DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2015/1

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G E U S

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Summary

This report presents the results of an investigation of palynology and clay mineralogy of the major part of the Paleocene succession in core 1 from the Nena-1 well. The location of the well within the Siri Canyon, Danish North Sea, is shown in Fig. 1. The report presents the results of 1) a biostratigraphic analysis of the interval 2174.25–2132.50 m (core depth) in the Nena-1 well, based on the contents of fossil dinoflagellate cysts (dinocysts) in 24 selected core samples and 2) a clay mineralogical analysis of 8 core samples. The focus of the report is on core samples and consequently core depths are used in the text below. The core depths differ from the log depths by *c*. 4 m. The lower boundary of the Lista Formation is at 2173.5 m core depth and 2177.5 m log depth.

The Nena-1 well penetrated the Neogene and the Palaeogene successions in the north-eastern part of the Siri Canyon. The primary objective of Nena-1 was to evaluate the presence of sandstones in the Våle and Lista formations and to test the presence of commercial oil volumes in this setting (Petersen et al. 2014). The well is deviated, and the final depth of 2220 m MDRT corresponds to 1850 m TVDRT. Core 1 has a length of 55 m (2130–2185 m MDRT) and represents a 33 m thick succession of Paleocene strata (Fig. 8).

The palynology is based on fossil dinoflagellate cysts (dinocysts) and relates to the biozones of Heilmann-Clausen (1985) and the biostratigraphic schemes in Schiøler et al. (2007). The biostratigraphic data are summarized in a range chart (Enclosure 1). The clay mineralogy is determined from X-ray diffractograms of oriented, pre-treated samples of the clay fraction. The mineralogical data are summarized in Table 2.

Of the 24 core samples included in the palynological study, stratigraphically significant palynomorph assemblages were recovered from the ten uppermost samples (2157.70–2132.50 m). The eight lowermost samples were totally barren of palynomorphs (2174.25–2168.45 m). The samples from 2167.25 m to 2161.30 m vary with respect to their content of palynomorphs (see Enclosure 1).

Generally, the palynomorph assemblages are of low diversity and the dinocysts are often broken and with torn processes. A gradual increase in terrestrial palynomorphs is seen from 2146.50 m and upwards, and in the uppermost two samples (2135.70 m and 2132.50 m) the palynomorph assemblages are dominated by pollen.

Reworked palynomorphs are only recorded in the upper part of the studied succession and the number increases upwards. The reworked specimens comprise Jurassic palynomorphs and the dinocyst *Palaeoperidinium pyrophorum* known to occur in the Danian and (abundantly) in the Selandian. The increasing numbers of pollen, reworked palynomorphs and also the recordings of a few freshwater algae (*Pediastrum* spp.) in the upper part of the studied succession may reflect an increased terrestrial input.

Despite the barren or low producing samples and the relatively low diversity, it is possible to identify two dinocyst zones, Zone 4 and 5 of Heilmann-Clausen (1985).

The chalk sample 2174.25m from the Ekofisk Formation consists of 80% calcite and the clay fraction is dominated by quartz, with subordinate smectite. The two claystone samples 2169.35 m and 2172.30 m with 70 – 80% clay (particles <2µm) and the samples 2146.50 m, 2153.05 m 2153.35 m 2164.32 m and 2166. 46 m with 40 – 60% clay are dominated by

a smectite of the montmorillonite subgroup and for samples 2146.50 m, 2153.05 m 2153.35 m and 2166.46 m with small amounts of illite and kaolinite. The smectite appears to have larger crystal thickness in the clay rich samples 2169.35 m and 2172.30 m clay and smaller thicknesses in the samples above (Table 2).

Based on the biostratigraphic results, the clay mineral assemblage, the gamma-ray log and the lithologies documented in the core photos, a lithostratigraphic subdivision of the Paleocene in Nena-1 is proposed. Depths are core depths MRDT, the lithostratigraphic units are from Schiøler et al. (2007).

2114.5 m (or 2118.5 m log depth): base of the Sele Formation, lowermost Eocene
2146.8 m: base of Bue Member (Lista Formation), Thanetian (Upper Paleocene)
2173.5 m: base of Ve Member (Lista Formation), Thanetian (Upper Paleocene)
2173.5 m (or 2177.5 m log depth): top of the Ekofisk Formation, Danian, Lower Paleocene
2216 m (or 2220 m log depth) TD in the Ekofisk Formation

In the Nena-1 well the Ekofisk and Lista formations are separated by an erosional unconformity, which corresponds to the Våle Formation and the lower part of the Lista Formation (the Vile Member and probably the basal part of the Ve Member). Due to the lack of palynomorphs in the samples from the Ekofisk Formation it is not known, whether the unconformity includes the top of the Ekofisk Formation (Fig. 8, Enclosure 1).

List of figures and tables

Introduction

The Paleocene deposits in the North Sea are referred to the Ekofisk Formation of the Chalk Group and to the Våle and Lista formations of the Rogaland Group (Schiøler et al. 2007; Fig. 2). The purpose of the present study has been to correlate the cored succession in Nena-1 to the complete lithostratigraphy, and to determine whether the boundary between the Chalk Group and the Rogaland Group is an erosional unconformity. Twenty-four core samples (plugs) have been examined for palynology and eight of these have also been studied for clay mineralogy (Table 1). The samples are shown in a simplified log (Fig. 8). The number of samples and their position was selected by Dong Energy (see Table 1 and Fig. 3).

The present report is based on core samples from the Danish Nena-1 well (Figs1, 2). The purpose of the study is to provide data on the hiatus between the limestones of the Ekofisk Formation and the overlying mudstones of the Lista Formation.

The results of the study follow the lithostratigraphy for the Palaeogene – Lower Neogene succession of the Danish North Sea by Schiøler et al. (2007). The dinocyst biostratigraphy was defined for the Danien to Lower Eocene succession onshore Denmark by Heilmann-Clausen (1985).

