

Dinoflagellate Cyst Stratigraphy and Palaeoenvironment of the “Utsira Sand” in the Northern North Sea

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Abstract

Safe CO₂ storage in the Utsira Formation is one of many solutions to climate change mitigation. A major leakage had occurred in the Utsira Formation in 2008, due to water injection in what was believed to be the Utsira Formation. Studies indicated that the rock formation for injection of produced water was not appropriate, and this reflected poor understanding of the stratigraphy of the Tampen area (North Sea).

Thirteen palynological samples between 1125.65 and 1141.65 m of well 34/8-A-33H in the Tampen area, northern North Sea have been studied in order to understand the stratigraphy and provide information on age and palaeoenvironment. The studied interval is mapped as the Utsira Formation.

The investigated interval was dated to 2.6 -3.7 Ma (late Pliocene) based on dinoflagellate cysts and acritarchs, such as *Operculodinium? eirikianum*, *Operculodinium centrocarpum*, *Bitectatodinium raedwaldii*, *Lingulodinium machaerophorum*, *Cymatiosphaera? invaginata* and *Lavradosphaera crista* which were correlated to stratigraphic ranges from reference sections in the North Atlantic Sea and adjacent seas. The absence of typical early Pliocene species (*Batiacasphaera minuta*, *Corrudinium devemaliae*, *Echinidinium euaxum*, *Operculodinium tegillatum*, *Pyxidinosopsis vesiculata*, *Bitectatodinium serratum* and *Reticulatosphaera actinocoronata*) in the studied interval supports this conclusion.

According to the marine dinoflagellate cysts and terrestrial palynomorphs (pollen and spores), and depending on palaeoenvironmental indices (Sporomorph / Dinoflagellate cyst index, Warm / Cold index, Inner neritic / Oceanic, Outer neritic / Oceanic, Neritic /Oceanic and Inner neritic / Outer neritic index, Gonyaulacoid / Protoperidinioid index), the palaeoenvironment is shown to be an outer neritic setting with warm to temperate conditions.

The studied interval well 15/9-A23 (Piasecki et al., 2002) was estimated to be early Pliocene, and the core dinoflagellate cyst assemblages indicated outer shelf deposition under cool climate. The Nordland Group mudstone, well 15/9-A-11 (Head et al., 2004) was considered to be Gelasian (early Pleistocene) in age, with outer neritic environment, deposited under cool conditions. By comparison the estimated age in this study (well 34/8-A-33H), is considered to be younger than the age in well 15/9-A23 (Piasecki et al.,

2002) and older than the age in well 15/9-A-11 (Head et al., 2004). Therefore the studied interval in this study is believed to be representing the uppermost part of the Utsira Formation.

1. Introduction

Water and drill cuttings injected into “Utsira Formation” have lead to leaks at the sea-floor (Eidvin and Øverland, 2009) and represented the poor understanding of the stratigraphy in the Tampen area (North Sea). The Miocene-Pliocene “Utsira Formation” is successfully used for CO₂ storage due to the fact that the dominantly sandy Utsira Formation which forms the basal part of the Nordland Group is covered by the dominantly argillaceous strata of the Nordland Group, considered to be the significant sealing unit. The “Utsira Formation (also known as Utsira Sand)” forms an elongate-restricted sand body unit, approximately 75 x 450 km² (Head et al., 2004; Deegan and Scull, 1977). The depocenter is located in the center of the northern North Sea (Viking Graben). The total thickness reaches 250-300 m at 58°N (Viking Graben) and at the Tampen Spur at 61°N, the sand body reaches a thickness of almost 200 m. The Utsira Formation overlies the uppermost Hordaland group shales centrally but meets the underlying Middle Miocene Unconformity eastwards on the basin flank (Chadwick et al., 2000). The Utsira Formation is dominated by sands and is overlain by dominantly argillaceous unit (Piasecki, Gregersen and Johannessen, 2002; Isaksen and Tonstad, 1989).

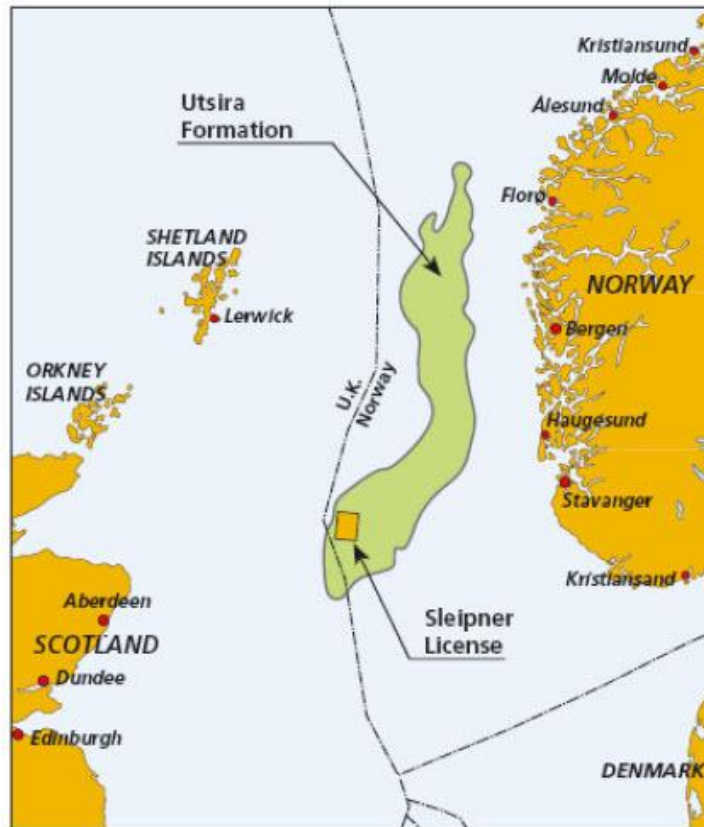


Figure 1. Location map shows areal extent of the Utsira Formation

<http://decarboni.se/publications/carbon-dioxide-storage-geological-security-and-environmental-issues-case-study-sleipner-gas-field-norway/81-background>.

The determination of the age of Utsira Formation sands has varied from Middle Miocene to late Miocene, according to earlier studies as (Isaksen & Tonstad, 1989), to Middle Miocene to earliest Pliocene more recently based on foraminifera biostratigraphy (Piasecki, Gregersen and Johannessen, 2002; Eidvin, Riis and Rundberg, 1999). The precise determination of the age of the Nordland Group mudstones remained however uncertain, but dinoflagellate cyst, pollen and spore, foraminifera and stable isotopic analyses had suggested Gelasian age (Head et al., 2004). In this present paper dinoflagellate cyst stratigraphy has been utilized for the age determination.

The dinoflagellate cyst stratigraphy is based on the highest occurrence ranges of significant species that extend into the Upper Miocene-Pliocene and are geographically widespread in the North Atlantic Region and adjacent seas. The correlation of dinoflagellate cyst assemblages with reference sections of the North Atlantic region such

as DSDP Site 610 of the eastern North Atlantic (De Schepper and Head, 2008; 2009), ODP Hole 907A in the Iceland Sea (Schreck, Matthiessen and Head, 2012), the eastern North Sea Basin, Denmark (Dybkjær and Piasecki, 2010) and ODP Hole 642B on the Vøring Plateau (Beck, 2013) is adopted in this thesis.

The organic-walled dinoflagellate cysts are considered sensitive paleoenvironmental indicators (e.g. Versteegh, 1994; Wall et al., 1977). Dinoflagellate cysts provide a powerful tool for the reconstruction of marine paleoenvironments as the organic walled dinoflagellate cysts are sensitive to the slightest changes in the physiochemical parameter of surface watermasses (e.g. Sluijs, Pross and Brinkhuis, 2005; Mudie and Harland 1996). Acritarchs are another important group of the North Atlantic and adjacent seas, relative to their distinctive morphology, high diversity and abundance, especially in higher northern latitudes (De Vernal & Mudie 1989a, b; Head et al., 1989a, b, c; Head 1996; Matthiessen et al. 2009a; Schreck et al. 2012, 2013).

In the present study, count and description of important dinoflagellate cysts and acritarchs which were prepared from the well 34/8-A-33H in the Tampen area “Utsira Formation” in the northern North Sea are used to obtain the details of the stratigraphy and paleoenvironment and for age estimation.

1.1 Aims

The aims of this master thesis are to establish the age and reconstruct palaeoenvironment of the interval between 1125.65 and 1141.65 in industry well 34/8-A-33H of the “Utsira Formation” in the Tampen area in the northern North Sea based on a dinoflagellate cyst and acritarch analysis. Dinoflagellate cysts (marine organic-walled microfossils) are an excellent tool for correlation and palaeoenvironmental reconstructions in the mid-to high latitude oceans.

2. PALYNOLOGY AND BIOSTRATIGRAPHY

Palynology is the study of microscopic objects of macromolecular organic composition which vary in size between 5-500 μm . The microscopic organic structures which have acid resistant potential can be of marine or continental origin and the time correlative events between these two environments put palynology in significant position in biostratigraphy. Palynology is one of the most effective tools to reconstruct past environment and on a large scale palynology can identify broad environmental trends. And thus palynology is a branch of geological science and biological science which studies fossil palynomorphs from the Precambrian to the Holocene.

Biostratigraphy is a method of relative age determination of sedimentary rocks and deals with the distribution of fossils in the stratigraphic record and the organization of strata into units based on fossil contents. Biostratigraphic units are bodies of strata that are characterized on the basis of their contained fossils and they are termed as (biozones).

Biostratigraphic units may be depended on a single taxon, on combinations of taxa, on relative abundances, on specified morphological features, and or on variations in any of the many other features related to the content and distribution of fossils in strata according to Murphy and Salvador (1999). The evolutionary changes through geologic time in the stratigraphic record make the biostratigraphic unit is distinct from other kinds of stratigraphic units. And thus the fossil assemblages of any one age differ from any other (Murphy and Salvador, 1999). There are 6 kinds of biostratigraphic units such as Taxon-range zone, interval zone, assemblage zone, abundance zone, lineage zone and concurrent-range zone. In this study, the interval zone which depends on highest occurrence zone is particularly important and used.

