DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/28

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Danish North Sea sector - and correlation to onshore sections

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

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Contents

Abstract

The dinocyst assemblage from an almost complete Upper Oligocene – Middle Miocene succession in the Danish North Sea area (Frida-1) is presented. The dinocyst assemblage is generally rich and well preserved. The thick succession is subdivided into four depositional sequences, A-D, in accordance with the sequence stratigraphic model for the eastern North Sea Basin. Each sequence is dated based on stratigraphically important last occurrences of dinocyst species and the dinocyst assemblage is compared to the assemblage in the corresponding sequence onshore.

Sequence A (Chattian): The lower part is characterised by a consistent occurrence of *Distatodinium biffi*, this interval is at present not known from onshore sections. The uppermost part, characterised by common *Homotryblium plectilum* and *Deflandrea phosphoritica*, correlate with the upper part of Sequence A onshore (upper part of the Brejning Clay).

Sequence B (?latest Chattian – Aquitanian): The lower part is characterised by abundance of *Homotryblium* spp. and sporadic occurrences of *Chiropteridium* spp., *Membranophoridium aspinatum* and *Deflandrea phosphoritica*. *Ectosphaeropsis burdigalensis* occurs in a narrow interval. The assemblage in this part of the sequence compare to the assemblage in Sequence B onshore (the Vejle Fjord Clay, Vejle Fjord sand, Hvidbjerg sand and Billund sand). The dinocyst assemblage in the upper part (up to the last occurrence of *Caligodinium amiculum*), with only sporadic *Homotryblium* spp., is not comparable to any known onshore assemblage, either due to different facies or to missing sections onshore. A large hiatus is present onshore between Sequences B and C.

Sequence C (Burdigalian): The general assemblage and the last occurrences of *Thalassiphora pelagica* in the lower part and of *Tityrosphaeridium cantharellus* in the uppermost part, indicate a correlation to Sequence C onshore (the lower part of the Arnum Formation and the Bastrup sand).

Sequence D (Burdigalian – Langhian): Strong caving hinders a detailed comparison of the assemblage to the onshore sections, but the last occurrence of *Tityrosphaeridium cantharellus* in the sequence below and the last occurrence of *Distatodinium paradoxum* in the upper part strongly support a correlation with Sequence D onshore (the upper part of the Arnum Formation and the Odderup Formation).

The dinocyst assemblages thus support the correlations between the onshore and offshore sequences as suggested by (Rasmussen, in prep., a). The succession in Frida-1 is stratigraphically more complete than that of the onshore succession; Sequence A includes an older part of the Chattian than known from onshore sections and the hiatus between Sequences B and C present onshore is not recognisable in Frida-1.

Keywords: Denmark; North Sea; Oligocene; Miocene; biostratigraphy; palynology

Introduction

During the last couple of years the knowledge about the Oligocene – Miocene succession onshore Denmark has improved considerably due to series of new boreholes, new seismic data and studies of outcrops. The new interest in this succession is related to the large and relatively shallow sandbodies, comprising aquifers for groundwater. An updated geological model, based on the seismic data, geophysical logs, sedimentology, palynofacies and dinoflagellate cyst (dinocyst) stratigraphy are presented in Dybkjær and Rasmussen (2000), Rasmussen (in prep., a), Rasmussen (in prep., b) Rasmussen and Dybkjær (in prep.) and Dybkjær (in prep., a, b).

The amount of data from the Oligocene – Miocene succession in the Danish North Sea sector has also improved somewhat 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). However, as the targets for the seismic and the wells have been deeper lying, possible hydrocarbon bearing successions, the Oligocene – Miocene succession has been offered little attention and most data from this interval have never been published. The geology of this part of the North Sea deposits is therefore at present not very well known. Palynological data of varying quality can be found in reports, while published palynological information from the Oligocene – Miocene succession in the North Sea area is very limited (see below).

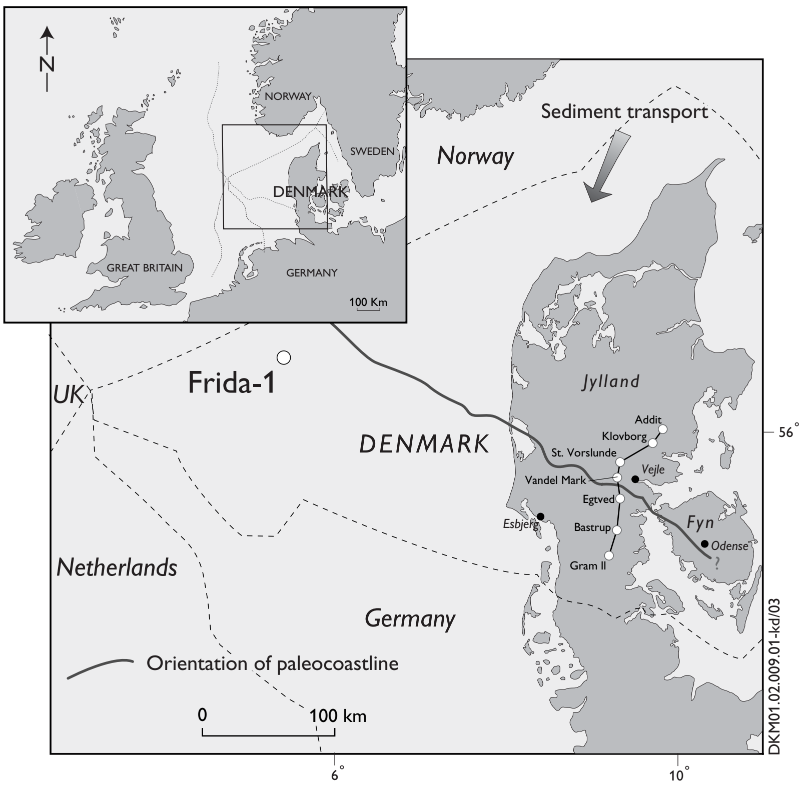

Figure 1. The location of the Frida-1 well and the orientation of the coastline in the Late Oligocene. The sediments came from the north-northeast. The location of the boreholes studied by (Dybkjær, in prep., a) is indicated.

The Danish North Sea well Frida-1 (Fig. 1) is unique in comprising a thick Chattian - Aquitanian succession. The purpose with the present study is to document the dinocyst assemblage in the Upper Oligocene – Middle Miocene succession, in Frida-1. Furthermore, a correlation with Danish onshore sections, based on dinocyst stratigraphy, will be attempted.