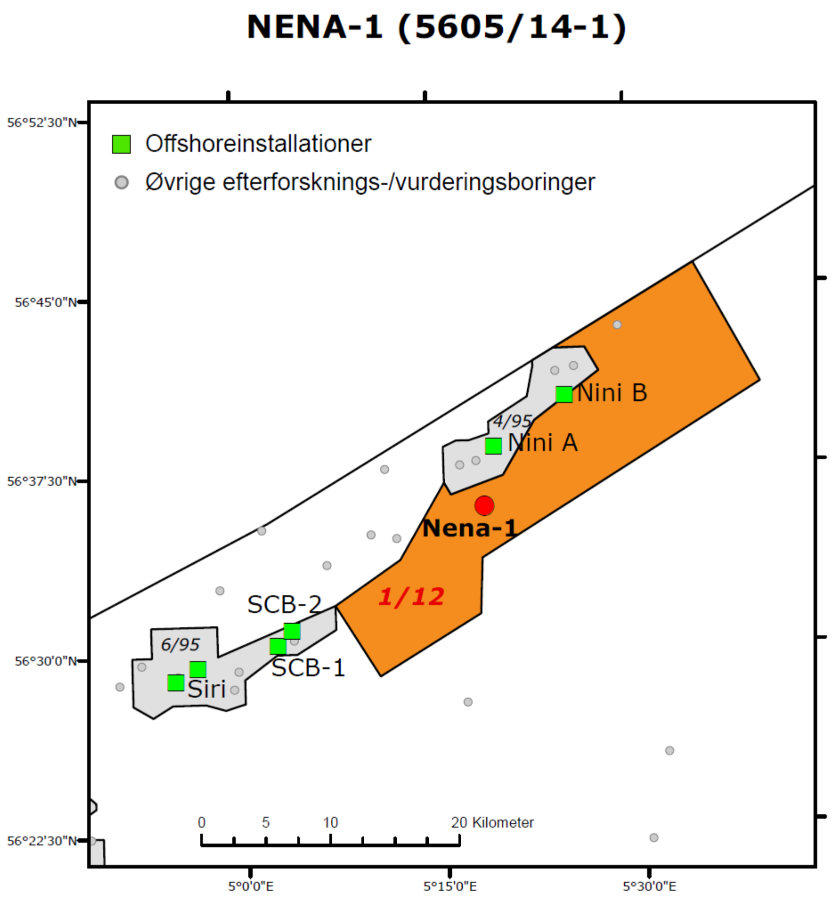

Figure 1: Location of the Nena-1 well, map from Energistyrelsen.

Geological setting

The Paleocene succession in the Danish part of the North Sea, including the Central Graben, includes Danian limestone (Ekofisk Formation, Chalk Group) overlain by Selandian and Thanetian red, green and grey mudstones (the Våle and Lista formations of the Rogaland Group) (Schiøler et al. 2007; Fig. 2). The Paleocene–Eocene boundary is located at the base of the dark grey, laminated mudstones of the Sele Formation, which shows a characteristic peak on the gamma ray log at 2118.5 m (log depth) corresponding to a core depth of 2114.5 m Fig. 8). The basal part of the Sele Formation was deposited during a brief climatic warming, the PETM (Paleocene Eocene Climatic Maximum; Knox et al. 2010, McInerney & Wing 2011).

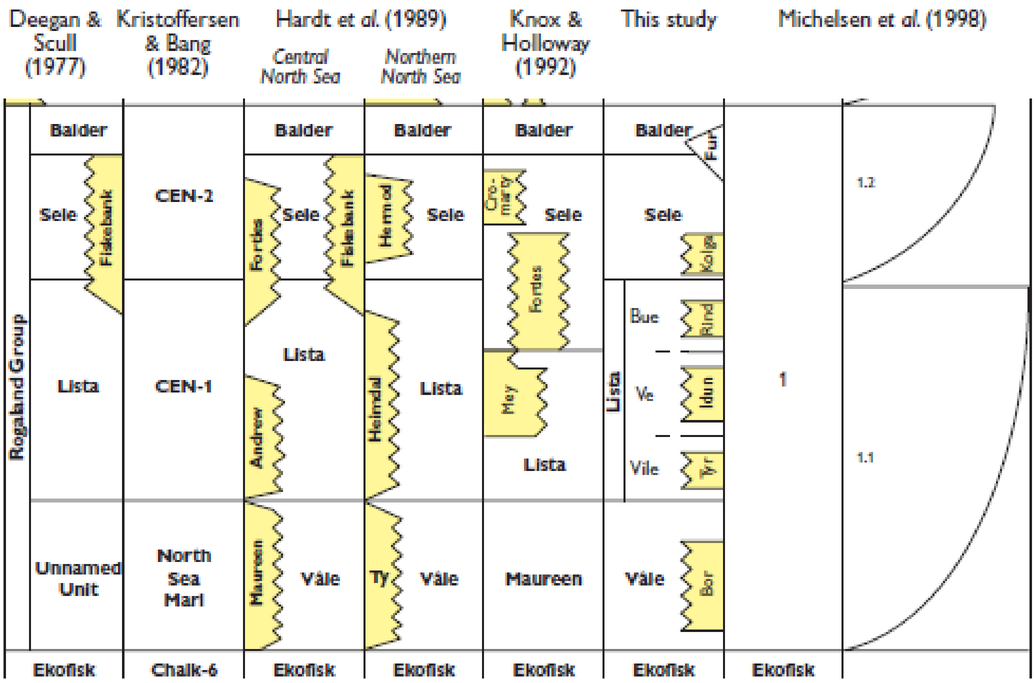

Fig. 2. Correlation chart showing approximate correlation between key lithostratigraphic schemes for the central and eastern North Sea and the Norwegian part of the Northern North Sea at formation and member levels. The sequence stratigraphic subdivision of Michelsen et al. (1998) is added for comparison. Sandstone-dominated units are indicated in yellow (Schiøler et al. 2007: fig. 4).

The Siri Canyon constitutes the exception to the condensed, layer-cake stratigraphy of the Paleocene and Eocene of large parts of the North Sea. In the submarine canyon the mudstones are interbedded with glauconitic sandstones deposited by high-density gravity flows. The geometry of the sandstone varies within short distances, and the sandstones are locally intrusive (Hamberg et al. 2006, 2007). The sandstones are referred to the Bor, Tyr, Idun, Rind and Kolga members of the Våle, Lista and Sele formations (Fig. 2). The Nini-3 well, *c.* 10 km northeast of the Nena-1 well has en erosional unconformity between the Ekofisk Formation and the sandstone-dominated Tyr Member of the Lista Formation (Schiøler et al.