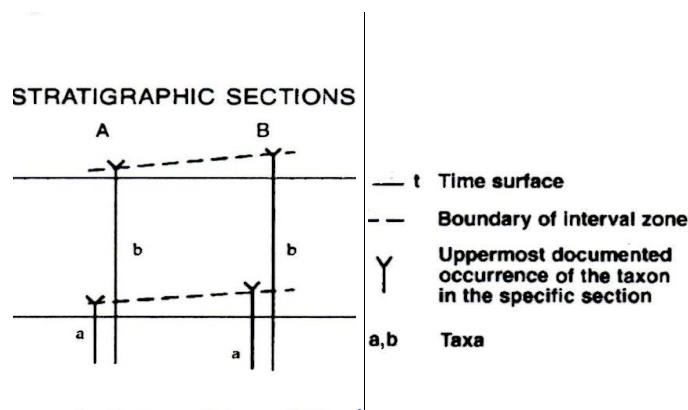


Figure 2. Interval zone (highest occurrence zone) used in the present study.

2.1. Dinoflagellates and their cysts

Dinoflagellates are eukaryotic, primarily single-celled organisms which vary in diameter from 20 to 100 μm , and their motile cells contain a unique combination of pigments which are used in photosynthesis. They occur in all aquatic environments such as seas, oceans, rivers, ponds, swamps, and in brackish- and salt water lakes. The vast majority of species, around 1600 species, is marine while 220 species live in freshwater (Taylor and Pollinger, 1987). The majority of dinoflagellates are free living; about 50% of dinoflagellates are autotrophs, others are heterotrophs, mixotrophs, parasitic or symbionts. Dinoflagellate cysts, being important indicators of rapid evolution, provide excellent tool for biostratigraphy.

Dinoflagellates are distributed from polar to tropical regions according to water temperature, nutrient supply, water depth, and salinity. Dinoflagellates are much more diverse in the tropical waters than in the polar waters, and are also more diverse and abundant in the warmer months of the year. Dinoflagellate diversity increases towards the neritic regimes as a result of high nutrients in these regions (Taylor, 1987b).

In certain living dinoflagellates, the cell is covered by the theca during the motile stage of their life cycle. The theca is composed of thin plates of cellulose (Evitt, 1985), not present in the fossil state, having been destroyed by bacteria. In contrast, sporopollenin cysts are generally highly resistant and are geologically long lived. Dinoflagellates possess two dissimilar flagellae which acting in concert, give a characteristic spiral motion for the swimming cells (Jann et al., 1965; Le Blond and Taylor, 1976). Those flagellae are composed of a transverse ribbon-like flagellum with multiple waves (a short-period beat), which beats to the cell's left, while the other one is a conventional longitudinal flagellum with only one or two waves (a long-period beat), beating posteriorly (Fensome et al., 1993). The transverse flagellum is located in the cingulum which divides the theca into an anterior "epitheca" and posterior "hypotheca". The longitudinal flagellum on the other hand, lies in a ventral depression located mainly in the hypotheca, known as the sulcus. Both flagellae arise from the ventral side of the cell (Figure 3). The different compositions of dinoflagellate thecae and cysts, is reflected upon their different degree of resistance to degradation in nature and in the laboratory.

Dinoflagellates are mainly represented as fossils by fossil dinoflagellate cysts, which have a long geological record with lowest occurrences during the mid Triassic (Mac Rae et al., 1996).

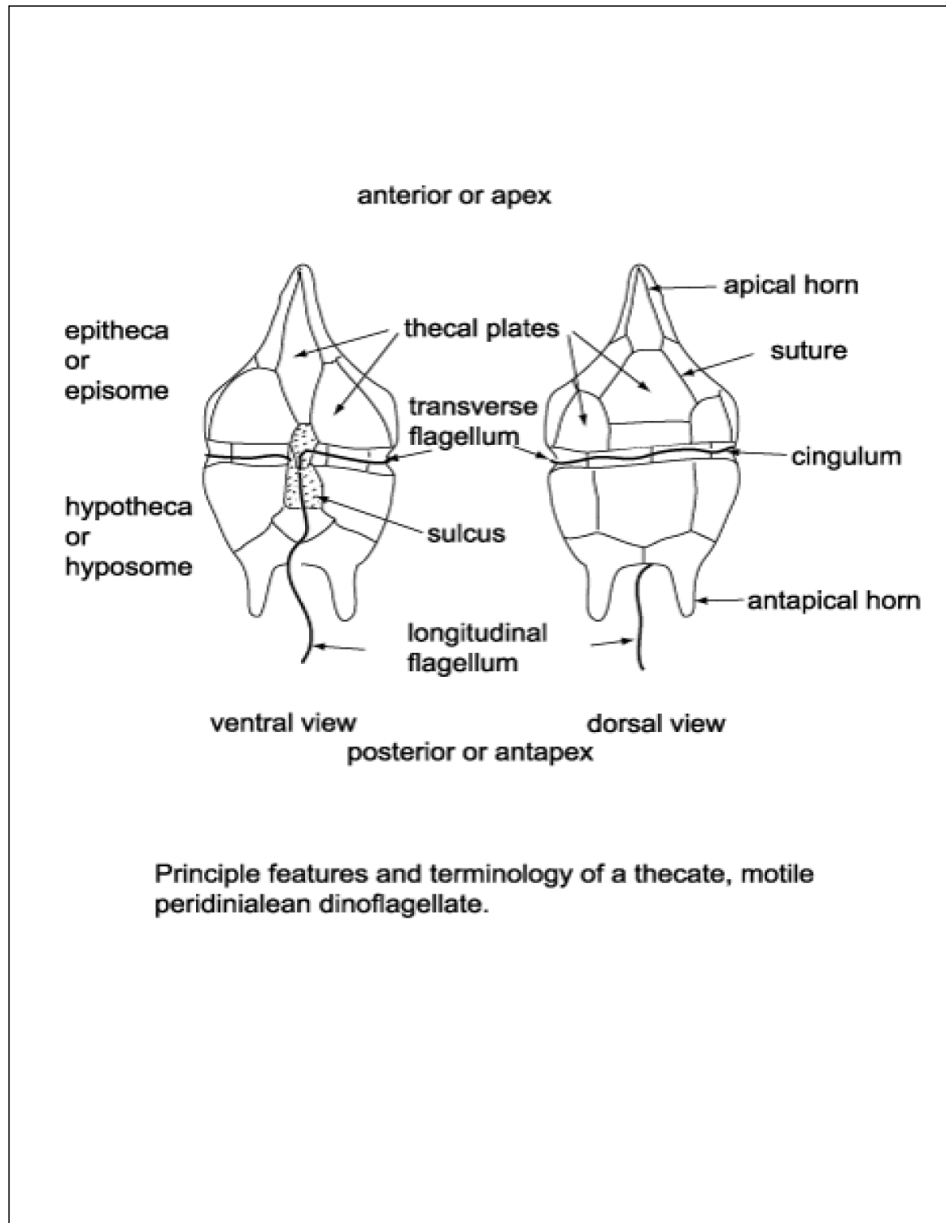


Figure 3. The principle features and terminology of a thecate, motile peridinialean dinoflagellate (redrawn from Fensome et al., 1996).

2.1.1. The life cycle of dinoflagellates

Life cycle of dinoflagellates may be complex and composed of several stages (Fensome et al., 1993). The life cycle usually involves phases of vegetative and sexual reproduction, as shown schematically in (Figure 4). During periods of the rapid growth and population expansion, vegetative fission dominates, yielding successive generations of schizonts that are haploid in chromosome count. More complex life cycles and a sexual reproduction also occurs (Evitt, 1985) when two schizonts, now behaving as gametes join to form one cell which develops into a zygote, diploid in chromosome count. After as long as 15 days, the flagellae are lost and the cell becomes nonmotile (i.e. a hypnozygote). With the appearance of cyst walls, the thecal plates break apart or get destroyed by bacteria and the completed cyst is exposed. The last stage (nonmotile) occurs when the dormant cyst falls to the ocean bottom and get buried in sediment, where they have the potential to stay in this state for years and form a resting stage or hypnozygote which are called “dinoflagellate cyst” or “resting cyst”. Right conditions and availability of oxygen they may lead to start the germination (excystment), completing the life cycle.

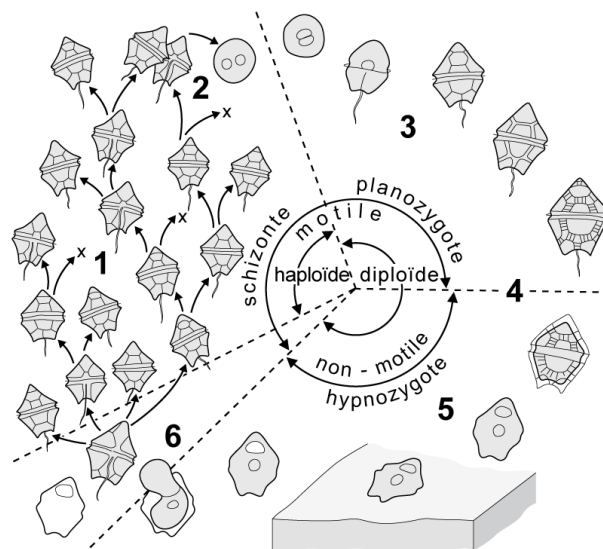


Figure 4. Growth and population expansion by vegetative division at (1). Schizonts act as gametes and pair up to form zygotes, one or more theca may be lost at (2). A new theca is formed (3). Cell activity diminishes, flagella are lost, cyst forms within theca (4). Thecal plates are completely lost and the cyst behaves as a sedimentary particle (5). Following a period of dormancy the cell excysts, grows a theca and becomes motile again (6). (Evitt, 1985).

2.1.2. Feeding strategies of dinoflagellates

There are several nutritional strategies of dinoflagellates, including; phototrophy, heterotrophy, and mixotrophy. Phototrophy is the process of converting carbon dioxide and water into organic material to be utilized in cellular functions such as biosynthesis and respiration. This process occurs when energy from sunlight, as well as chloroplasts & chlorophyll are available. Heterotrophic forms can by contrast, even survive in the absence of light, where dinoflagellate may survive by ingestion of other organisms such as diatoms, other dinoflagellates, bacteria, ciliates and organic debris (Schnepp and Elbrächter, 1992). They can feed on other organisms through either peduncle (feeding tube) or pallium (plasma extension). Many photosynthetic species are also capable of heterotrophy to obtain vitamins, and this strategy is known as mixotrophy.