Regional geological setting

The North Sea Basin formed as a failed rift basin in Jurassic times (Ziegler, 1982; Vejbæk, 1992). The sea had its maximum extent in the Late Cretaceous. During this period chalk and limestone were deposited. Large palaeogeographic 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 by ash-layers during the Late Paleocene (Heilmann-Clausen, 1995).

In 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 basinal marine clay. In the latest Oligocene, the overall Paleogene progradation had reached the present day Danish North Sea area and the paleoshoreline was located in the Danish onshore area, oriented NW-SE (Fig. 1). In these marginal marine areas fine-grained shelfal sediments and coarse-grained limnic sediments were deposited. In the basinal part of the North Sea Basin, more deep marine conditions existed (the hight of the clinoforms seen at the seismic indicate water depths exceeding 500m (pers. commun. Erik S. Rasmussen, GEUS, 2003) and a succession of gravity deposits interfingering with deep marine clay was deposited. In the earliest Miocene (the Aquitanian) the depositional environment changed to contourite deposition along the shelf slope (Hansen 2002). The Burdigalian and Middle Miocene succession consists of marine shelf deposits (pers. commun. Erik S. Rasmussen, GEUS, 2003).

Local geological setting, lithostratigraphy and sequence stratigraphy

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 1740 m up to 851 m. Lithostratigraphically, this section is referred to the Lark Formation (Knox and Holloway, 1992) the sandy interval from 1622 m to 1485 m is referred to the Freja Member (Schiøler et al., in prep.) (Fig. 2). The sequence stratigraphic subdivision in Frida-1 follows the sequence stratigraphic subdivision of the eastern North Sea Basin suggested by Rasmussen (in prep., a; b). The interpretations of seismic data (sequence boundaries and depositional environments), mentioned in the following, are based on Rasmussen et al. (2002) and pers. commun. Erik S. Rasmussen, GEUS, 2003.

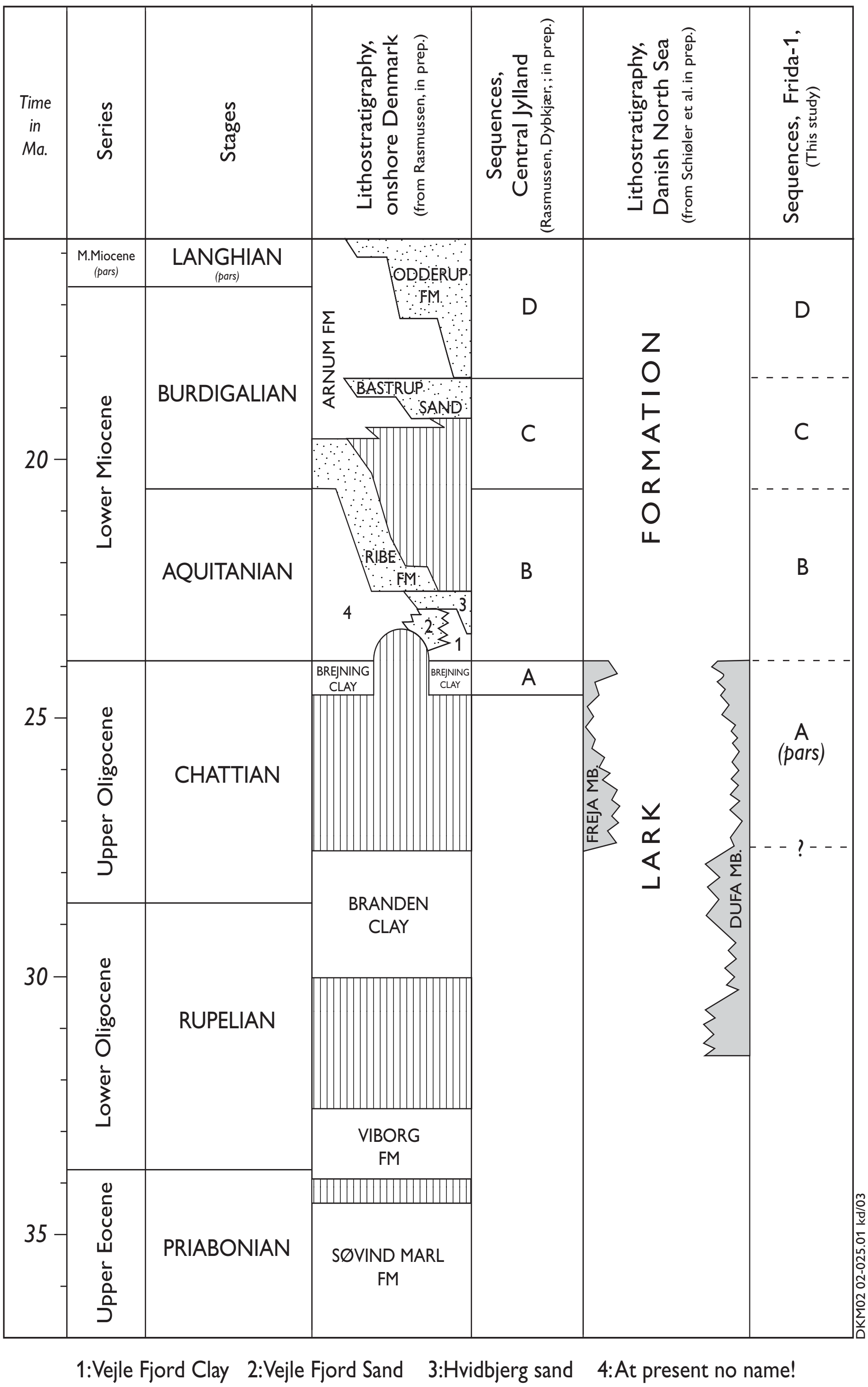

Figure 2. Chronostratigraphy, lithostratigraphy and sequence stratigraphy onshore Denmark, lithostratigraphy in the Danish North Sea area and sequence stratigraphy in Frida-1.

Sequence A (?*pars*) (1740 m –1485 m): The location of the lower boundary of this sequence is questionable. It may be located below the studied succession or it may be located at the gamma-low seen around 1720 m on the log. The succession from 1740 m to 1622 m consists of grey and dark grey shale and greyish-green claystone. From 1622 m to 1530 m the succession consists of dark grey shale, greenish-grey claystone and grey clayey fine-grained sandstone. From 1530 m up to 1485 m the deposits consists of dark brown to dark greyish-brown, clayey siltstone to fine-grained sandstone with mica. The fine-grained deposits from 1740 m to 1622 m are interpreted as deep marine clay deposits. The series of sandstone layers from 1622 m to 1485 m are interpreted as gravity deposits/turbiditic sand.