2007: figs 26, 27). A series of bioevents were identified by Heilmann-Clausen (1985) for the Paleocene–Eocene succession in Denmark and were correlated to the onshore lithostratigraphy. A correlation between the onshore and offshore lithostratigraphic units is presented in Schiøler et al. (2007: fig. 5). Most important in the present study is the *A. gippingensis* acme in the Ve Member and the last occurrence of *Alisocysta margarita* close the the boundary between the Ve and Bue members (Schiøler et al. 2007: fig. 5a).

Core depth	Palynology	Clay mineralogy		Core depth	Palynology	Clay mineralogy
2132.50	X			2164.32	X	
2135.70	X			2165.55	X	X
2141.50	X			2166.45	X	X
2146.50	X	X		2167.25	X	
2148.25	X			2168.45	X	
2150.25	X			2169.35	X	X
2153.05	X	X		2169.70	X	
2153.35	X	X		2171.15	X	
2155.70	X	X		2172.30	X	X
2157.50	X			2173.53a	X	
2161.30	X			2173.53b	X	
2164.25	X			2174.25	X	

Table 1: The studied samples

Lithostratigraphy

The Rogaland Group comprises the Paleocene Våle and Lista formations, and the Lower Eocene Sele and Balder formations. The Lista Formation is subdivided into the three mudstone members (Vile, Ve, and Bue) and three sandstone members (Tyr, Idun, and Rind; Fig. 2). The Våle and Lista formations constitute sequence 1.2 of Michelsen et al. (1998) and a major basinward shift in coastal onlap is interpreted close to the boundary between the Lista and Sele formations.

The Vile Member consists of dark olive grey to dark grey, non-calcareous, smectitic mudstones, and has a thickness of 0–30 m. The Vile Member has a basinwide distribution, although it is known to be eroded locally in the Siri Canyon. Dinoflagellate cysts are found in the Vile Member (Schiøler et al. 2007).

The Ve Member consists of mottled green, bluish green, reddish brown and brown mudstones, with a thickness of 0–21 m. The middle part of the member is often characterized by a thick dark reddish brown interval. Very little organic material is present in the non-calcareous mudstones, which are rich in smectite. The Ve Member has a basinwide distribution (Schiøler et al. 2007).

The Bue Member consists of light grey to greyish black mudstones, 0–18 m thick, which are generally rich in smectite. Moderately to intensely bioturbated intervals are interbedded with laminated intervals. The Bue Member contains dinoflagellate cysts and pollen. The Member probably has a basinwide distribution (Schiøler et al. 2007).

Core depths differ by c. 4 m from log depths in Nena-1. The top of the Ekofisk Formation is located at 2173.53 m in the core and at 2177.5 m in the petrophysical logs. It is therefore probable that the base of the Sele Formation (PETM) at a log depth of 2118.5 m corresponds to a core depth of 2114.5 m. Consequently the uppermost 15.5 m of the Bue Formation (2130–2114.5 m) is above the cored section (Fig. 8, Enclosure 1).

The biostratigraphic study

Material and methods

The biostratigraphic (palynological) part of this study is based on 24 samples from core 1. The samples were processed following standard palynological preparation methods, including treatment with HCl, HF, heavy liquid separation and brief oxygenation with HNO_3.

Following sieving on 21 µm filters the organic residue was mounted on glass slides using a glycerine jelly medium. The dinocyst content was analysed using a normal light microscope. A semiquantitative analysis consisted of counting at least 200 dinocysts from each sample, where possible. All freshwater algae and spores and pollen observed while counting the 200 dinocysts, were registered in order to assess the abundance of dinocysts relative to these other palynomorph groups. The qualitative analysis consisted of a thorough study of two palynological slides per sample in order to register all dinocyst species occurring in each sample. The taxonomy used herein follows Heilmann-Clausen (1985).

The results of the palynological study are presented in a range chart (Enclosure 1). The variations in the dinocyst assemblage reflect partly stratigraphic changes and partly changes in the depositional environment e.g. in salinity, nutrient availability and sea water temperature. Dinocyst and spore/pollen taxa, which are interpreted as a result of reworking are marked with an “R”. Occurrences marked with a ”?” indicate that the identification to species or genus level is questionable.

Based on first- and last occurrence of the stratigraphically important species (”events”) the studied interval have been subdivided into dinocyst zones (Heilmann-Clausen, 1985). The zonation of Heilmann-Clausen (1985) for the Danien to lower Eocene succession onshore Denmark is shown in Figure 4. This zonation was correlated with the onshore lithostratigraphy by Heilmann-Clausen. The correlation between the onshore and offshore lithostratigraphy is shown in Schiøler et al. (2007, fig. 2).