2.1.3. Dinoflagellate cyst morphology

Dinoflagellate cysts are composed of several major parts such as, the epicyst, paracingulum, hypocyst, and parasulcus and these regions represent respectively, the epitheca, cingulum, hypotheca, and sulcus of the theca. The surface of the cyst may include parasutures, which correspond to thecal sutures and divide the surface into more or less polygonal areas. The polygons on the cyst are particularly clear and simple examples of paraplates. The number and arrangement of paraplates on the cyst are known as paratabulation. Cyst paratabulation is important in the taxonomy of fossil dinoflagellates. The apical, or anterior end, and the antapical, or posterior end, are known as such with respect to the principal direction of motion of the swimming cell. The ventral surface is defined by the sulcus and parasulcus and the dorsal surface and right-left are determined accordingly. The measurement of the length corresponds to the anterior-posterior dimension, while the width represents the right-left distance, and the thickness measures the dorsal-ventral dimension. The wall of most of dinoflagellate cysts is composed of “dinosporin” or “sporopollenin-like”, a macromolecule, highly resistant to bacterial degradation, digestion, and aggressive mineral acids (HF) but that could be degraded by oxidation (Fensome et al., 1993).

The classification of dinoflagellate cyst, used in this study, is based on significant features, such as general morphology (e.g. ridges, processes, shape, and size of the cyst),

wall structure and surface features, paratabulation; and archeopyle (the opening in the cyst wall) (Evitt, 1985).

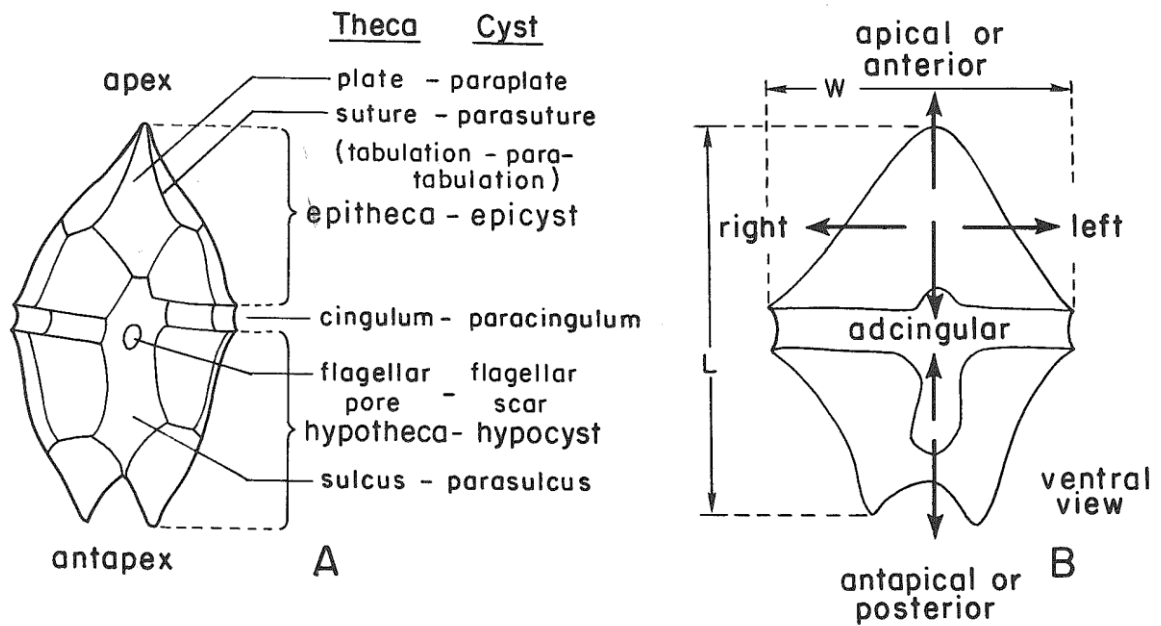


Figure 5. The terminology and organization of dinoflagellate cysts (Evitt, 1985).

2.2. Acritarchs

Fossilized organic-walled cysts of protists, that can not be assigned to specific known groups of organisms, are known as acritarchs. Most of acritarchs may be present throughout the geological column, but are particularly common in the Lower Paleozoic and most of them represent the resting cysts of marine phytoplankton (Strother, 1996).

Acritarchs are characterized by single hollow vesicle (theca) which may have processes or spines that vary in size from $<10 \mu\text{m}$ to $>1 \text{mm}$, but most species range between 15 to $80 \mu\text{m}$. The position of the processes on the vesicle can lead to forming morphological patterns based on descriptive characteristics. The acritarchs wall may be composed of sporopollenin which has the potential to survive diagenesis (Strother, 1996). The wide range of acritarchs in the rock records make them important in biostratigraphy and paleoenvironmental studies.

2.3. The Late Miocene and Pliocene

According to Gradstein et al. (2012), the Neogene period is composed of two epochs; the Miocene and Pliocene. The late Miocene is divided into two stages; the Tortonian (11.63 Ma to 7.25 Ma) and Messinian (7.25 Ma to 5.33 Ma), where the latter represents the latest Late Miocene (Hilgen et al., 2012). The Pliocene epoch is on the other hand, divided into the Zanclean (5.33 Ma to 3.60 Ma) and Piacenzian (3.60 Ma to 2.58 Ma) stages, according to Hilgen et al. (2012).

During the late Miocene, evidence of general global cooling could be shown both in the oceans (Zachos et al., 2001) and on the continents (Pound et al., 2012). The continental latitudinal temperature-gradients seem to have gradually become steeper, becoming close to preindustrial conditions during the Messinian, also according to Pound et al (2012).

Continuing through the Pliocene this trend of global cooling developed further into high magnitude glacial interglacial oscillations of the Pleistocene epoch (e.g. Salzmann et al., 2011). Despite the progressive cooling that had taken place, the Pliocene was a generally warmer epoch compared to the present time (e.g. Salzmann et al., 2011).

3. GEOLOGICAL SETTING

3.1. The geology of area

The northern North Sea was an epicontinental subsiding basin during the Late Cenozoic time. The North Sea basin was surrounded by the Scandinavian, British landmasses, and shelf areas in the north to the Norwegian-Greenland Sea. These were affected by about 400 m uplift, which led to increased sediment influx (Galloway et al., 1993). The Late Cenozoic depositional systems along the eastern North Sea margin were affected also by climatic fluctuation contributing to the sediment influx by glacial erosion. The basin in the Norwegian sector includes major Mesozoic highs and grabens, where the Central Graben in the south-central of the basin and the Viking Graben in the north. In the Paleocene-Eocene, the North Sea Basin deepened as a result of uplifting of the surrounding landmasses, whereas from the Shetland platform and West Norway, the Deltaic sequences headed towards the deep basin. The progradation continued in the Oligocene and Miocene and formed the depocentres, which varied through the time. Generally, the depocentres vary from 200 to 600 m of Oligocene to Lower Pliocene sands (Eidvin and Rundberg, 2001; 2005; 2007, and Gregersen and Johannessen, 2007). The Hordaland Group shales was deposited in the northern North Sea Basin in the Miocene and it consists of three sand-dominated units; the Frigg, Gridd and Skade formations (Isaksen and Tonstad, 1989). The Hordaland Group in the eastern flank of the basin is characterized by unconformity in the middle Miocene (Fyfe et al., 2003; Ziegler, 1981).

The Nordland Group, overlying the Hordaland Group, is composed of the basal, dominantly sandy Utsira Formation and overlying dominantly argillaceous units (unnamed) (Eidvin et al., 1999; Isaksen and tonstad, 1989).

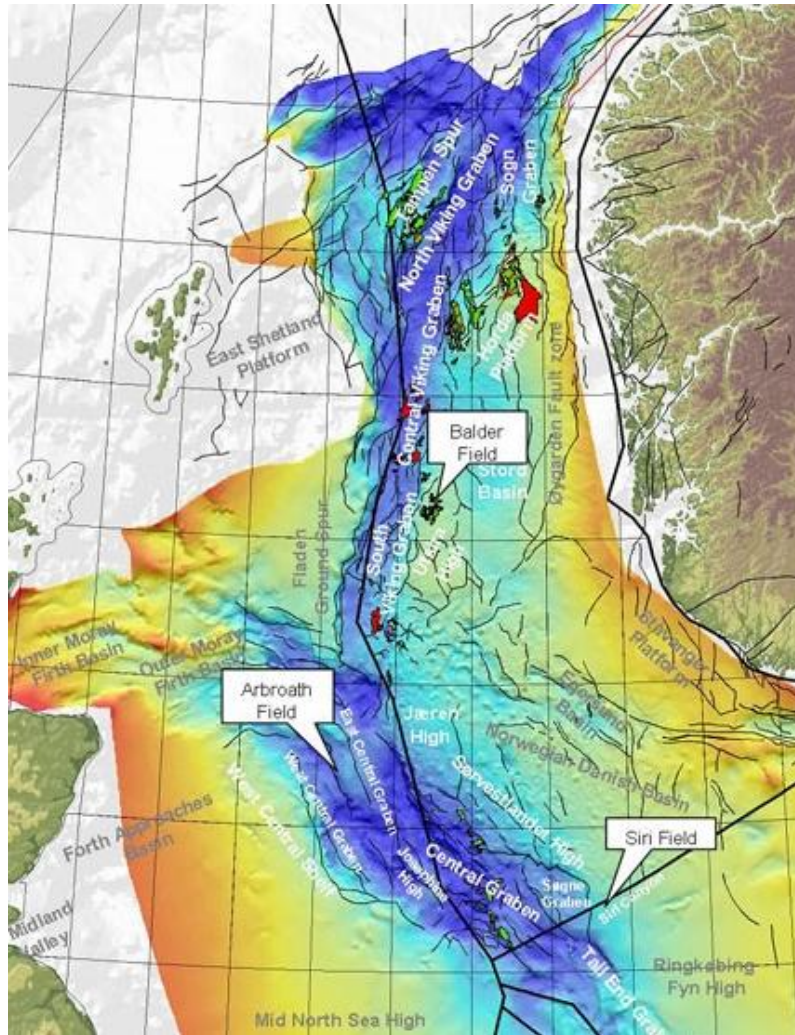


Figure 6. Structural elements of the Norwegian North Sea at BCU level, with the first Paleogene hydrocarbon discoveries in Norway, UK and Denmark. The map shows the Tampen area.

<http://nhm2.uio.no/norges/litho/rogaland.php>

During the Late Miocene to Early Pliocene, a strait between deeper water in the Møre Basin and the central North Sea in the northern North Sea appeared. Large amounts of clean sands (Utsira Formation) reached the strait and thus the Utsira Formation represents a huge sedimentary depositional system in the northern North Sea. The formation covers an area 450 x 90 km² which was deposited along the Viking Graben area, with a major sandy depocentre, 250-300 m thick in the southern Viking Graben and 80-100 m thick sandy deposits in the northern Viking Graben (Chadwich et al., 2000). Between these depocentres a large deltaic system was formed in the western central area, and it

prograded eastwards in the Early and Middle Miocene. Then the sediments of Utsira Formation become thin or absent in the Upper Miocene to Lower Pliocene.