Sequence B (1485 m-1050 m): The lower boundary is located at the top of the series of gravity deposits referred to the Freja Member at a distinct change from relatively low gamma values to higher gamma values. The boundary can be seen as a regional seismic marker with downlap and onlap, locally with erosional features, and with conformal strata in basinal areas. The succession consists of brownish, clayey siltstone with mica interpreted as contouritic clay (Hansen, 2002).

Sequence C (1050 m-955 m): The lower boundary is located 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 the maximum flooding surface. On the seismic sections the sequence boundary constitutes a regionally mappable marker horizon with downlap and onlap, but conformal in basinal areas. The succession consists of brownish clayey siltstone to fine-grained sandstone with mica, interpreted as marine shelf deposits.

Sequence D (pars) (955m-851m): The lower boundary is located based on seismic data where it is seen as a regional marker horizon, locally with erosional features. The boundary can be correlated to incised valleys onshore Denmark. The distinct log-break at 975m is an artifact due to casing at that level. The succession consists of dark grey to brownish claystone with regular occurrence of shells and is interpreted as marine shelf deposits.

Previous palynostratigraphic studies of the Upper Oligocene – Middle Miocene in the North Sea area and adjacent areas

Several palynological studies from the North Atlantic have been published during the last thirty years. Most of them are based on material from DSDP and ODP- boreholes, e.g. Habib (1972), Manum (1976), Costa and Downie (1979), Bujak (1984), Edwards (1984), Brown and Downie (1985), Powel (1988), Manum et al. (1989), Engel (1992), Poulsen et al. (1996) and Williams and Manum (1999).

From the central and northern North Sea area very little information is available at present. From the northern North Sea exist an unpublished Ph.D. thesis by Ioakim (1979) and an abstract by Costa (1980). From the central North Sea exists only the work by Gradstein et al. (1992).

From the eastern and southeastern North Sea area only a single paper (Michelsen et al., 1998) presents data from offshore boreholes (Danish North Sea area). Several studies from onshore boreholes and outcrops exist. From Denmark can be mentioned Piasecki (1980), Dybkjær and Rasmussen (2000), Rasmussen and Dybkjær (in prep.) and Dybkjær (in prep., a, b).

From Germany several studies have been made, e.g. Maier (1959), Gerlach (1961), Benedek (1972, 1980), Benedek and Müller (1974), Heilmann-Clausen and Costa (1989), Daniels et al. (1990), Köthe (1990, 2000), Strauss and Lund (1992), Lund et al. (1993), Lund and Heilmann-Clausen (2001) and Strauss et al. (2001).

From the Netherlands Herngreen (1983, 1987) has published papers on Miocene dinocyst stratigraphy while data from Belgium have been published by Louwye and Laga (1998) and (Louwye et al., 1999, 2000).

Broad zonations for northwest Europe have been published by Harland (1978) and Costa and Manum (1988). Köthe (1990) revised the zonation by Costa and Manum based on German data, while Powell (1992) presented a zonation for the British area.

Sequence stratigraphy and palynostratigraphy in the uppermost Oligocene – Lower Miocene onshore Denmark

A detailed sequence stratigraphic model for the uppermost Oligocene - Miocene succession in the central and southern parts of Jylland was suggested recently by Rasmussen (in prep., b). The succession was subdivided into 6 Sequences, A to F. Dybkjær (in prep., a, b) presented the variations in the dinocyst assemblages in Sequence A to C and discussed the age of the sequences.

Sequence A (latest Chattian)

In the area studied by Rasmussen (in prep., b) and Dybkjær (in prep., a) a large hiatus occurs at the basal boundary of Sequence A. Marl of Middle to Upper Eocene age is overlain by Upper Oligocene clay, the Brejning Clay. In the studied onshore area the Brejning Clay correspond to Sequence A.

There is general agreement to a Late Oligocene (Chattian) age assigned for the Brejning Clay (and thus of Sequence A), but a more exact placement within the Chattian is not clear. Molluscs in the lower part indicate a Late Oligocene age, Chattian B (Schnetler and Beyer, 1987, 1990). Foraminifera from the same part also indicate a Late Oligocene age (King, 1983; Ulleberg, 1987). Based on a study of foraminifers in the Danish Harre-1 borehole, King (1994) dated it as latest Chattian. In the study of the Brejning Clay by Dybkjær (in prep., a) the absence of the dinocyst species *Distatodinium biffi* made the author suggest that Sequence A should be dated as latest Chattian (the part **above** the last occurrence of *D. biffi*, see Fig. 3). According to Hardenbol et al. (1998) *D. biffi* appears at the base of the Chattian and its last occurrence is in the latest part of the Chattian at 24.50 Ma.

The dinocyst assemblage of Sequence A is dominated by *Spiniferites* spp. and show a common occurrence of *Apteodinium australiense*, *Chiropteridium* spp., *Dapsilidinium pseudocolligerum*, *Deflandrea phosphoritica*, *Distatodinium paradoxum*, *Homotryblium plectilum*, *Hystrichokolpoma rigaudiae*, *Lingulodinium machaeophorum*, *Operculodinium centrocarpum* and *Systematophora placacantha*. *Distatodinium paradoxum*, *Hystrichokolpoma rigaudiae* and *Operculodinium centrocarpum* are most common in the TST. The relative abundances of *Chiropteridium* spp., *Deflandrea phosphoritica* and *Homotryblium plectilum* increase in the HST.

Sequence B (latest Chattian and/or early Aquitanian)

Sequence B comprises a succession deposited in a marginal, partly restricted marine, low-salinity environment. The organic-rich clay is referred to the Vejle Fjord Clay, while the sequence in addition comprises several sand units of different origin, e.g. the Vejle Fjord sand (storm sand), the Hvidbjerg sand (spit-system sand) and the Billund sand (deltaic) (see further Rasmussen, in prep., b).
Palynologically, the boundary between Sequences A and B is characterized by the distinct decrease in relative abundance of *Deflandrea phosphoritica* and *Chiropteridium* spp. In Sequence B these species only occur sporadically. Otherwise, the sparse dinocyst assemblage of Sequence B is characterised by a common to abundant occurrence of *Homotryblium* spp. *Homotryblium plectilum* dominates the lower part of the TST. Following a flooding surface within the TST, *Homotryblium tenuispinosum* becomes more common and above the maximum flooding surface *H. tenuispinosum* dominates the assemblage (Dybkjær, in prep., b, Figs. 3, 4). This development indicates that the changes from a dominance of *H. plectilum* to a dominance of *H. tenuispinosum* is related to increased salinity (Dybkjær, in prep., 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 (Fig. 3). The presence of *Ectosphaeridium burdigalensis* in the upper part of the sequence in one of the studied boreholes (Vandel Mark) indicates an age not older than the very latest Chattian (Hardenbol et al., 1998). However, the low salinity facies may have resulted in a delayed appearance of this species and the interval below may thus be Aquitanian (Dybkjær, in prep., a).