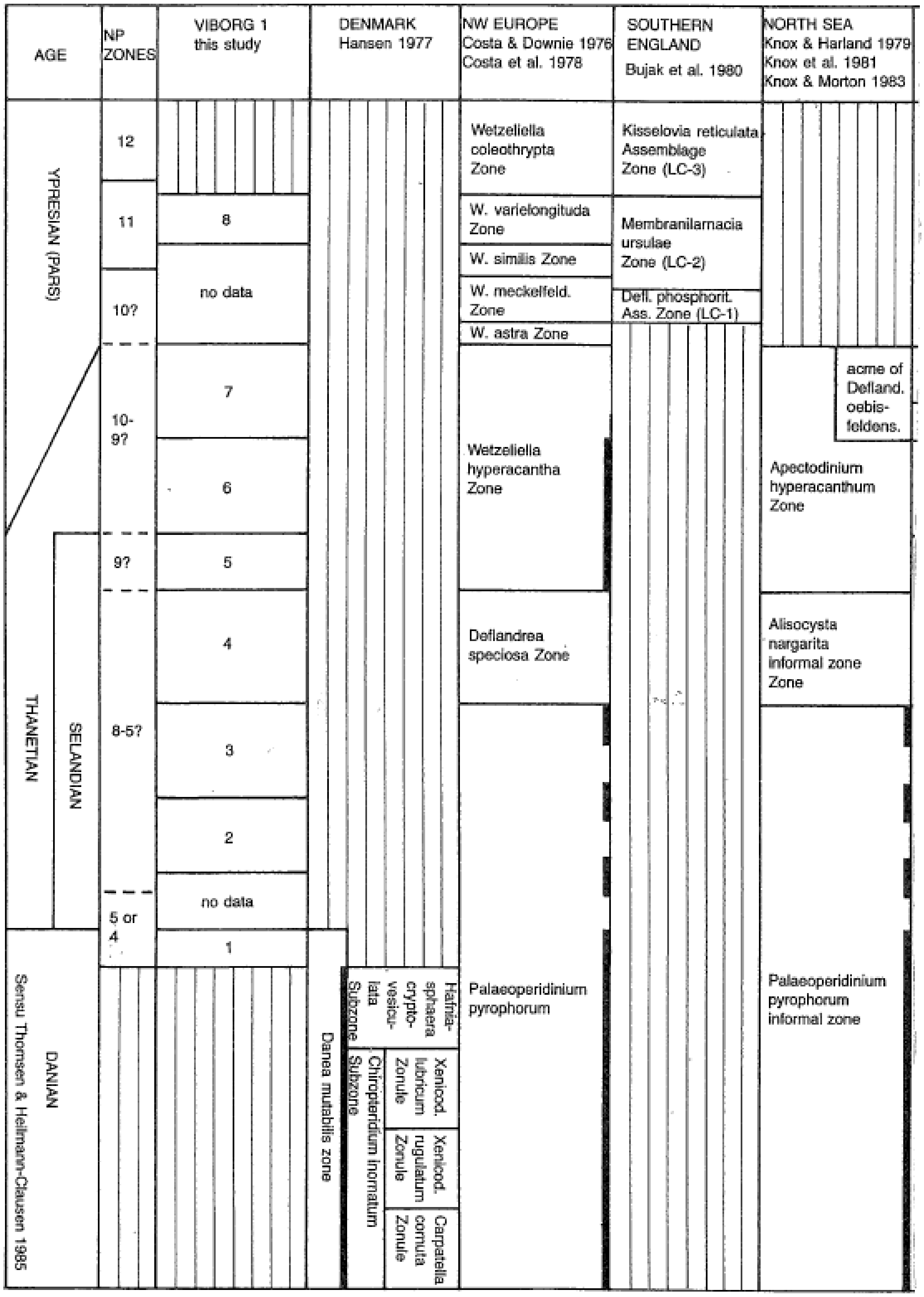

Fig. 3. Dinoflagellate zonation in the Viborg 1 borehole (Heilmann-Clausen 1985: fig. 13). The Lista Formation in the North Sea corresponds to Zones 3–5. In the Nena-1 well the presence of Zone 3 is not proven. See also Schiøler et al. (2007: fig. 5).

Results

The results of the palynological analysis are presented in Enclosure 1 and are discussed below. The resulting stratigraphic subdivision is presented from the base of the succession and upwards. For each depth interval, the recorded dinocyst assemblage is described, the depositional environment is interpreted, the dinocyst zonation and the lithostratigraphy is discussed and the age of the interval is proposed.

2174.25 m – 2168.45 m:

All the samples from this interval are barren of palynomorphs and can therefore not be used for biostratigraphy.

2167.25 m: Zone 3 or Zone 4 of Heilmann-Clausen (1985)

Dinocyst assemblage

Only a few dinocysts were recorded in the sample at 2167.25 m and about half of them are only minor, unidentifiable broken pieces of cysts. Most identifiable specimens were referred to *Spiniferites* spp. In addition the following taxa were identified: *Alisocysta margarita*, *Conneximura fimbriata*, *Hystrichosphaeridium tubiferum* and *Operculodinium* spp.

Depositional environment

The content of organic matter is low. The limited dinocyst assemblage indicates a marine depositional environment. The sporadic occurrence of bisaccate pollen, the very sporadic occurrence of non-saccate pollen (only 1 specimen recorded) and the absence of freshwater algae suggest a marine depositional environment without nearby freshwater sources.

Dinocyst zonation and lithostratigraphy

The combined occurrence of *Alisocysta margarita* and *Conneximura fimbriata* indicates that this sample represents either Zone 3 or Zone 4 of Heilmann-Clausen (1985). The interval with barren samples below and the very sporadic recordings from this sample, suggests however that the sample represents the upper part of Zone 4. According to Heilmann-Clausen (1985) this zone falls within the onshore Holmehus Formation, equivalent with the offshore Ve Member of the Lista Formation. The Holmehus Formation is often completely barren of organic matter, probably due to pre-diagenetic oxidation (Heilmann-Clausen et al. 1985).

Age

Thanetian (Late Paleocene).

2166.45 m – 2148.25 m: Zone 4 of Heilmann-Clausen (1985)

Dinocyst assemblage

This interval comprises two barren samples (2164.32 m, 2161.30 m), one almost barren sample (2164.25 m), two samples with a sporadic assemblage (2157.70 m and 2155.50 m) and six samples with a relatively rich dinocyst assemblage (two samples from the lower part of the interval: 2166.45 m and 2165.55 m and four samples from the upper part: 2153.35 m, 2153.05 m, 2150.25 m, 2148.25 m).

The dinocyst assemblage in the sample from 2166.45 m is dominated by *Spiniferites* spp, while *Deflandrea denticulata*, *Areoligera gippingensis* and *Achomosphaera* spp. are common.

In the sample from 2165.55 m the dinocyst assemblages are dominated by *Areoligera gippingensis*, *Areoligera* cf. *senonensis* and *Areoligera*/*Glaphyrocysta* spp., while *A*. cf. *coronata* and *Alisocysta margarita* are common.

In the sample from 2164.25 m only one specimen of *Spiniferites* spp. was found.

The sporadic dinocyst assemblages in the two samples from 2157.70 m and 2155.50 m, respectively, mainly consist of specimens referred to the genera *Areoligera* and *Fibrocysta*.

In the more productive upper four samples the dinocyst assemblages are dominated by *Areoligera* cf. *coronata* (especially in the lower 3 of these 4 samples) and *Spiniferites* spp., while other *Areoligera* species, *Achomosphaera* spp., *Alisocysta margarita*, *Fibrocysta* spp. and *Oligosphaeridium complex* are common.

Depositional environment

The varying but in some levels rich dinocyst assemblage indicates a fully marine depositional environment. The sporadic occurrence of bisaccate pollen and the absence of both spores and non-saccate pollen, as well as freshwater algae suggest a long distance to shorelines and freshwater sources.