In the Middle/Late Miocene, the progradation of the delta stopped and sediments of the Utsira Formation were transported to the delta slope. The Utsira Formation in the Tampen area consists of a thin glauconitic unit dated to close to the Late Miocene/Early Pliocene boundary and overlying the Oligocene and Lower Miocene as a cap to the main Utsira Formation sands in the northeastern part of the basin (Figure 7) (Rundberg and Eidvin, 2005; Eidvin and Rundberg, 2001, 2007; Eidvin et al., 2013c and d). The glauconitic unit within the Tampen area is locally absent and Upper Pliocene deposits lie unconformably on Oligocene sediments (Eidvin, 2009; Eidvin and Øverland, 2009). The Utsira Formation merges with parts of the Hutton sand in the western part of the Norwegian sector block 30 and 25 (Figure 8).

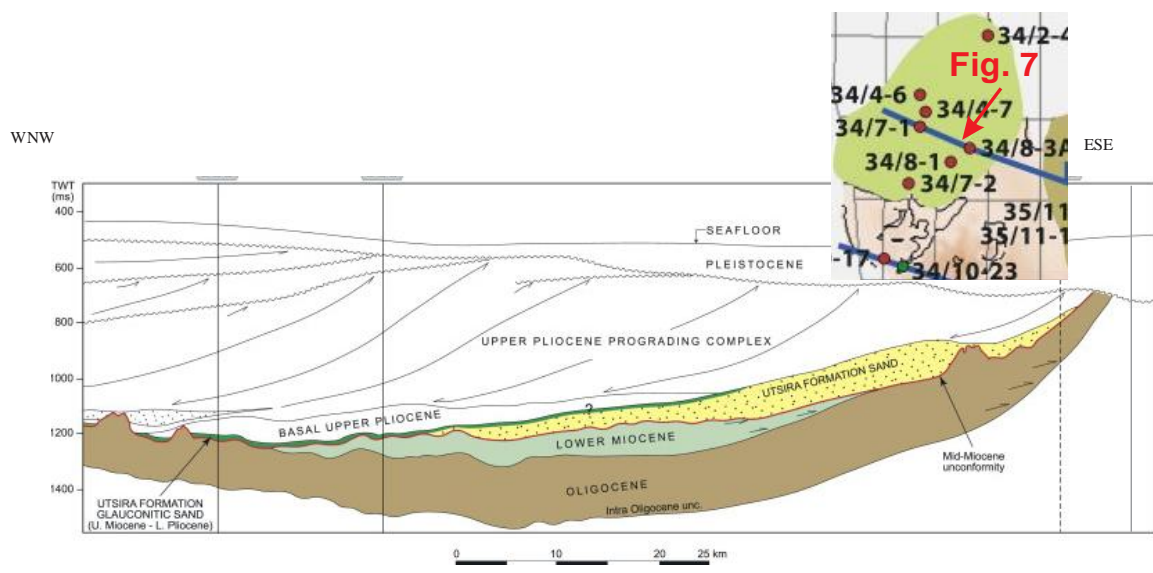


Figure 7. The east-west profile of the northern North Sea (Tampen area) with main sequences and lithology of the post-Eocene strata. The figure shows the Middle Miocene unconformity (red line) (Eidvin et al., 2014).

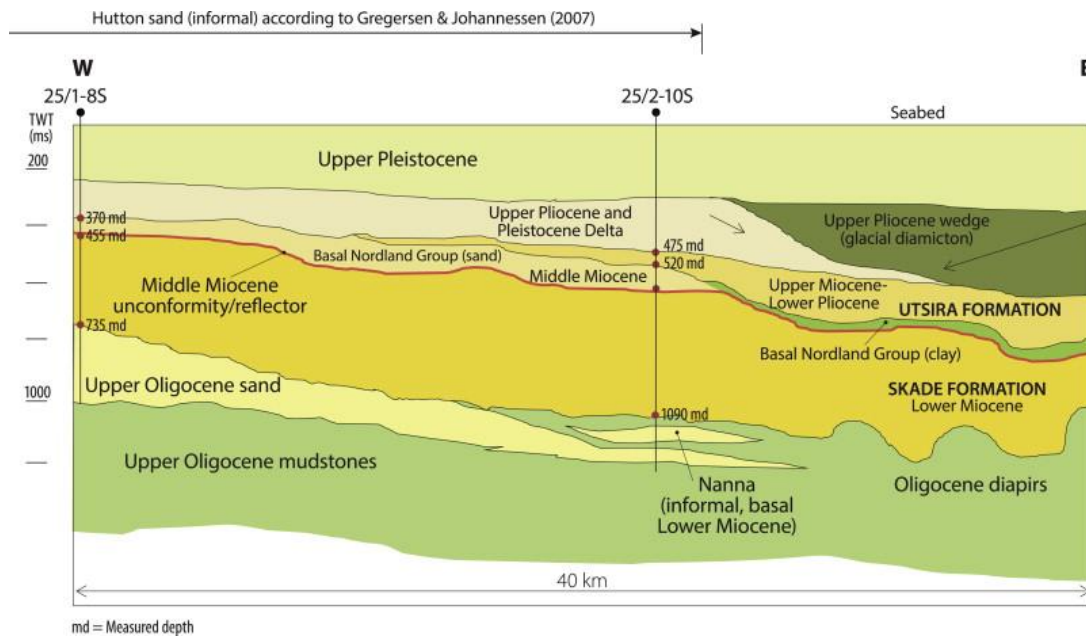


Figure 8. The geo-section illustrating shows the Lower Miocene Skade Formation is turbiditic in origin in Norwegian waters which overlies Oligocene mudstones. A mud prone, distal, middle Miocene unit and thins out westwards from the delta front towards the Hutton sand overlying by the Utsira Formation. An Upper Pliocene and Pleistocene delta was built out on top of the Utsira Formation in the east of the Hutton sand. (Eidvin et al., 2014, modified after Gjeldvik et al., 2011).

4. MATERIAL & METHODS

4.1. Sites and samples

The 13 palynological slides were prepared and examined from a short core in industry well 34/8-A-33H. The well was drilled in 1986 and is located on the northern North Sea at latitude 61° 22' 13.5'' N, longitude 2° 27' 34.63'' E, in some 335.0 m of water and in total depth 1733.0 measured depth (MD) in meter rotary Kelly bushing [m RKB] (Figure. 9). The investigated interval between 1125.65 and 1141.65 m is thought to belong to the Utsira Formation. Between 161 and 611 dinoflagellate cysts were counted for each sample, and the numbers of acritarchs, foraminiferal linings, pollen and spores were also noted during the counting. Tabel.1 below shows the palynomorphs are preserved through sediments which consist of dominantly marine sandstones with thinner intercalated claystones. The sandstones are clear to white, often lightly greenish; normally very fine to fine grained. Soft, light-greenish claystones and siltstones separated the sandstone beds.

The weight of dried sediment varies between the samples, and (Table.1) shows the biggest weight value to be (25 g) at sample 1139.99 m while the smallest was (11 g) at 1138.76 m. All the samples were treated with HCL & HF. Only one sample, 1140.27 m, was exposed to oxidation. All the samples were sieved by 20 µm. Apart from two samples almost all the samples were exposed ultrasonic treatment.

WELL	SAMPLES (m)	LITHOLOGY	WEIGHT (g)	(HCL) TREATMENT	(HF) TREATMENT	OXIDATION	SIEVES (µ)	ULTRASONIC TREATMENT
34/8-A-33H	1125.65	sand	20	X	X	NO	20	Short ultrasonic
34/8-A-33H	1129.28	clayey sand	20	X	X	NO	20	NO
34/8-A-33H	1130.82	clay	20	X	X	NO	20	NO
34/8-A-33H	1132.63	silty sand	17	X	X	NO	20	Short ultrasonic
34/8-A-33H	1133.28	silty clay	15	X	X	NO	20	Short ultrasonic
34/8-A-33H	1133.67	silty clay	20	X	X	NO	20	Short ultrasonic
34/8-A-33H	1134.25	dark grey	20	X	X	NO	20	Short ultrasonic
34/8-A-33H	1138.65	silty clay	25	X	X	NO	20	Ultrasonic
34/8-A-33H	1138.76	fine sand	11	X	X	NO	20	Ultrasonic
34/8-A-33H	1139.99	very fine sand	20	X	X	NO	20	Ultrasonic
34/8-A-33H	1140.27	fine sand	25	X	X	YES	20	Ultrasonic
34/8-A-33H	1141.18	fine sand	20	X	X	NO	20	Ultrasonic
34/8-A-33H	1141.65	fine sand	20	X	X	NO	20	ultrasonic

Table 1. An overview of the sample information and palynological preparation of the samples in this study, from shallowest/youngest at the top to deepest/oldest sample at the bottom.