A correlation to eustatic sea-level curves indicates that the Oligocene – Miocene boundary is located at the boundary between Sequences A and B, and that Sequence B thus is lower Aquitanian (Dybkjær, in prep., a).

Sequence C (early to mid-Burdigalian)

In the onshore area studied by Dybkjær and Rasmussen (2000) and Dybkjær (in prep., a) there is a hiatus at the boundary between Sequences B and C, spanning the late Aquitanian and the earliest Burdigalian. Sequence C clearly consists of more open marine deposits than Sequence B, although the most proximal (northernmost) parts of the study area continued to be strongly influenced by freshwater (Dybkjær, in prep., a, b). The marine clay of Sequence C is referred to the Arnum Formation while the more coarse-grained fluvio-deltaic deposits are referred to the Bastrup sand.

In the central and southern (distal) parts of the study area the dinocyst assemblage showed a distinct change across the boundary between the Sequences B and C, from a low-diversity *Homotryblium*-dominated assemblage to a higher-diversity assemblage dominated by *Impletosphaeridium insolitum*, *Operculodinium centrocarpum*, *Spiniferites* spp. and *Systematophora placacantha*. *Homotryblium* spp. occurs sporadically only. In the northern parts *Homotryblium* continues to dominate the assemblage up through Sequence C.

Sequence C was dated as early to mid-Burdigalian based on the last occurrence of *Thalassiphora pelagica* and the first occurrence of *Hystrichosphaeropsis obscura* within the TST combined with the last occurrence of *Tityrosphaeridium cantharellus* in the sequence above (Dybkjær, in prep., a) (Fig. 3). An early to mid-Burdigalian age for the Arnum Formation is supported by earlier studies of dinocysts (Dybkjær and Rasmussen, 2000) and of foraminifera (Laursen and Kristoffersen, 1999).

Material and methods

The Frida-1 well is located in the Danish North Sea area, see Fig. 1. The studied succession covers the interval from 1740 m to 851 m. A total of 45 ditch cuttings samples and 4 conventional core samples has been studied (Enclosure 1). The ditch cuttings samples represent intervals of 5 or 10 m (851 m-1390 m: 10 m interval, 1390 m-1740 m: 5 m interval). The depths for the ditch cuttings samples mentioned in the text and in the range chart are the base depths of the interval represented by each sample.

The sample material was processed using standard palynological processing methods including treatment with HF and HCl to dissolve silicates and heavy liquid separation to remove the undissolved mineral matter. The residue was sieved at an 11 μm mesh and a 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 on a 20 μm mesh to concentrate the dinocysts, two additional slides were produced.

Results

The results from the palynological study are presented in Figs. 2, 3 and Enclosure 1.

Sequence A (?*pars*) (1740 m – 1485 m)

Dinocyst assemblage

Spiniferites spp. dominates the dinocyst assemblage throughout the sequence. The lower part of the sequence, up to 1670 m, is characterised by common occurrences of *Dapsilidinium pseudocolligerum*, *Hystrichokolpoma rigaudiae*, *Impletosphaeridium insolitum* and *Systematophora placacantha*. In the upper part of the sequence *Systematophora placacantha* also occur commonly, and abundantly in the sample at 1532.10 m. *Homotryblium plectilum* occurs commonly to abundantly from 1650 m – commonly up to 1590 m and abundantly from 1560 m and into the basal part of Sequence B. *Glaphyrocysta* spp. occur consistently from 1650 m. *Deflandrea phosphoritica* occur commonly from 1528.38 m and up to the sequence boundary and *Homotryblium tenuispinosum* is common from 1510 m and into Sequence B.

The samples at 1528.30 m and 1522.30 m are characterised by abundance of the acritarch species *Cyclopsiella elliptica* and *Paralecaniella indentata*.

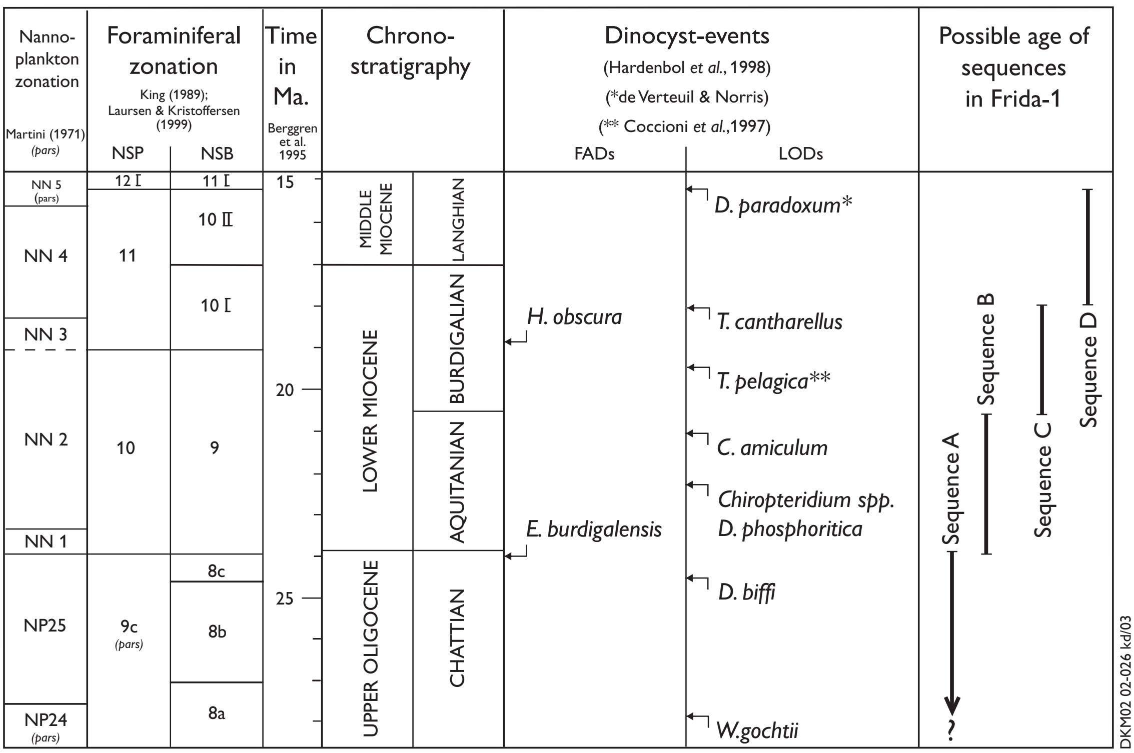

Figure 3. The possible age of the sequences in Frida-1, based on dinocyst events. The dinocyst events are correlated to nannoplankton zonation, foraminiferal zonation, absolute age and chronostratigraphy.

