latest Aquitanian to early Burdigalian).

A correlation, based on the dinocyst stratigraphy combined with well logs and seismic data, is proposed from the expanded and stratigraphically complete succession in Frida-1 with the

more marginal settings onshore Jylland. This correlation confirms the earlier proposed ages of the onshore sequences, i.e. a latest Chattian age for Sequence A (the Brejning Clay) and of the presence of several hiati. Furthermore, the correlation made it possible to subdivide the succession in Frida-1 into sequences A–C, as defined onshore. The Mi-1 glaciation event and thus the Oligocene–Miocene boundary are proposed to correlate to the boundary between the sequences A and B.

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