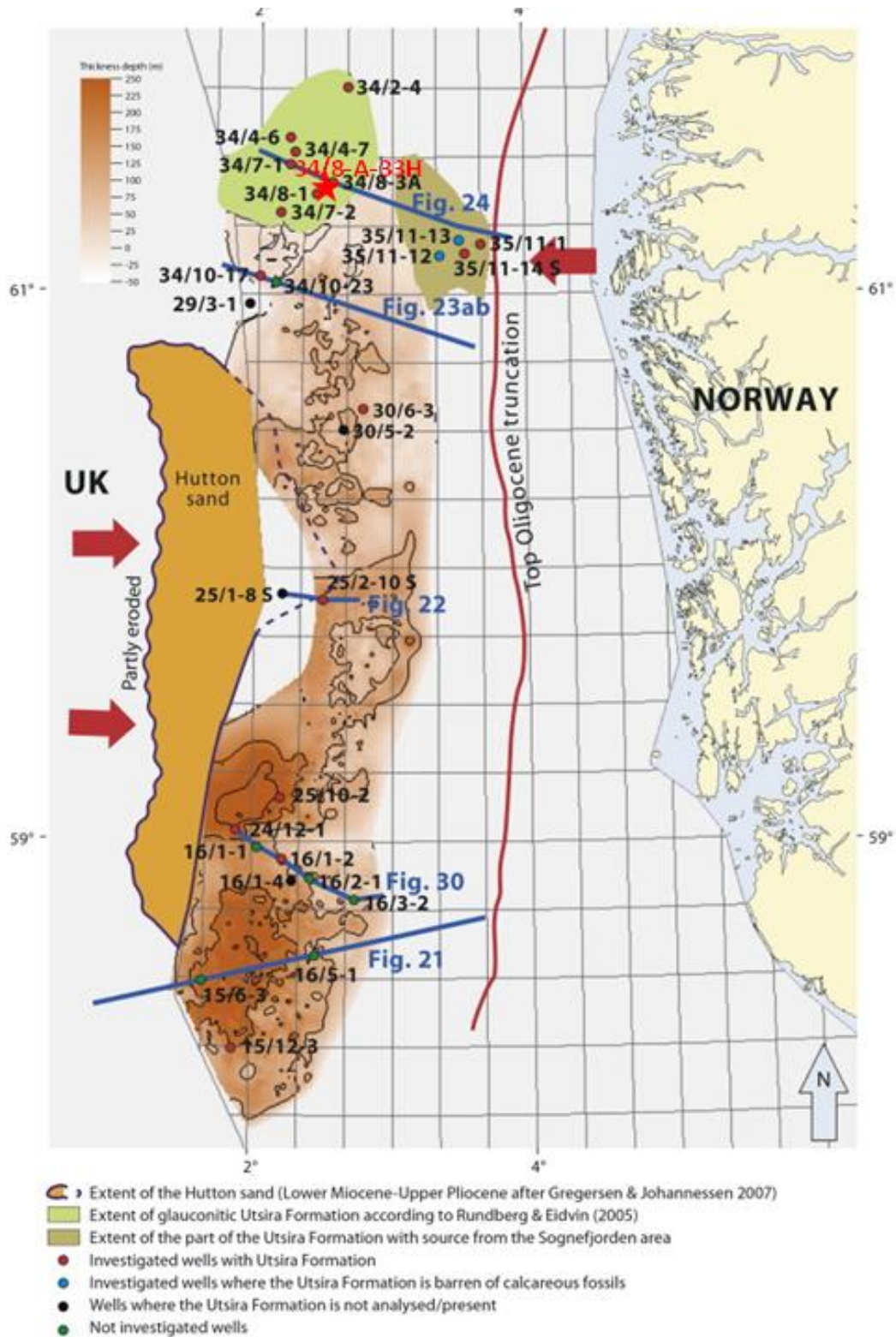


Figure 9. The well location in this study is marked by the red star at the Tampen area “Utsira Formation” in the northern North Sea. (Eidvin et al., 2014).

4.2. PALYNOLOGICAL PREPARATION TECHNIQUES

The preparation of all palynological samples from well 34/8-A-33H were done by Malcolm Jones of the company Palynological Laboratory Services in Holyhead, United Kingdom. The standard preparation method for samples was used according to (Wood et al., 1996) which is described below. The method involves the use of chemicals and sieving techniques to extract and concentrate the organic palynoflora content from a cutting sample. Each sample was spiked with *Lycopodium cavatum* spores for concentration calculations of organic palynoflora.

The specified weight of sample was crushed using a hammer and bashing plate, and placed into a liter Tripour beaker. One *Lycopodium* tablet was added to the beaker before the chemical degradation began. A small amount of water was added to the sample prior the addition of (HCL) to avoid a rapid reaction. Slowly 50% HCL was added to the sample to remove the calcium carbonate, and the addition for the HCL was continued until the sample had stopped reacting, depending on its CaCO₃ content. The sample was then topped up fully with water stirred and allowed to settle. Then the diluted supernatant liquid was sieved through a 20 micron nylon sieve cloth with using plenty of water, and the collected residue returned to the Tripour with using water from a wash bottle. Slowly, added 100 ml of 60% hydrofluoric acid (HF) to remove silicates from the sample. The sample was then stirred and left for two days. After this the sample was topped up with water for dilution as before and the entire residue sieved and collected, before it was placed in 250 ml Pyrex glass. The collected residue was then checked under the microscope to ensure that the silicates have been dissolved. If the residue still contains un-dissolved silicates, it may be necessary to repeat the HF stage.

After silicate removal, the sample was then ready for oxidation. The oxidation is carried out using 50% cold Nitric acid and this was added to the residue in the beaker (in 25 ml of water) and left for the required time (varies depending on the preservation of the residue/palynomorphs present). Ultrasonic treatment then preceded the sieving. The residue was sieved out as before using water, and checked under the microscope prior to storing in a glass vial ready for mounting. The residue was mixed with a 1% solution of PVA (Polyvinyl alcohol) to prevent clotting and stained if necessary. It was then pipetted onto a 32 X 22mm cover slip on a low temperature drying plate and allowed to dry. Once dry the cover slip was mounted onto the glass microscope slide using Norland 63 optical

adhesive (Glycerine jelly if possible). The slide was then cleaned and labeled with the appropriate sample details and lab number. The slide was checked under the microscope to ensure the residue is free of bubbles and distribution on the cover slip is correct. The used palynological preparation procedure is shown in (Figure.10).

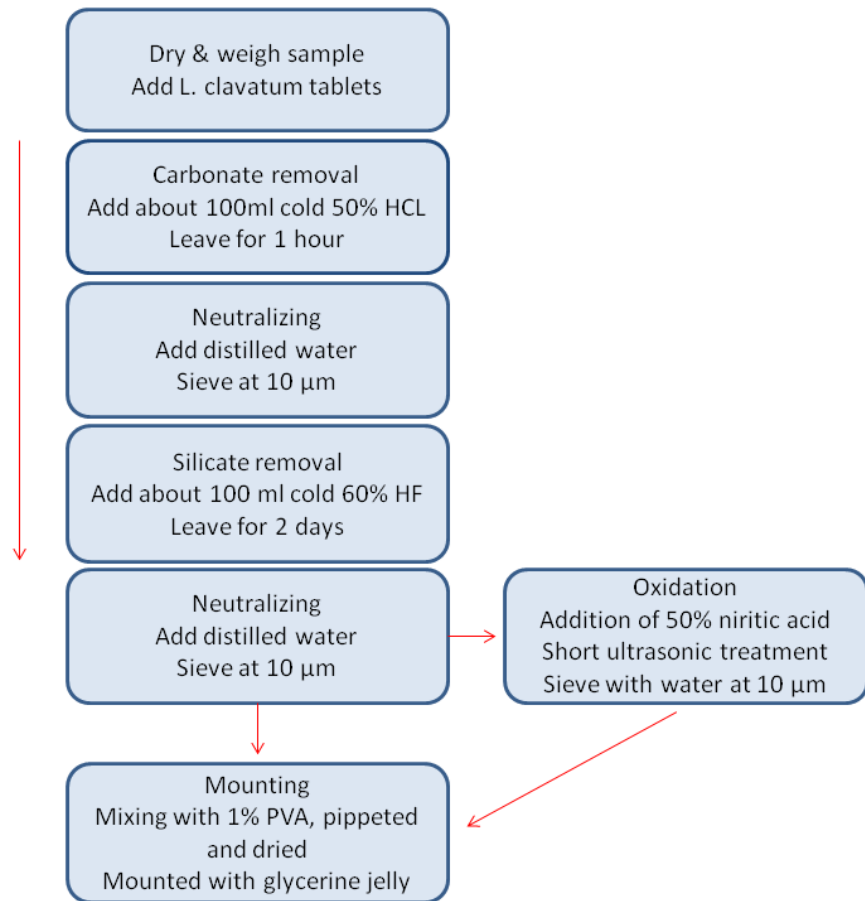


Figure 10. A sketch illustrating the palynological preparation technique.

4.3. Counting and equipment

The current study is based on 13 samples from the well 34/8-A-33H. The palynological slides were examined using a Zeiss Axioplan light microscope, scanning continuously along non-overlapping lines from beginning from the top of the slide. Each slide was initially examined under a 63x and 40x objectives, until obtaining the required about 300 dinoflagellate cysts, sometimes referring to 100x objective, in order to outline certain details more specifically, but later using 20x for counting rare species for the remainder of slide. The “England finder slide” had also been used, in order to determine the location of the good preserved specimen in the slide. A Zeiss Axiocam ERc5s digital camera was used for photography, with 100x magnification, while Zen 2012 was used as the software program for digital imaging for light microscopy.

4.4. LO-analysis

The LO-analysis described by Erdtman (1956) is used to recognize the different wall surface patterns of some dinoflagellate cyst species, or other palynomorphs, such as pollen or spore wall surfaces. LO-analysis is especially important for distinguishing the genera (e.g. *Bitectatodinium*, *Filisphaera*, *Habibacysta* and *Pyxidinospis*).

In the LO-analysis, the wall patterns of a palynomorph in surface view are recorded in two successive focal planes. Starting from the upper to the lower focus, wall structures will go from light to dark (LO-patterns) representing raised structures (convexities), and from dark to light (OL-patterns) to indicate depressed structures (concavities).

The method therefore presents an easy and effective way to recognize e.g. a reticulate wall from a scabrate wall. The LO-analysis was used in the surface pattern recognition of *Bitectatodinium raedwaldii* (Figure 11).

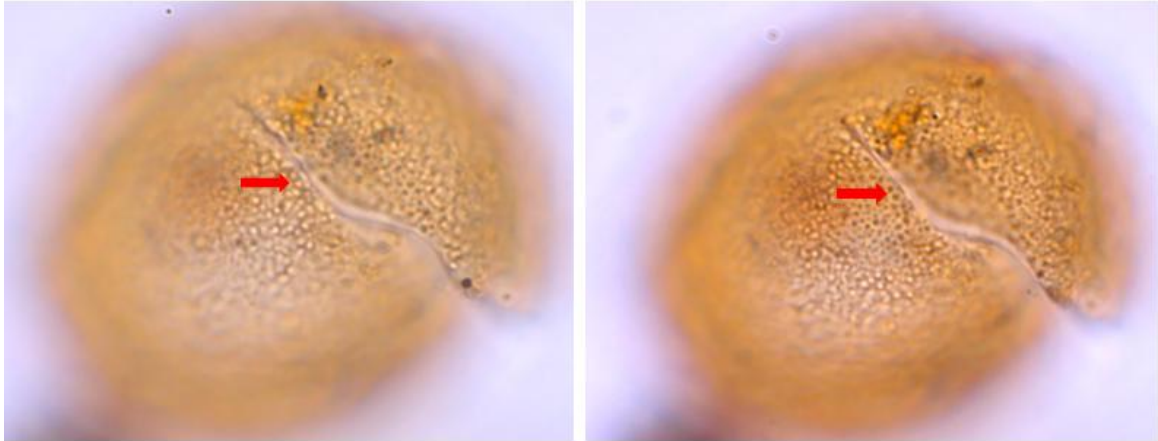


Figure 11. The wall patterns of *Bitectatodinium raedwaldii*. Starting from the upper to the lower focus, wall structures will change from light to dark (convexities) The picture to the left is on high focus while the left one, lower focus. Sample depth: 1133.28England Finder: O45/0.