Except for the above mentioned taxa *Apteodinium australiense*, *Chiropteridium* spp., *Distatodinium paradoxum*, *Heteraulacacysta campanula*, *Lejeunecysta* spp., *Lingulodinium machaerophorum*, *Nematosphaeropsis labyrinthea*, *Operculodinium centrocarpum*, *Palaeocystodinium golzowense*, *Reticulatosphaera actinocoronata*, *Spiniferites pseudofurcatus*, *Tectatodinium pellitum* and *Tityrosphaeridium cantharellus* all occur consistently to commonly throughout the sequence.

The stratigraphic important dinocyst species *Wetzeliella gochtii* occur in the two lowermost samples, up to 1720 m, while *Distatodinium biffi* occur consistently in the lower part of the sequence, up to 1630 m.

Age

1740 m – 1630 m: Late Oligocene (Chattian).

According to (Hardenbol et al., 1998) the last occurrence of *W. gochtii* occur in the Rupelian in NW Europe, while it occur in the Chattian in the Mediterranean area. In contrast to this, (Pross, 2001, Fig. 1) shows diachronism of last occurrences of e.g. *W. gochtii* from a number studies in NW Europe with the youngest occurrences in the northernmost locations, in the Northwest European Tertiary Basin. He suggests palaeo-oceanographic changes within the seaway connecting the Northwest European Tertiary Basin and the Tethyan realm as the reason for the diachronism. According to the studies referred to by Pross (2001, Fig. 1), the last occurrence of *W. gochtii* varies from the lower part of NP23 (mid Rupelian) for localities in the southern Upper Rhine Graben (Rauscher and Weiler, 1988; Schuler, 1990; Pross, 1997) to the uppermost part of NP24 (lower Chattian) for localities in Belgium and northern Germany (Heilmann-Clausen and Costa, 1989; Köthe, 1990; Stover and Hardenbol, 1993). It is therefore assumed that the last occurrence of *W. gochtii* in the lowermost part of the studied succession (at 1720 m) indicates a lower Chattian age (Fig. 3). The consistent occurrence of *Distatodinium biffi* within the interval from 1740 m to its last occurrence at 1630 m and the absence of *Enneadocysta pectiniformis* further support an age not older than the Chattian. The former has its first appearance in the lowermost Chattian according to Hardenbol et al. (1998) and the latter has its last occurrence in the upper part of the Rupelian (Köthe, 1990, 1996; Hardenbol et al., 1998). The last occurrence of *Distatodinium biffi* at 1630 m indicates an age not younger than the Chattian (Hardenbol et al., 1998).

1630 m – 1490 m: latest Oligocene (latest Chattian).

The last occurrence of *Distatodinium biffi* at 1630 m strongly indicates a latest Chattian age for that level. The common occurrence of *Deflandrea phosphoritica* in the uppermost part of the sequence and the occurrences of *Caligodinium amiculum* and *Chiropteridium* spp. indicate an age not younger than the early Aquitanian (Hardenbol et al., 1998). The correlation of this interval with Sequence A onshore, referred to the Brejning Clay (see further below), strongly indicate a Chattian age (Dybkjær, in prep., a).

Depositional environment

Dinocyst assemblages recorded from deep marine settings often comprise a mixture of allochtonous and autochtonous cysts, that is cysts produced in the deep palaeo-sea close to where the cysts have been found and cysts transported into the deep marine setting from the other areas by currents (e.g. Dale and Dale, 1992). This is probably also the case for the assemblage in Sequence A. For example *Nematosphaeropsis* cysts may be *in situ* as this genus is known to occur mainly in fully marine, outer neritic to oceanic settings (Wall et al., 1977; Harland, 1983; Wrenn and Kokinos, 1986), while high numbers of *Chiropteridium*, *Glaphyrocysta* and *Homotryblium* indicate inner neritic environments (Zevenboom, 1996; Brinkhuis, 1994; de Verteuil and Norris, 1996). The latter three species are thus probably transported from marginal areas into the deep basin. Such mechanisms, in combination with reworking and caving, makes detailed environmental interpretations based on dinocysts rather doubtful and will not be attempted here. Only distinct changes will be discussed.

The relative abundance of *Homotryblium plectilum* increases at 1650m and *Glaphyrocysta* spp. appears at that level. These changes possibly reflects progradation of the coastline and/or increased transportation from marginal marine settings into the deep marine setting, due to decreasing relative sea-level.

The distinct increase in relative abundance of *Deflandrea phosphoritica* in the uppermost part of the sequence, from 1550 m up to the upper sequence boundary, may be *in situ*, reflecting increased influx of nutrients as a result of the progradation, or the cysts may have been transported from marginal marine settings. *D. phosphoritica* probably represents an heterotrophic peridiniod dinoflagellates. Such forms strongly depend on nutrient availability in the seawater. Abundance of these is thus characteristic for upwelling zones and river mouths (Bradford and Wall, 1984; Harland, 1988; Brinkhuis et al., 1992; Brinkhuis, 1994). There are no indications of upwelling in the study area, while large river mouths are known to have occurred in the area which at present is located onshore Jylland (Rasmussen, in prep., b; Rasmussen and Dybkjær, in prep.).

The abundance of *Paralecaniella* in the core samples at 1528.38 m -1522.30 m was probably derived from marginal marine settings, as this genus is know to occur mainly in marginal marine depositional environments (Brinkhuis and Schiøler, 1996; Powell et al., 1996; Schiøler et al., 1997).

Reworking/caving

Sporadic occurrences of reworked Upper Triassic-Jurassic spores and pollen were found in the lower part of the sequence, up to 1630 m. Sporadic reworked Paleocene, Eocene and Lower Oligocene dinocysts occur throughout the sequence, more common in the samples at 1720 m (seen on the log to represent a minor coarse-grained interval, probably gravity deposits) and at 1528.38 m-1522.30 m (within the Freja Member, also interpreted as gravity deposits).