Dinocyst zonation and lithostratigraphy

The presence of *Deflandrea denticulata* throughout this interval combined with the abundance of the genus *Areoligera* strongly indicate that this interval should be referred to Zone 4 of Heilmann-Clausen (1985). This is further supported by the presence of *Alisocysta margarita* through all of this interval and of the occurrence of *Ceratiopsis medcalfii* in the sample at 2166.45 m.

According to Heilmann-Clausen (1985) Zone 4 occurs within the onshore Holmehus Formation. This formation corresponds to the offshore Ve Member of the Lista Formation.

Age

Thanetian (Late Paleocene).

2146.5 m – 2132.50 m: Zone 5 of Heilmann-Clausen (1985)

Dinocyst assemblage

This interval comprises four samples (2146.50 m, 2141.50 m, 2135.70 m, 2132.50 m). Dinocysts have been recorded in all four samples, but due to a dramatic increase in the number of pollen, the dinocyst assemblages, especially in the two uppermost samples, are diluted and the recordings are therefore rather sparse.

In the lowermost sample in this interval (2146.50 m), the dinocyst assemblage is dominated by *Spiniferites* spp., while *Areoligera* species*, Achomosphaera* spp.*, Adnatosphaeridium robustum, Deflandrea oebisfeldensis, Fibrocysta* spp., *Hafnia septata*, *Impletosphaeridium* spp. and *Melitasphaeridium pseudorecurvatum* are common.

In the upper three samples, the dinocyst assemblages are dominated by *Impletosphaeridium* spp. and *Spiniferites* spp., while *Ceratiopsis speciosa glabra*, *Deflandrea oebisfeldensis* and *Hafnia septata* are common. A gradually increasing number of recorded *Palaeoperidinium pyrophorum* are interpreted as reflecting increasing reworking of Danien or Selandian deposits.

Depositional environment

The rich dinocyst assemblage in the lowermost sample of this interval indicates a fully marine depositional environment. The common occurrence of bisaccate pollen and the presence of few non-saccate pollen suggest a minor freshwater influence from a remote shoreline. The distinct increase in both bisaccate, but especially non-saccate pollen upwards, combined with a few occurrences of the freshwater algae *Pediastrum* strongly indicate the progradation of a shoreline and increased freshwater influx.

Dinocyst zonation and lithostratigraphy

The first occurrences of *Deflandrea oebisfeldensis* and *Lingulodinium machaerophorum* at 2146.50 m strongly indicate that this sample should be referred to the lower part of Zone 5. The first occurrence of *Palaeocystodinium lidiae* in the uppermost sample at 2132.50 m indicates that also this sample should be referred to Zone 5. Referring this interval to Zone 5 is further supported by the first occurrences of *Adnatosphaeridium robustum*, *Alisocysta* sp. 2 of Heilmann-Clausen (1985), *Ceratiopsis speciosa glabra* and *Microdinium* cf. *ornata* at 2146.50 m, and of *Palaeotretradinium minusculus* and of *Phthanoperidinium crenulatum* at 2141.50 m.

According to Heilmann-Clausen (1985) the lowermost part of Zone 5 correlates with the uppermost part of the onshore Holmehus Formation, corresponding to the offshore Ve Member of the Lista Formation. This lowermost part of Zone 5 is characterised by the last occurrence of *Alisocysta margarita* (Fig. 3).

The overlying, lower part of Zone 5 correlates with the basal part of the onshore “dark grey non-calcaerous clay”, now referred to the Østerrende Clay, equivalent to the offshore Bue Member of the Lista Formation. This part of Zone 5 is characterised by the first occurrences of *Alisocysta* sp. 2 Heilmann-Clausen (1985) and *Adnatosphaeridium robustum* and by the presence of *Palaeocystodinium lidiae*.

As the first occurrences of both *Alisocysta* sp. 2 Heilmann-Clausen (1985) and *Adnatosphaeridium robustum* were recorded from 2146.50 m, and *Palaeocystodinium lidiae* were recorded from 2132.50 m, all of this interval probably should be referred to the Bue Member of the Lista Formation.

Age

Thanetian (Late Paleocene).

Clay mineralogy

Material and methods

Sample preparation:
8 samples were selected for clay mineralogical analysis (Table 2). The bottom sample 2174.25 m was a chalk sample and the other samples were clays. The samples were dispersed by ultrasonic treatment in distilled water. The silt fraction was separated by sedimentation and the clay fraction by centrifugation in a continuous flow centrifuge. The resulting suspensions of silt and clay were flocculated with NaCl and the water removed by centrifugation. The fractions were washed with water and dried at 35 ºC.

Two subsamples of the clay minerals were saturated with K^+ and Mg^{2+} respectively. A portion of the Mg^{2+}-saturated clay minerals were saturated with glycerol. Oriented specimens of these three subsamples were prepared by the pipette method.

For analysis of the bulk mineralogical composition, the calcite-rich sample 2174.25 m was treated with a sodiumacetate buffer at pH 4.5–5.0 to remove the calcite. The residue was sedimented with NaCl, washed with water and air-dried to obtain a calcite-free residue.

X-ray diffraction:
The oriented specimens were scanned with CoKα-radiation in a Philips 1050 diffractometer at 4–31 º2θ with 10s/0.1º2θ steps and 1/4ºslits. The residue sample was scanned at 5–50 º2θ with 10s/0.1º2θ steps and slits 1º.

Results

The results are shown in Table 2 and the diffractograms in Figures 4–7. The calcite-free residue of the sample 2174.25 m constituted 80% of the sample and quartz was the dominating mineral (Figure 4). The clay fraction of sample 2174.25 m was dominated by quartz and small amounts of smectite was present.

The samples 2169.35 m and 2172,30 m were similar and consisted of 70-80% clay, 20% silt and <10% sand. The dominating peak was due to a smectite (Figures 5–7). The samples 2164.32 m and 2166.45 m consist of 40–50% clay, 40–50% silt and 8–15% sand. Smectite peaks were large and in sample 2166.45 m illite and kaolinite were present in small amounts. The samples 2153.35 m, 2153.05 m and 2146.50 m consisted of 47–57% clay, 22–28% silt and 19–27% sand. The smectite peak was large and small amounts of illite and kaolinite were present.