4.5. The lycopodium marker-grain method

According to the method of Stockmarr (1971), the dinoflagellate cyst and acritarch concentration have been calculated. One *Lycopodium clavatum* spore tablet, which is produced by the University of Lund, Sweden, added to each sample before the chemical degradation. The batch number of Lycopodium tablet which was used, is 483216 and the number of *Lycopodium* spore per tablet is 18583 ± 1708 . The *Lycopodium clavatum* spores were counted like the other palynomorphs. The numbers of dinoflagellate cysts/acritarchs in the samples were then calculated following the equation:

$$c = (dc \times Lt \times t) / (Lc \times w)$$

Where:

C : concentration (number of dinoflagellate cysts/gram dried sediment)

dc : number of counted dinoflagellate cysts

Lt : number of *Lycopodium* spores/tablet

t : number of tablets added to the sample

Lc : number of counted *Lycopodium* spores

w : weight of dried sediment (g)

The total error is calculated following the equation:

$$e = \sqrt{(e1^2 + e2^2 + e3^2)}$$

Where:

e1: error on number of *Lycopodium clavatum* spores in marked tablets

e2: (the square root of cyst/acritarchs counted divided by the cysts/acritarchs counted) = error on dinoflagellate cysts counted.

e3: (the square root of *Lycopodium clavatum* spores counted divided by the spores counted) = error on the number of *Lycopodium clavatum* spores counted.

4.6. Systematic palynology

Through counting and describing the palaeontological samples, the different taxa have been founded. Because of bad preservation, e.g. lost color, broken specimens or degraded specimens by chemical treatments, some of dinoflagellate cyst species were not easy to identify and they were only counted as dinocyst spp.indet. As a result of poor stratigraphic value, some species were only grouped down relative to genera e.g. most *Spiniferites* and *Achomosphaera*, which were named together under *Spiniferites* /*Achomosphaera* spp.indet. Also most *Amiculosphaera* and *Invertocysta* were counted under *Amiculosphaera* /*Invertocysta* spp.indet. Some dinoflagellate cysts in the present study were interpreted as reworked, and were therefore not classified, and only counted as reworked dinocysts spp. These were not considered important for the aim of this study.

A list with full names is given in Appendix 3. A selection of dinoflagellate cyst and acritarch species considered as an important for this thesis, are illustrated on Plate 1, 2, 3 and 4 in Appendix 2.

4.7. Palaeoecological methods

Most of the dinoflagellate cyst species with palaeoecological significance are selected from the studies of Versteegh and Zonneveld (1994); Marret and Zonneveld (2003); De Schepper (2011), Verhoeven and Louwye (2013) and Head (1996, 1997 and 1998). These studies deal with the palaeoecology of the Late Pliocene of the Atlantic oceans & adjacent seas.

Important species from the literatures:

Bitectatodinium tepikiense: is characteristic for temperate / cold water masses (Verhoeven and Louwye, 2013; Marret and Zonneveld, 2003). This taxon can be considered to be a typical inner neritic species (Versteegh, 1994; De Schepper, 2006).

Impagidinium aculeatum: This species can dominate association in subtropical / tropical oceanic sites (Marret and Zonneveld, 2003). This taxon is associated with warm oceanic watermass, (Versteegh, 1994; Head, 1998).

Impagidinium paradoxum: This species can be considered to be an oceanic species, characteristic for temperate to tropical fully marine environment (Marret and Zonneveld, 2003; Versteegh, 1994).

Lingulodinium machaerophorum: can be considered to be a temperate to tropical, coastal species, present in regions with summer SST exceeding 12°C (Marret and Zonneveld, 2003). This taxon is mainly reported from inner neritic sites (Versteegh, 1994).

Operculodinium israelianum: is considered to be a temperate/subtropical to tropical species. They are confined in their distribution to fully marine sites with high salinity environments (Marret and Zonneveld, 2003). This species is particularly known from inner neritic environments (Versteegh, 1994).

Spiniferites elongatus: This is a cold to temperate species, characteristics for recent sediments deposited in the outer neritic realm (Marret and Zonneveld, 2003; Versteegh, 1994).

Tectatodinium pellitum: may be regarded as a warm-temperate subtropical to tropical coastal species (Marret and Zonneveld, 2003). This species is particularly known from inner neritic environments (Versteegh, 1994).

Tuberculodinium vancampoae: can be regarded as a subtropical/tropical species. This taxon is deposited in the inner neritic and lagoonal sediments (Versteegh, 1994).

Bitectatodinium raedwaldii: is suggested in inner neritic to oceanic, temperate/tropical climatic range, Head (1997).

Filisphaera filifera: due to it is known mainly from the high latitudes, it can generally be considered a cool-water species (De Schepper et al., 2011) or moderately cold-tolerant species (Head, 1996).

Habibacysta tectata: is a cool-tolerant species (Head, 1994) or a cold water species (Versteegh, 1994).

Operculodinium? eirikianum: can be regarded as a mid/high latitude, cold sensitive species (De Schepper et al., 2011).

Achomosphaera andalousiensis: is considered a cool or warm, outer neritic species (Head, 1996, 1997).

In the present study, several curves have been used in order to reconstruct and interpret the palaeoenvironmental conditions in the Late Pliocene.

4.7.1. Sporomorph / Dinoflagellate cyst curve (S/D index)

The S/D curve plots the continental- versus marine influences. The presence of dinoflagellate cysts being indicative of marine influence, whereas the presence of spores and pollens reflects terrestrial influences. All dinoflagellate cyst species indicate marine conditions.

$$S/D = nS / (nD + nS)$$

Where:

n = number of specimens counted

S = Pollen and spores

D = Dinoflagellate cysts and other marine palynomorphs (Actritarches)

4.7.2. Warm / Cold curve (W/C index)

The W/C index represent a proxy for the changes in the sea surface temperatures (SST) by applying the ratio W/C.

$$W/C = nW / (nW + nC)$$

Where:

n = number of specimens counted

W= warm water indicating dinoflagellates (*Impagidinium acuelatum*, *Impagidinium paradoxum*, *Lingulodinium machaerophorum*, *Tecatodinium- pellitum*, *Tuberculodinium vancampoae*, *Operculodinium ? eirkianum*, *Operculodinium israelianum* and *Bitectatodinium raedwaldii*).

C = cold water indicating dinoflagellates (*Bitectatodinium tepikiense*, *Spiniferites elongatus*, *Habibacysta tectata* and *Filisphaera filifera*).

4.7.3. Inner neritic / Oceanic, Outer neritic / Oceanic, Neritic /Oceanic and Inner neritic / Outer neritic curves (IN/O, ON/O, N/O and IN/ON index)

The IN/O index are plot Inner neritic- versus oceanic dinoflagellate cysts which indicates the variations in the inner neritic watermass influence, Versteegh (1994). The ON/O is a measure for the influence of the outer neritic watermass relative to the oceanic watermass. The N/O ratio indicates the total (inner and outer) neritic watermass influence relative to the oceanic watermass. The IN/ON the ratio of inner neritic watermass conditions versus outer neritic water mass conditions.

$$IN/O = nN / (nN + nO)$$

$$ON/O = nO / (nO + nO)$$

$$N/O = nN / (nN + nO)$$

$$IN/ON = nIN / (nIN + nON)$$

Where:

n = number of specimens counted.

N = dinoflagellate cysts indicating neritic conditions.

O = dinoflagellate cysts indicating the oceanic conditions. (*Impagidinium acuelatum*, *Impagidinium paradoxum*, *Nemateosphaeropsis labyrinthus* and *Filisphaera filifera*).

IN = dinoflagellate cysts indicating inner neritic conditions. (*Lingulodinium machaerophorum*, *Tecatodinium pellitum*, *Tuberculodinium vancampoae* and *Operculodinium israelianum*).

ON = dinoflagellate cysts indicating outer neritic conditions. (*Spiniferites elongatus*, *Spiniferites ramsous*, *Spiniferites rubinus*, *Spiniferites spp.*, *Achomosphaera andalusiensis*).

4.7.4. Gonyaulacoid / Protoperidinioid curve (G/P)

The ratio of the abundance of gonyaulacoid - versus peridinioid dinoflagellate cysts can reflect the productivity (Versteegh, 1994, 1995). In areas rich in nutrients, heterotrophic protoperidinioid can be found in relatively big amounts such as upwelling area, coastal area, fronts between watermasses (Wall et al., 1977) and arctic ice margins (Aksu et al., 1992). Autotrophic gonyaulacoid prefer stable environments such as open ocean environments.

$$G/P = nG/(nG + nP)$$

Where:

n = number of specimens counted

P = peridinioid dinoflagellate cysts (*Lejeunecysta spp.*, *Barssidinium spp.*, *Selenopemphixspp.*, *Trinovantedinium spp.*, *Brigantidinium spp.* and Round brown cysts).

G = gonyaulacoid dinoflagellate cysts (all other dinoflagellate species except *Tuberculodinium spp.* and *Amiculosphaera spp.*).

5. RESULTS

5.1. Palynomorph preservation

In this study, the observation and counting of the 13 palynological samples recovered moderately to well preserved, rich and diverse palynomorph assemblages. Marine organic matter such as dinoflagellate cysts and acritarchs are predominant and abundant in most of the samples. Almost all of the samples were in good condition. The specimens in the sample 1140.27 m were dominantly pinkish, due to the addition of (Safranin-O) during the staining process that was intended to make the observation easier. And this sample was exposed to oxidation in order to remove the amorphous organic matter (AOM) which could hinder the counting and identification. In some intervals, it was difficult to accurately recognize some species such as some species of *Spiniferites/Achomosphaera*, *Invertocysta /Amiculosphaera*. The spacing between the sample depths varies between the samples of the core; the deepest/oldest sample, which lies to the right of (Table 2, appendix 1), was 1141.65 m in depth, whereas the depth of shallowest/youngest sample, which lies to the left of table 2, was 1125.65 m

5.2. Palynomorph assemblages

Palynomorph assemblages from the well 34/8-A-33H analyzed by the microscope are diverse as including dinoflagellate cysts, acritarchs, microforaminifera lining, pollen and spores. There are 47 different dinoflagellate cyst and 5 acritarch taxa are recorded in the present study (Table 2, appendix 1). The number of dinoflagellate cyst taxa per sample varied between 14-26 taxa with an average of 19 taxa per sample. Generally, *Operculodinium*, *Lingulodinium*, *Spiniferites*, *Amiculosphaera* and round brown cysts are abundant and persistent in all the samples. *Bitectatodinium*, *Pyxdinoposis* and *Achomosphaera* are less frequent. *Impagidinium*, *Nematosphaeropsis* and some species of *Brigantedinium* and *Selenopemphix* are present in small numbers and only in few interval depths and the same applies for *Barssidinium pliocenicum* and *Habibacysta tectata* which also are rare. Dinoflagellate cyst reworking occurred also in some studied intervals. The acritarch taxa (*Cymatiosphaera*, *Lavradosphaera* and *Nannobarbophora*) are present and dominantly recorded in the deepest part of the well. The terrestrial palynomorphs (pollen and spores) are also present and counted in this study.