Correlation to onshore sections

The lower part of Sequence A in the Frida-1 well, at least up to the last occurrence of *Distatodinium biffi* at 1630 m, represents a succession which probably is older than the part of Sequence A present onshore Jylland (the Brejning Clay) as *Distatodinium biffi* was not recorded in the onshore succession (Dybkjær, in prep., a) (Fig. 2).

The dinocyst assemblage in the upper part of Sequence A in Frida-1 (above the last occurrence of *D. biffi*), compare closely with the assemblage from Sequence A (the Brejning Clay) onshore Jylland (see descriptions of the assemblages above). Especially the consistent occurrence of *Chiropteridium* spp. and the increase in relative abundance of *Distatodinium phosphoritica* and *Homotryblium plectilum* in the uppermost part of the sequence, towards the overlying SB, are common features that support the correlation of these successions as suggested by Rasmussen (in prep., a).

Sequence B (1485 m – 1050 m)

Dinocyst assemblage

Spiniferites spp. occurs abundantly throughout the sequence. *Homotryblium plectilum* dominates in the lowermost sample and occurs commonly up to 1310 m, with a minor decrease in abundance between 1390 m and 1370 m. *Homotryblium tenuispinosum* occurs commonly up to 1290 m. *Operculodinium centrocarpum* and *Systematophora placacantha* occur commonly from 1390 m. The decrease in relative abundance of *Homotryblium* at 1310 m-1290 m seems to be balanced by an increase in abundance of *Operculodinium centrocarpum* and *Systematophora placacantha* accompagnied by *Apteodinium australiense*, *Hystrichokolpoma rigaudiae* and *Impletosphaeridium insolitum*. *Melitasphaeridium choanophorum* and *Operculodinium piaseckii* occur consistently from 1270 m.

The stratigraphic important taxa *Caligodinium amiculum*, *Chiropteridium* spp., *Deflandrea phosphoritica*, *Membranophoridium aspinatum* and *Thalassiphora pelagica* all occur sporadically, while *Tityrosphaeridium cantharellus* occur consistently throughout the sequence. *Ectosphaeropsis burdigalensis* occurs in a very narrow interval from 1330 m to 1290 m.

Age

Latest Oligocene? – earliest Miocene (latest Chattian? – Aquitanian).
The last occurrence of *Distatodinium biffi* in the sequence below indicates an age not older than the latest Chattian (Hardenbol et al. 1998) (Fig. 3). The occurrences of *Chiropteridium* spp. up to 1370 m and *Deflandrea phosphoritica* up to 1130 m indicate an age not younger than the early Aquitanian for the lower part of the sequence while the occurrence of *Caligodinium amiculum* throughout the sequence indicates an age not younger than Aquitanian.

In the study by Dybkjær (in prep., a) a correlation between the onshore sequences and eustatic sea-level changes indicated that the Oligocene – Miocene boundary is located at the boundary between Sequence A and B and that all of Sequence B thus should be dated as Aquitanian.

Depositional environment

The abundance of *Homotryblium plectilum* in the lowermost part of the sequence and the common occurrences of *H. plectilum* and *H. tenuispinosum* together with a consistent occurrence of *Glaphyrocysta* spp. up to 1290 m may indicate a marginal marine depositional environment (e.g. Brinkhuis, 1994; de Verteuil and Norris, 1996; Dybkjær, in prep., b). However, the regional geology and the seismic interpretations strongly indicate that the succession was deposited in a deep basin some distance from the shore. It must therefore be assumed that the *Homotryblium* and *Glaphyrocysta* cysts were transported into the deep basin from marginal marine areas.

The first appearance of *E. burdigalensis* in the HST of Sequence B onshore Jylland was interpreted as a “delayed” first appearance, possibly due to high freshwater influx during deposition of the lower part of the sequence (Dybkjær, in prep., a). The appearance of *E. burdigalensis* was thus recorded above the succession with abundant *H. plectilum*. In Frida-1 *E. burdigalensis* likewise appears above the interval with common *H. plectilum*.

The upper part of the sequence with only sporadic occurrences of *Homotryblium tenuispinosum* and common occurrences of *Apteodinium australiense*, *Dapsilidinium pseudocolligerum*, *Hystrichokolpoma rigaudiae*, *Operculodinium centrocarpum* and *Systematophora placacantha* probably reflects a more fully marine depositional setting and/or a lower input of transported dinocysts.

Reworking/caving

Reworked Paleocene, Eocene and Lower Oligocene dinocysts were recorded sporadically in the lower part of the sequence, up to 1290 m. Reworked Upper Triassic - Jurassic spores and pollen were recorded from 1290 m and up to the upper sequence boundary.

Correlation to onshore sections

The dinocyst assemblage in the lower part (up to 1290 m), compare closely to the assemblage in Sequence B onshore Denmark (Vejle Fjord Clay and –Sand, Billund sand and Hvidbjerg sand), characterised by abundance of *Homotryblium plectilum* and *H. tenuispinosum*, sporadic occurrences of *Chiropteridium* spp., *Deflandrea phosphoritica*, *Caligodinium amiculum* and the occurrence (in a narrow interval) of *E. burdigalensis*. The dinocyst assemblage in the succession from 1290 m to the upper sequence boundary, above the last occurrence of *Chiropteridium* spp. and with only sporadic occurrences of *H. tenuispinosum* does not compare to any assemblages seen onshore. This may be due to either (1) different depositional environments or (2) a missing section in the areas studied onshore;

(1) Frida-1 represents an area located some distance from the shore and thus from influx of freshwater and nutrients, while Sequence B in mid- and southern Jylland clearly represents an inner-neritic, restricted marine, possibly brackish water environment with high influx of freshwater and nutrients (Rasmussen, in prep., b; Dybkjær, in prep., a, b). The decrease in *H. plectilum* from 1390m to 1370m and the disappearence/decrease in *H. plectilum*/*H. tenuispinosum* at 1310m/1290m may very well represent flooding surfaces, that moved the coastline north-eastwards, and thus further away from the study-area. A number of flooding surfaces were also identified in the onshore succession, but the biostratigraphic resolution does not allow a safe correlation.

(2) The upper part of Sequence B in Frida-1 may represents a succession that is not represented in the area studied by Dybkjær (in prep., a) and Dybkjær and Rasmussen (2000). In these areas the sequence boundary between Sequences B and C represents a major hiatus, representing a time-interval of approximately 3.5Ma (Dybkjær and Rasmussen, 2000). It is very likely that deposits representing parts of that time-interval is present in the basinal areas.