The smectite swelling characteristics were the same in all samples. The smectite swelled to 15Å when Mg^{2+}-saturated and air-dry, and to 17Å when Mg^{2+}-saturated and glycerolated. The smectite produced a broad shoulder at 12–13Å, when K^+-saturated and air-dried, showing that it is a smectite montmorillinite subgroup mineral. The shapes and positions of the smectite peaks were similar for all samples and did not indicate significant mixed-layering. However, in Mg^{2+}-saturated specimens the *001* reflections of the smectite in the samples 2172.30 m and 2169.35 m were tenfold more intense compared to the *001* reflections of the samples 2166.45m, 2164.32 m 2153.35 m, 2153.05 m and 2156.50 m. This may be caused by larger coherent scattering domains of the smectite in the 2172.30 m and 2169.35 m samples, i.e. larger crystal thicknesses. In contrast, the other five samples 2166.45m, 2164.32 m 2153.35 m, 2153.05 m and 2156.50 m had thinner crystals when Mg^{2+}-saturated. In conclusion, smectite dominated in all samples except the chalk samples, but changes between the samples in relative intensity of the smectite peaks are probably due to changes in crystal thickness of the smectite (montmorillonite).

Table 2. Clay mineralogical investigation of samples from Nena-1

Depth, m	Grain size distribution %			Mineralogy clay fraction			
	250-20µm	20-2µm	<2µm	Clay mineralogy			Other minerals
				smectite	illite	Kaolinite	
2146.50	19	28	53	+++	+	+	Quartz:+
2153.05	20	22	57	+++	+	+	Quartz:+
2153.35	27	26	47	+++	+	+	Quartz:+
2164.32	15	47	38	+++	-	-	Quartz:+
2166.45	8	44	48	+++	+	+	Quartz:+
2169.35	8	21	71	+++	-	-	Quartz:+
2172.30	2	20	79	+++	-	-	Quartz:+
2174.25◊	53	30	17	+	-	-	Quartz:+++

+: present; +++: dominant

◊: calcite not removed, all fractions contain large amounts of calcite.

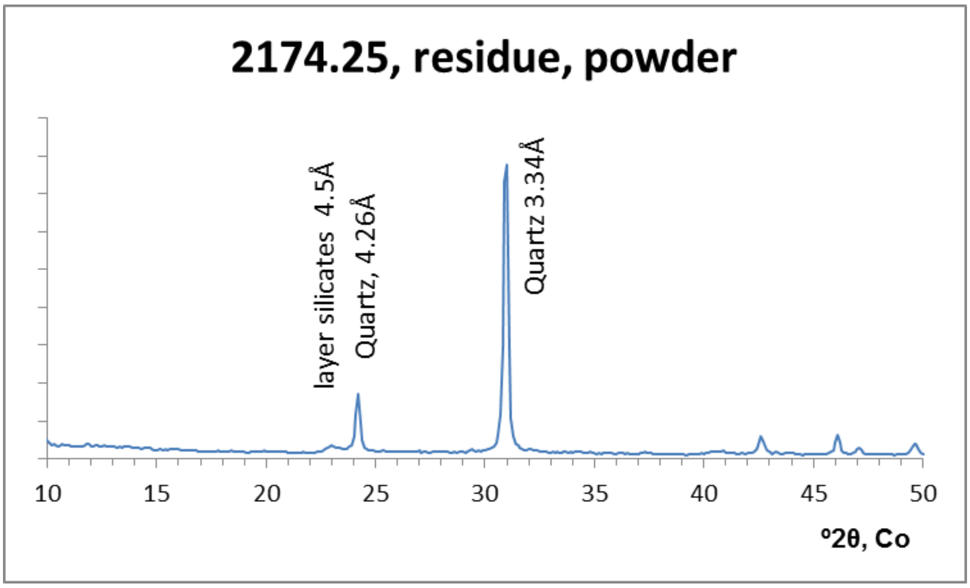

Figure 4. X-ray diffractogram of the calcite-free residue of sample 2174.25 m.

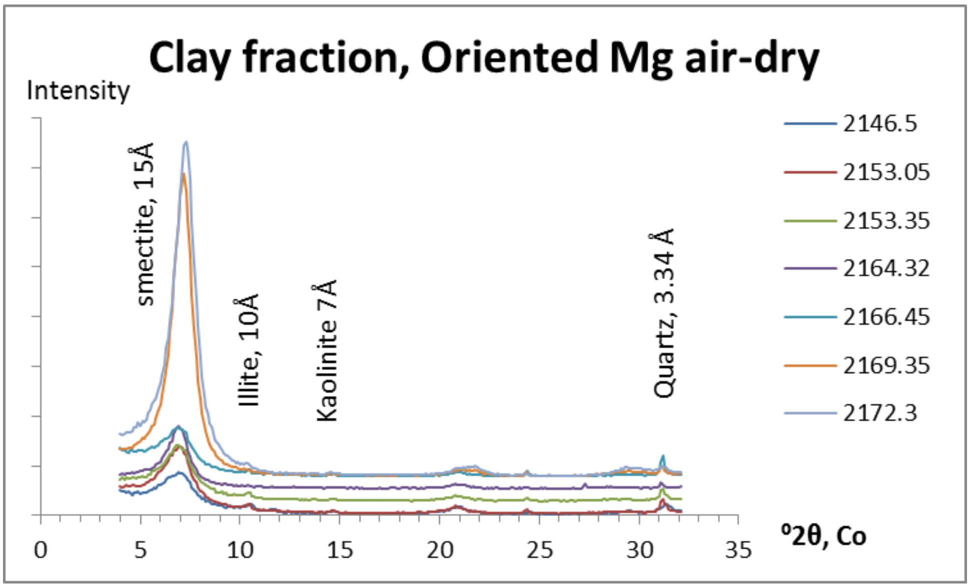

Figure 5. X-ray diffractogram of the Mg^{2+}-saturated air-dry specimens of the clay fractions of the clay samples.