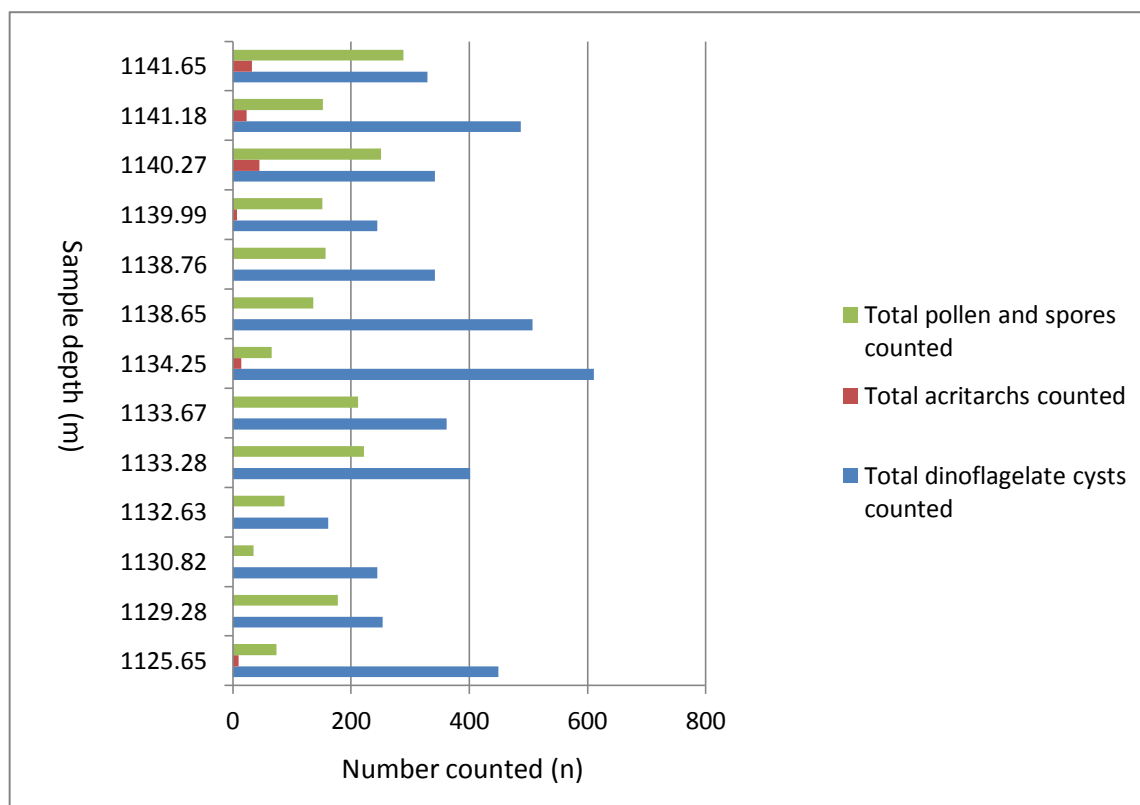


Figure 12. An overview of the relationship between dinoflagellate cysts, acritarchs and terrestrial palynomorphs. Where the vertical axis represents the sample depth and horizontal axis includes the number counted.

5.3. Concentrations of dinoflagellate cysts and acritarchs

The concentration of marine palynomorphs (dinoflagellate cysts and acritarchs) and terrestrial palynomorphs (pollen and spores) varied between the palynological samples. The highest dinoflagellate cyst concentration measures 28,888 cyst/g and is found at depth 1138.76 m, while the lowest concentration measures 1,629 cyst/g and is present at depth 1132.63 m, with an average of 8,479 cyst/g (Table 2, appendix 1). Between the depths of 1139.99 m and 1133.67 m, considerably high concentration of dinoflagellate cysts is observed, reflecting the presence of favorable environment for flourishing growth of dinoflagellate cysts. Immediately prior to this, an area of sharp drop in dinoflagellate cyst concentration is shown on the curve, with a lowest value of 2856 cyst/g, registered at 1140.27 m depth. At the same depth a corresponding reciprocal rise of pollen and spores,

peaks with a higher value of 2225 pollen/g (Figure 13). This may reflect a continental influence. A similar but smaller rise of pollen and spore concentration is observed at middle of the curve, corresponding to the latest part of the mentioned period of considerably high concentration of dinoflagellate cysts.

Acritarch is found in only few intervals, and in low concentrations. The average of acritarch concentration is 325 (acritarch/g), whereas the highest concentration is calculated at depth 1125.65 m with 619 acritarch/g and the lowest 20 acritarch/g at 1132.63 m (Table 2, appendix 1).

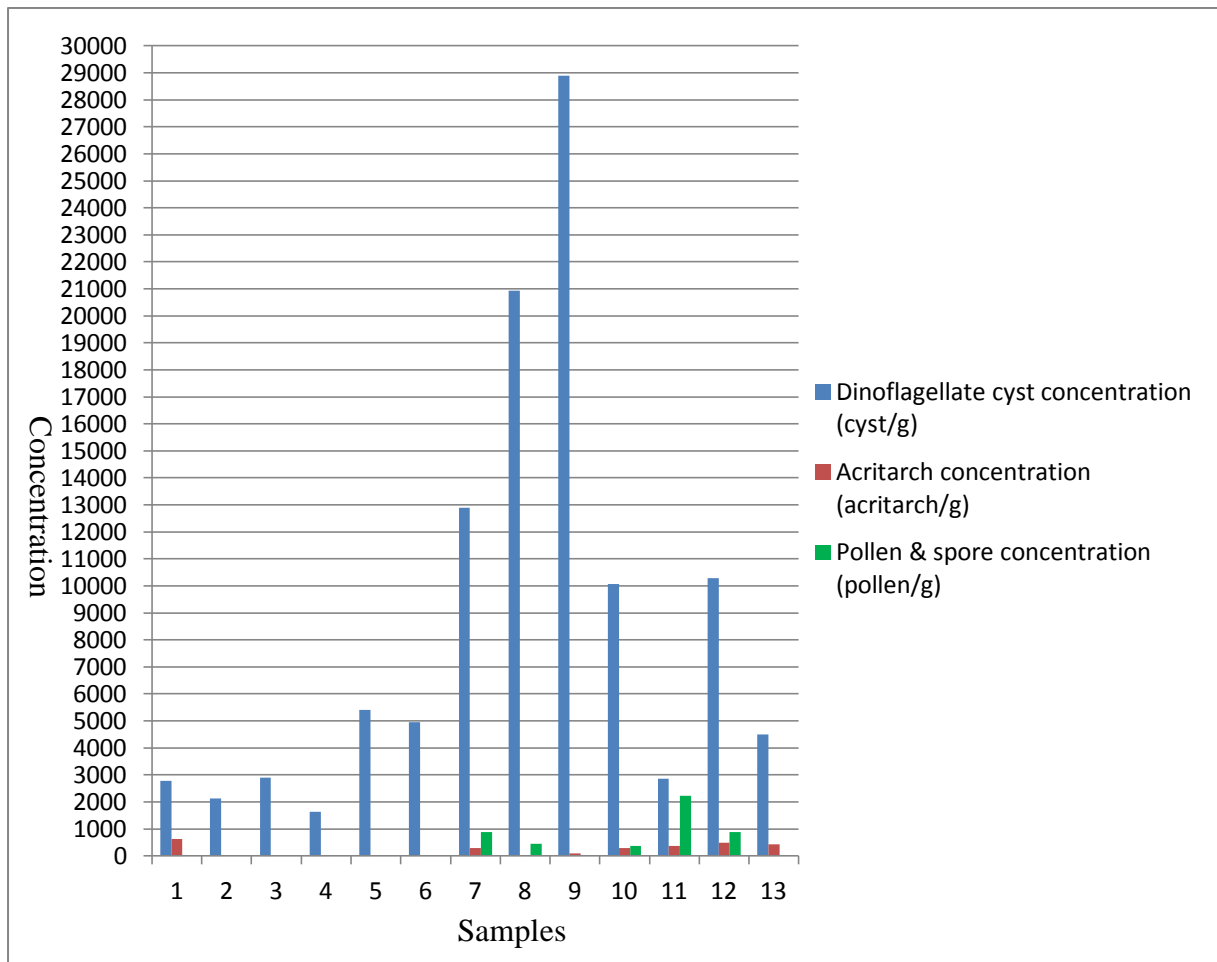


Figure 13. An over view on the concentration of dinoflagellate cysts, acritarchs, pollen and spores of the restricted studied interval between sample. 1 (1125.65 m) to sample. 13 (1141.65 m).

5.4. Reworking

Reworked dinoflagellate cysts originating from older ages, can be transported and deposited in sediments of younger age, and recognition of their percentages is important for better palaeogeographical reconstruction of the time of deposition. Reworking is at its maximum when sea levels are low, and is most importantly produced by erosions by rivers, in addition to in situ reworking. There are generally difficulties in recognizing reworked species, but they tend generally to exhibit signs of mechanical degradation during the reworking process, as well as being less susceptible to colorization by Safranin-O. Sporadic occurrences above persistent range of a species, might suggest reworking (De Schepper and Head, 2008).

5.5. Taxonomic remarks

Several dinoflagellate cyst taxonomical names are developed in the present study due to one or more reasons such as morphology, preservation, poor stratigraphical value or/and other conditions.

Bitectatodinium raedwaldi/tepikiense: This taxon represents a transitional form, as it shows typical morphological characteristics of both species, being similar to *Bitectatodinium raedwaldii* in having long and thick luxuria and to *Bitectatodinium tepikiense* in its wall structure.

***Amiculosphaera/Invertocysta* spp.**: Due to the presence of large folds in cysts, it was difficult to differentiate- between *Amiculosphaera* and *Invertocysta*, and to recognize the characteristic features of both such as funnel-shaped apical connection between endo- and periblast in *Amiculosphaera*, while there is no connection in *Invertocysta*.