Sequence C (1050 m – 955 m)

Dinocyst assemblage

The dinocyst assemblage in the lowermost sample is dominated by *Operculodinium centrocarpum*, *Spiniferites* spp. and *Systematophora placacantha*. *Spiniferites* spp. occurs in distinctly lower relative abundance in this sample, relative to the samples below and above. *Apteodinium australiense* and *Hystrichokolpoma rigaudiae* occur commonly. From the lowermost sample up to the sample at 990m a gradual decrease in *Apteodinium australiense*, *Hystrichokolpoma rigaudiae*, *Operculodinium centrocarpum* and *Systematophora placacantha* occur, while the abundance of *Homotryblium tenuispinosum* and *Spiniferites* spp. increase.

The first appearances, in the sample at 970 m, of a mixture of Lower, Middle and Upper Miocene species, e.g. *Achomosphaera andolousiense*, *Cannosphaeropsis passio*, *Cousteaudinium aubryae* and *Labyrinthodinium truncatum*, are interpreted as a result of caving. A casing is located at 975 m and down to this level severe caving seems to have occurred. Below the casing no indications of caving have been recognised.

Of stratigraphic importance must be mentioned the last occurrence of *Thalassiphora pelagica* at 1050 m and of *T. cantharellus* at 990 m.

Age

Early Miocene (Burdigalian). The last occurrence of *Caligodinium amiculum* in the sequence below indicates an age not older than the latest Aquitanian (Fig. 3). The last occurrence of *Thalassiphora pelagica* in the lower part of Sequence C indicates a Burdigalian age. The occurrence of *Tityrosphaeridium cantharellus* in the upper part of the sequence indicates an age not younger than Burdigalian. The first appearance of *Hystrichosphaeropsis obscura* at 970 m supports a Burdigalian age if it is *in situ*.

Depositional environment

The deposits of Sequence C are interpreted as marine shelf deposits based on seismic data and a sedimentological study of the R-1 well (pers. com. Erik S. Rasmussen, GEUS, 2003). The increasing gamma readings in the lowermost part of the sequence indicate a flooding surface. This is supported by the occurrence of *Impagidinium* spp. and the high relative abundances of *Apteodinium australiense*, *Hystrichokolpoma rigaudiae*, *Operculodinium centrocarpum* and *Systematophora placacantha* in the lowermost sample (at 1050 m). The following gradual increase in gamma readings are concurrent with a gradual decrease in the above mentioned species and an increase in *Dapsilidinium pseudocolligerum*, *Homotryblium tenuispinosum* and *Spiniferites* spp.

Reworking/caving

Severe caving down to the casing at 975 m has resulted in a mixture of Lower, Middle and Upper Miocene dinocyst species in the sample at 970 m.

Reworked Eocene or Oligocene dinocysts occur sporadically throughout the sequence, while only a single reworked Upper Triassic – Jurassic spore was recorded in the lowermost sample.

Correlation to onshore sections

The dinocyst assemblage in the lower part of Sequence C in Frida-1 is clearly comparable to the assemblage in the lower part of Sequence C (lower part of the Arnum Formation) onshore Denmark. The last occurrence of *Caligodinium amiculum* in the sequence below and of *Thalassiphora pelagica* in the lower part of the sequence both onshore and offshore, strongly indicate time-equivalence of the lower boundary (Fig. 2). The severe caving in Frida-1 down to the upper part of Sequence C hinders a thrustworthy comparison of the dinocyst assemblages in the upper part of the sequence. The last occurrence of *Tityrosphaeridium cantharellus* at 990 m may be the result of dilution of the *in situ* assemblage.

Sequence D (955 m – 851 m)

Dinocyst assemblage

The succession is strongly influenced by caving and for many species it is impossible to decide whether the recorded specimens are caved or *in situ*. The following description of the recorded assemblage must therefore be seen in that light.

Spiniferites spp. occurs abundantly while *Dapsilidinium pseudocolligerum*, *Habibacysta tectata*, *Lingulodinium machaerophorum*, *Operculodinium centrocarpum* and *Systematophora placacantha* occur commonly. The high diversity within the succession is probably false, being due to caving. The co-occurrence of species with last occurrences in the Langhian to lower Serravallian, e.g. *Apteodinium spiridoides*, *A. tectatum* and *Distatodinium paradoxum* and species appearing in the upper Serravallian as *Cannosphaeropsis passio*, strongly indicate caving.

The first occurrence of *Exochosphaeridium insigne* in the lower part of the sequence (at 930 m) and the last occurrence of *Distatodinium paradoxum* in the upper part (at 870 m) are of stratigraphic significance.

Age

Lower to Middle Miocene (Burdigalian to Langhian).
The last occurrence of *Tityrosphaeridium cantharellus* in the sequence below indicates an age not older than Burdigalian (Fig. 3). The last occurrence of *Distatodinium paradoxum* in the upper part (at 870 m) indicates a Langhian age.

Depositional environment

The deposits of Sequence C are interpreted as marine shelf deposits based on seismic data and a sedimentological study of the R-1 well (pers. com. Erik S. Rasmussen, GEUS, 2003). The dinocyst assemblage does not show any major changes and the caving makes it impossible to make any general conclusions about the depositional environment based on the cysts.

Reworking/caving

The whole succession is characterised by severe caving. Reworked Upper Triassic – Jurassic spores and pollen, a single Paleocene dinocyst and a couple of Oligocene dinocysts were recorded.

Correlation to onshore sections

The severe caving makes it difficult to compare the dinocyst assemblage from Frida-1 with the asemblage in Sequence D onshore Jylland. However, the first appearance of *Exochosphaeridium insigne* in the lower part of the sequence and the last occurrence of *Distatodinium paradoxum* in the upper part indicate that the succession corresponds to Sequence D onshore Jylland, referred to the upper part of the Arnum Formation and the Odderup Formation (Dybkjær et al., 2001). Onshore *Tityrosphaeridium cantharellus* has its last occurrence within Sequence D, while in Frida-1 it was found in the uppermost Sequence C. This discrepancy may be explained by dilution of the assemblage in Frida-1 by caved dinocysts.

Discussion

Correlation

The recorded succession of last occurrences of dinocyst species, from *Wetzeliella gochtii* in the lowermost part to *Distatodinium paradoxum* in the upper part of the studied succession (Fig. 3), generally correspond to data from other European Basins and from the western North Atlantic (see e.g. Hardenbol et al., 1998).