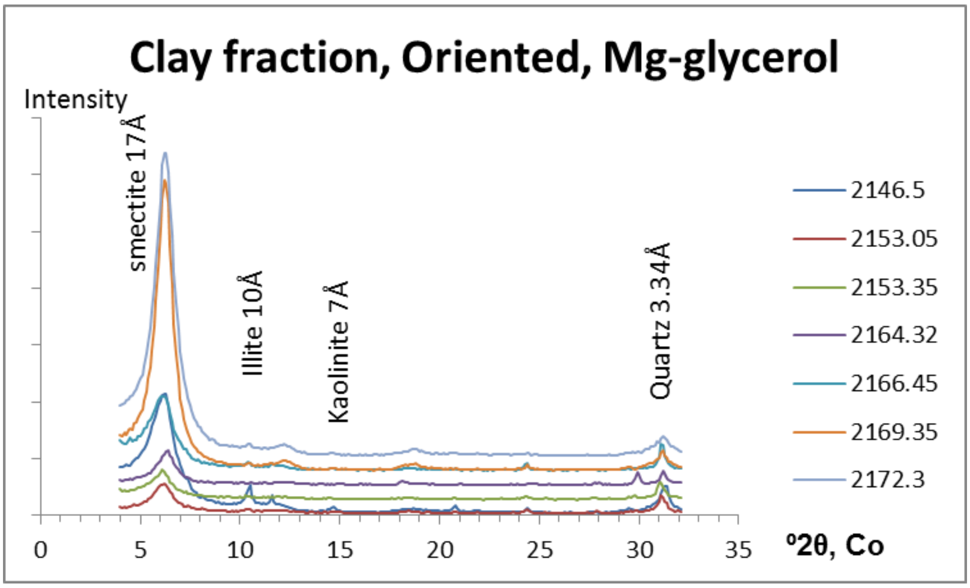

Figure 6. X-ray diffractogram of the Mg^{2+}-saturated and glycerolated specimens of the clay fractions of the clay samples.

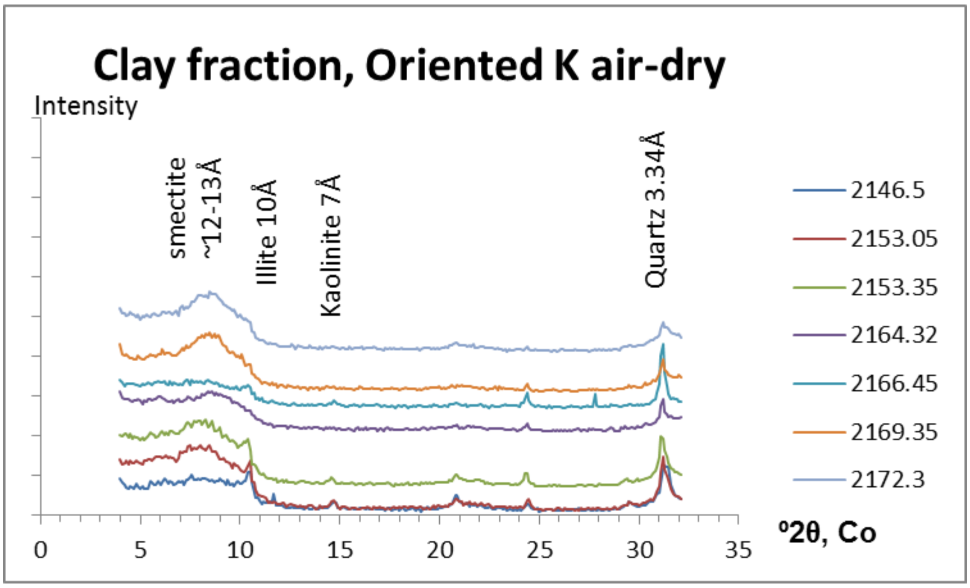

Figure 7. X-ray diffractogram of the K^{+}-saturated air-dry specimens of the clay fractions of the clay samples.

Lithostratigraphy

Two formation boundaries are readily recognized from the gamma log: the top of the Ekofisk Formation (core depth 2173.5 m MRDT (log depth 2177.5 m) and the base of the Sele Formation (log depth 2118.5 m, corresponding to a core depth of 2114.5 m) (Fig. 8).

Core 1 has a length of 55 m (2130–2184.2 m MDRT) and represents a 33 m thick succession of Paleocene strata (Fig. 3).The measurement of a sedimentological log of the core has not been part of the present study. However, the excellent core photos support the lithostratigraphic subdivision of the Paleocene succession.

The Ekofisk Formation (2216 m (TD)–2173.5 m)

Whitish, horizontally bedded chalk with few flint nodules forms the lowermost unit in the core. Dinocysts have not been observed in the samples, which may be due to poor preservation and/or very low density of dinocysts. The Ekofisk Formation is recognized from its distinct lithology.

The Våle Formation (not present)

The greyish green, strongly bioturbated marlstone of the Våle Formation is not present above the Ekofisk Formation in Nena-1, and it is therefore concluded that the Våle Formation is absent.

The Lista Formation (2173.5–2114.5 m)

The mudstones with moderately high gamma radiation between the Ekofisk Formation and the Sele Formation are referred to the Lista Formation, which comprises Selandian and Thanetian strata and is subdivided into the Vile, Ve and Bue members (Schiøler et al. 2007). The biostratigraphic data (Enclosure 1) indicate that the mudstones of the Lista Formation are Thanetian in age.

In Nena-1, the Lista Formation comprises dark red, smectitic mudstone, pale greenish mudstone and olive grey, laminated mudstone (Fig. 8).

The Vile Member (not present)

The Vile Member is characterized by dark olive grey to dark grey, non-calcareous, smectitic mudstones of Selandian age (Schiøler et al. 2007). The mudstones, which overlie the Ekofisk Formation fits neither the lithology nor the geological age of the Vile Member. It is therefore concluded that the Vile Member is not present in Nena–1.

The Ve Member (2173.5–2146.8 m)

The dark red, homogeneous claystone 2173.5–2169.5 m is characterized by a high content of smectite (sample 2172.30 m, Table 2). The claystone is interpreted as deposited in an oxic marine environment, possibly at a slow rate. The claystone is barren of dinocysts, probably due to lack of preservation. Red, smectitic claystone, referred to the middle part of the Ve Member, has a basinwide distribution in the Danish part of the North Sea (Schiøler et al. 2007: p. 40).

The occurrence of *A. gippingensis* above the red claystone, as well as other dinocysts of biozones 4 and 5, indicates a Thanetian age (Enclosure 1). This is consistent with the age of the middle to upper part of the Ve Member.

The Bue Member (2146.8–2114.4 m)

The dark olive grey laminated mudstone in the upper part of core 1 (2146.8–2130 m) indicates deposition in a weakly oxic to anoxic marine environment, in which the dinocysts are fairly common (Enclosure 1). The larger content of dinoflagellates may reflect better preservation of organic matter in the laminated sediments.