The occurrences of *Distatodinium biffi*, *Caligodinium amiculum*, *Chiropteridium* spp., *Deflandrea phosphoritica* and *Ectosphaeropsis burdigalensis* in the Danish North Sea allow a detailed correlation to the type section for the Oligocene – Miocene boundary, the Lemme – Carrosio section, northern Italy, and thus a dating of the uppermost Oligocene – lowermost Miocene succession in Frida-1. The dinocyst zonation erected for the type section is, however, not directly applicable, as several species defining the Italian zones were not found in Frida-1 and the abundance variations (of *Deflandrea* spp. and *Chiropteridium* spp.) are different (see discussion in Dybkjær, in prep., a). The exact location of the Oligocene – Miocene boundary remains questionable as none of the dinocyst events are located exactly at the boundary.

The dinocyst assemblages also allow a detailed correlation to Danish onshore sections. This correlation clearly shows that the succession in Frida-1 is more complete than the onshore succession, as would be expected, with Frida-1 being located in a basinal setting (Fig. 2). Onshore Sequence A only comprises deposits of latest Chattian age. In Frida-1 an older part of the Chattian is represented. Furthermore, there is probably no or only a minor hiatus between Sequences B and C in Frida-1, while this sequence boundary possibly represents a hiatus of approximately 3.5Ma in the onshore areas studied by Dybkjær and Rasmussen (2000) and Dybkjær (in prep. a, b). It is problematic to compare the upper part of Sequence C and Sequence D with the onshore sections due to severe caving but the overall dinocyst assemblages and a few stratigraphically important last occurrences strongly indicate time-equivalence.

Reworking

The reworked palynomorphs show a distribution pattern that possibly reflects different source areas. Reworked Jurassic spores and pollen were recorded from the lower part of Sequence A, in the upper part of Sequence B and in Sequences C and D. Reworked Paleocene, Eocene and Lower Oligocene dinocysts occur in most of the succession, except for the upper part of Sequence B, but are most common in the core-samples in the upper part of Sequence A, representing gravity flow deposits.

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Enclosure

Enclosure 1. Rangechart including gamma- and sonic logs, location of samples, cored interval and casing, the relative abundance of dinocyst taxa, acritarchs and freshwater algae, stratigraphically important dinocyst events and chronostratigraphy.

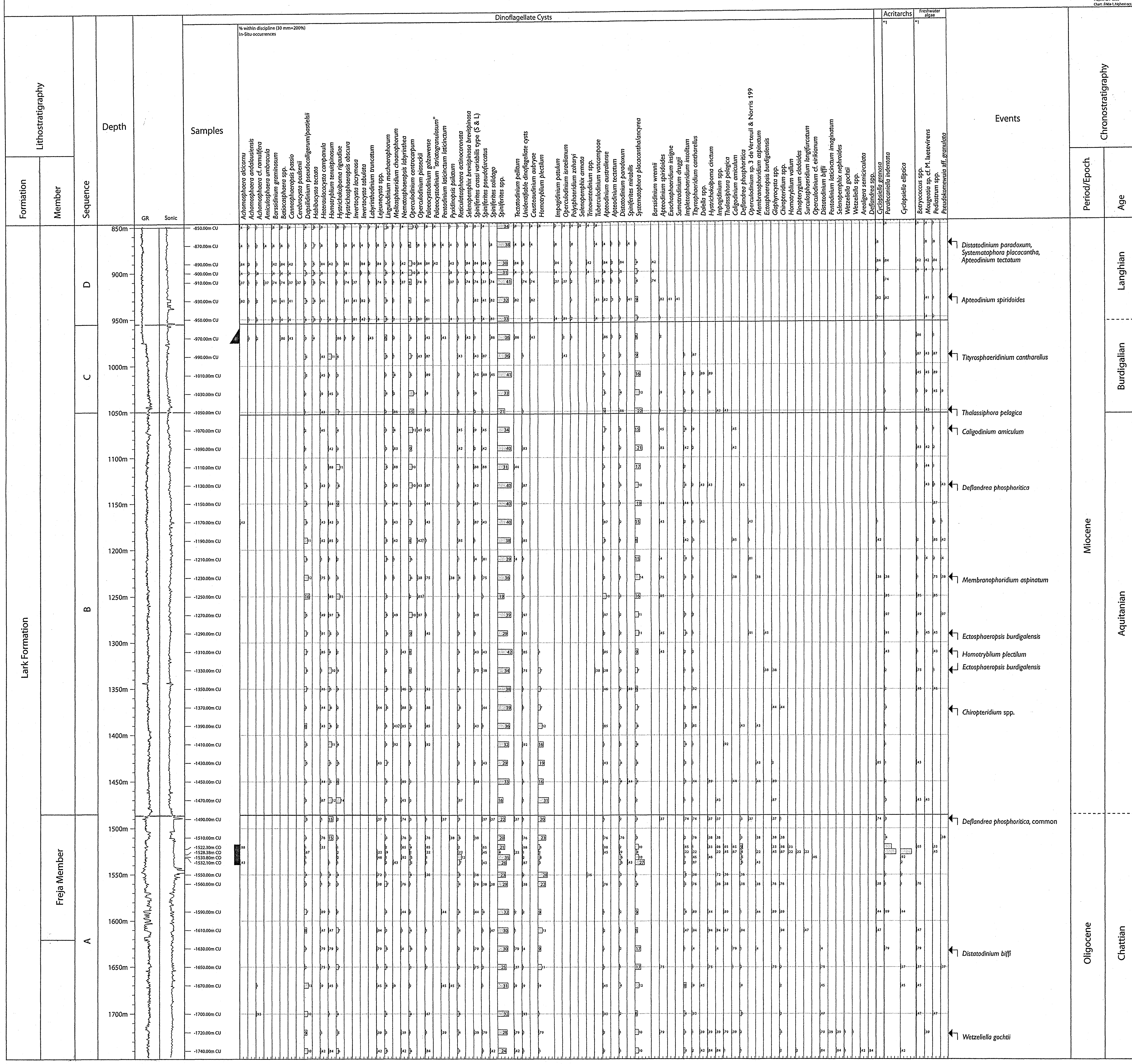
ENCLOSURE 1

Well Name : Frida-1
Interval : 850m-1745m
Scale : 1:2500
Chart date : 24 March 2003

G E U S
Report file no.
Enclosure
18995 (01/01)

GEUS
Copenhagen

Project : EFP-2000
Chart : Frida-1, highest occ.



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