The dark grey laminated mudstone corresponds well to the description of the Bue Member (Schiøler et al. 2007). This interpretation is supported by the last occurrence of *A. margarita* within this unit and the absence of *A. augustum*, which is characteristic of the earliest Eocene, and has an acme occurrence in the basal part of the Sele Formation.

The upper part of the Bue Member (2130–2114.5 m) of the Lista Formation, as well as the Sele Formation is only known from petrophysical logs in Nena-1.

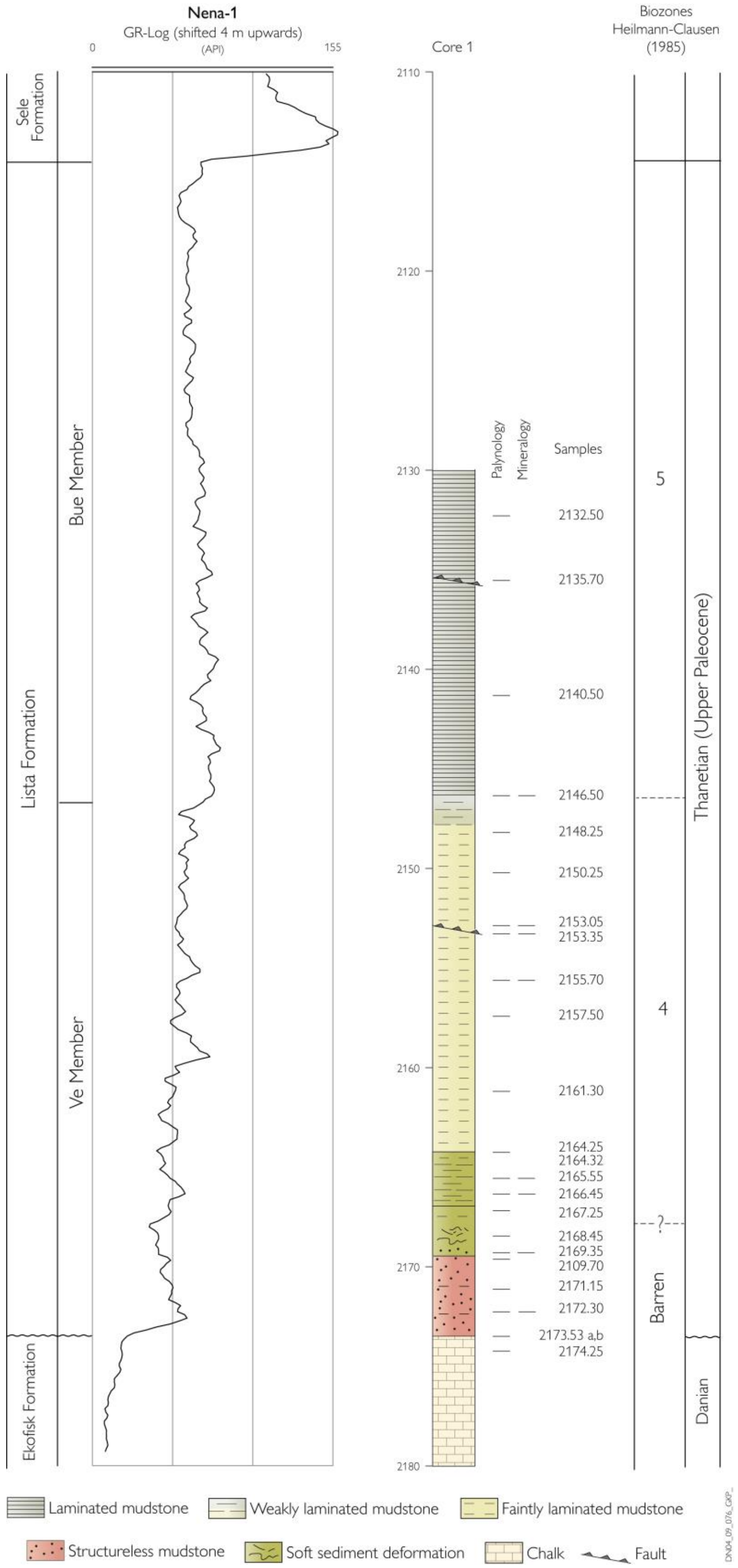

Fig. 8: The lithologies of core 1 in the Nena-1 well. The biostratigraphy is shown to the right, for details see Enclosure 1. The interpreted lithostratigraphy is shown to the left. The unconformity between the Ekofisk and Lista formations corresponds to the Våle Formation and the Vile Member of the Lista Formation (see text for further discussion)

Conclusion

The Paleocene sediments in core 1 from the Nena-1 well are referred to three lithostratigraphical units (of Schiøler et al. 2007).

The Ekofisk Formation, core depths 2185–2173.5 m MDRT: Whitish limestone with flint nodules, nanoquartz, and a low content of smectite. The samples are barren of palynomorphs. The Ekofisk Formation is of Danian age (Schiøler et al. 2007).

The Ve Member of the Lista Formation, core depths 2173.5–2146.8 m MRDT: Dark red to greenish claystone, with smectite dominating in the clay fraction, and with small amounts of kaolinite and illite in the greenish claystone. The red claystone is barren of dinocysts. The greenish mudstone contain dinocysts characteristic of Zone 4 of Heilmann-Clausen (1985). These indicate a Thanetian age.

The Bue Member of the Lista Formation, core depths 2146.8–2130 m MRDT: Laminated olivegrey mudstone, with smectite dominating the clay fraction, accompanied by small amounts of kaolinite, illite and quartz. The dinocysts are characteristic of Zone 5 of Heilmann-Clausen (1985), and indicate a Thanetian age.

The Ekofisk and Lista formations are separated by an unconformity, which corresponds to the Våle Formation, the Vile Member and the lower part of the Ve Member of the Lista Formation. The unconformity may possibly include the youngest part of the Ekofisk Formation.

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Enclosures

Enclosure 1: Palynological rangechart for Nena-1, 2180–2110 m (core depths). Note that the Gr-log has been shifted upwards by 4 m in order to fit to the depths of the core samples.

Well Name : Nena-1

Interval : 2110.00m - 2180.00m   Nena-1

Scale : 1:250

Chart date: 19 January 2015   Karen Dybkjær & Gunver Krarup Pedersen

GEUS

Enclosure 1