***Achomosphaera/Spiniferites* spp.**: This group includes spiniferate, thin walled cyst and with an ovoidal central body. Processes are hollow, distally open with bifurcate or trifurcate platforms.

Operculodinium centrocarpum/israelianum: Overlap in process length between these two species is observed, where the *Operculodinium israelianum* has processes mostly in the range 3.5-9.0 μm , with some having acuminate tips while the *Operculodinium centrocarpum* has longer processes.

Lavradosphaera canalis/crista: This acritarch taxon is similar to *Lavradosphaera canalis* in having a thick wall deeply incised by U- to V shaped channels with rounded bases. At the same time it is close to *crista*, and shows spherical to spheroidal vesicle bearing relatively straight intersecting crests that subdivide the surface into about nine polygonal fields (Plate 4, figure 10, 11).

6. DISCUSSION

6.1 Dinoflagellate cyst stratigraphy and age of the investigated interval

6.1.1 Stratigraphically significant dinoflagellate cyst and acritarchs in Well 34/8-A-33H.

The stratigraphic range of dinoflagellate cysts and acritarchs used for dating the studied section in this study are based on reference sections in the North Atlantic (DSDP Site 610 of the Eastern North Atlantic, De Schepper and Head, 2008, 2009), in the Iceland Sea (ODP Hole 907A, Schreck et al., 2012), the eastern North Sea Basin, Denmark (Dybkjær and Piasecki, 2010) and the Vøring Plateau, Norwegian Sea (ODP Hole 642B, Beck, 2013) (Figure 14, 14). *Amiculosphaera umbraculum*, *Achomospaera andalousiensis*, *Barssidinium pliogenicum*, *Habibacysta? tectata*, *Operculodinium? eirikianum*, and the acritarch.. *Cymatiosphaera? invaginata* have long stratigraphic ranges from Late Neogene to Quaternary with a highest occurrence (HO) in the latest Pliocene or Pleistocene of the North Atlantic region (e.g. De Schepper and Head, 2009; Dybkjær and Piasecki, 2010). *Lavradosphaera canalis* have short ranges in Pliocene on the eastern North Atlantic (DSDP 610A) (De Schepper and Head, 2008). The lowest occurrence (LO) of *Bitectatodinium tepikiense*, *Filisphaera microornata* and *Pyxidnopsis braboi* are recorded from latest Late Miocene-Pliocene to the Pleistocene and even modern times in the North Atlantic region and the eastern North Sea Basin (Denmark) (Marret and Zonneveld, 2003).

In this paper (Tapel 2), *Operculodinium centrocarpum* and *Operculodinium? eirikianum* are the most abundant taxa and are present in all examined-palyeological samples. The *Operculodinium centrocarpum* has recorded highest abundance at 1140.27 m and 1141.65 m while the highest abundance of *Operculodinium? eirikianum* is found at 1132.63 m, 1140.27 m and 1141.65 m. There are several other species in this study that is also observed with high abundance with presence in almost all the analyzed samples. *Lingulodinium machaerophorum* for example is present in all samples, but is lacking at 1138.76 m. The same applies for *Spiniferites spp.*, also being present in all samples excluding 1132.63 m. Likewise, *Bitectatodinium tepikiense* is not recorded at 1133.28 m and *Amiculosphaera umbraculum* is not recorded at 1129.28 m, but are otherwise present in all other samples. *Amiculosphaera umbraculum* shows higher abundance at 1141.65 m.

Spiniferites rubinus is also registered in almost all the samples, apart from at 1125.65 m and 1139.99 m.

Habibacysta? tectata and *Barrisidinium pliocenicum* are only registered in scant quantities, totally 3 specimens for each, and only at the deeper half of the core.

Filisphaera filifera occurs in 6 samples and has highest abundance at 1132.63 m.

Selenopemphix quanta, *Selenopemphix dionaeacysta* and *Cymatiosphaera? invaginata* are recorded interruptedly in several scattered samples throughout the core.

Lavradospaera canalis/crista and *Nannobarbophora walldalei* appear confined to the deepest parts of the core.

Specimens of *Achomosphaera andalouisiensis andalouisiensis* occur in most samples, but not uninterruptedly throughout the core and with higher abundance at 1138.76 m. Only few specimens of *Tectatodinium pellitum* could be registered non-continuously throughout the core, with higher abundance in the deepest part of the core.

Pyxidnopsis braboi, *Filisphaera microornata* and *Filisphaera filifera* occur persistently in 4 consecutive samples in the lowest upper part of the core and with higher abundance here, and are otherwise only registered sparsely in the lower part of the core, and with much lower abundance. *Trinovantedinium variabile* and *Trinovantedinium glorianum* are recorded with low occurrence at 1132.63 m.

Three specimens of *Labyrinthodinium truncatum* were recorded and only at depth 1130.82 m. Several other species were also recorded in this study, but with much less and relatively insignificant occurrences.

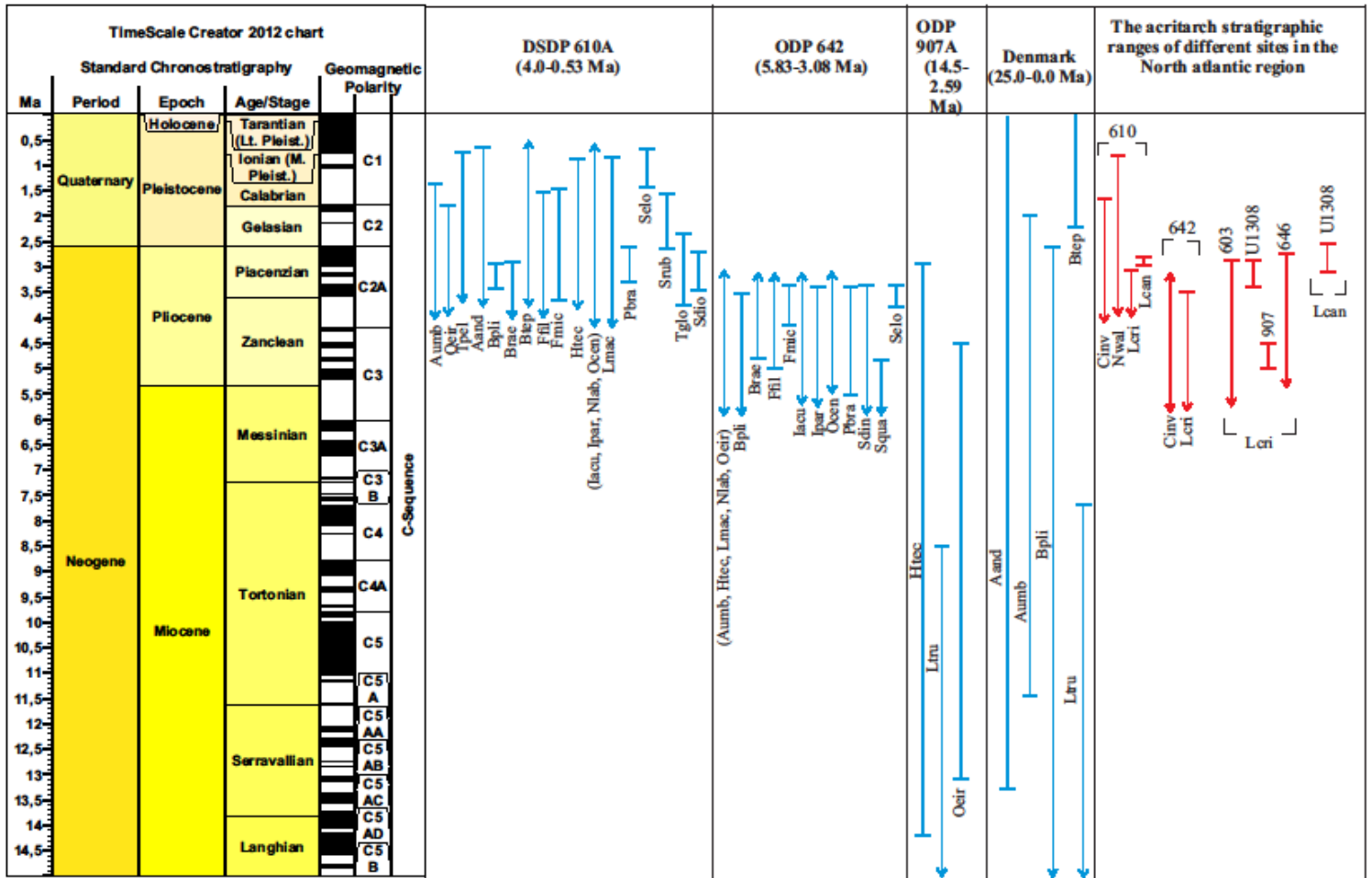


Figure 14. *Aumb*:*Amiculosphaera umbraculum*, *Aand*: *Achomosphaera andalousiensis*, *Bpli*: *Barssidinium pliocenicum*, *Btep*: *Bitectatodinium tepikiense*, *Brae*:*Bitectatodinium raedwaldii*, *Fmic*: *Filisphaera microonata*, *Htec*: *Habibacysta tectata*, *Ltru*: *Labyrinthodinium truncatum*, *Oeir*: *Operculodinium? eirikianum*, *Pbra*: *Pyxidinospis braboi*, *Tpel*: *Tectatodinium pellitum* and acritarchs.. *Cinv*: *Cymatiosphaera? invaginata*, *Lcri*: *Lavradospaera crista*, *Lcan*:*Lavradospaera canalis*. *Nwal*:*Nannobarbophora waldeili*, *Tglo*: *Trinovantedinium glorianum*, *Sdin*:*Selenopemphix dioncusta*, *Selo*:*Spiniferites elongatus*, *Srub*:*Spiniferite rubinus*, *Iacu*: *Impagidinium aculeatum*, *Ipar*: *Impagidinium paradoxum*. The horizontal lines showing the high- and low occurrences (HO and LO), the vertical lines representing the long biostratigraphic ranges of selected species of the different sites and the arrows explaining that the stratigraphic ranges of species could be longer. The blue color representing dinoflagellate cyst species while red color representing the acritarchs.

Stratigraphic ranges of selected dinoflagellate cyst and acritarch species for the North Atlantic region and adjacent seas are calibrated to the standard time scale of (GTS. Gradstein et al., 2012). Based on DSDP Hole 610A of the Eastern North Atlantic (De Schepper and Head, 2008, 2009), ODP Hole 642B in the Norwegian Sea (Beck, 2013) ODP Hole 907A in the Iceland Sea (Schreck et al., 2012) and the eastern North Sea Basin, Denmark (Dybkjær and Piasecki, 2010).

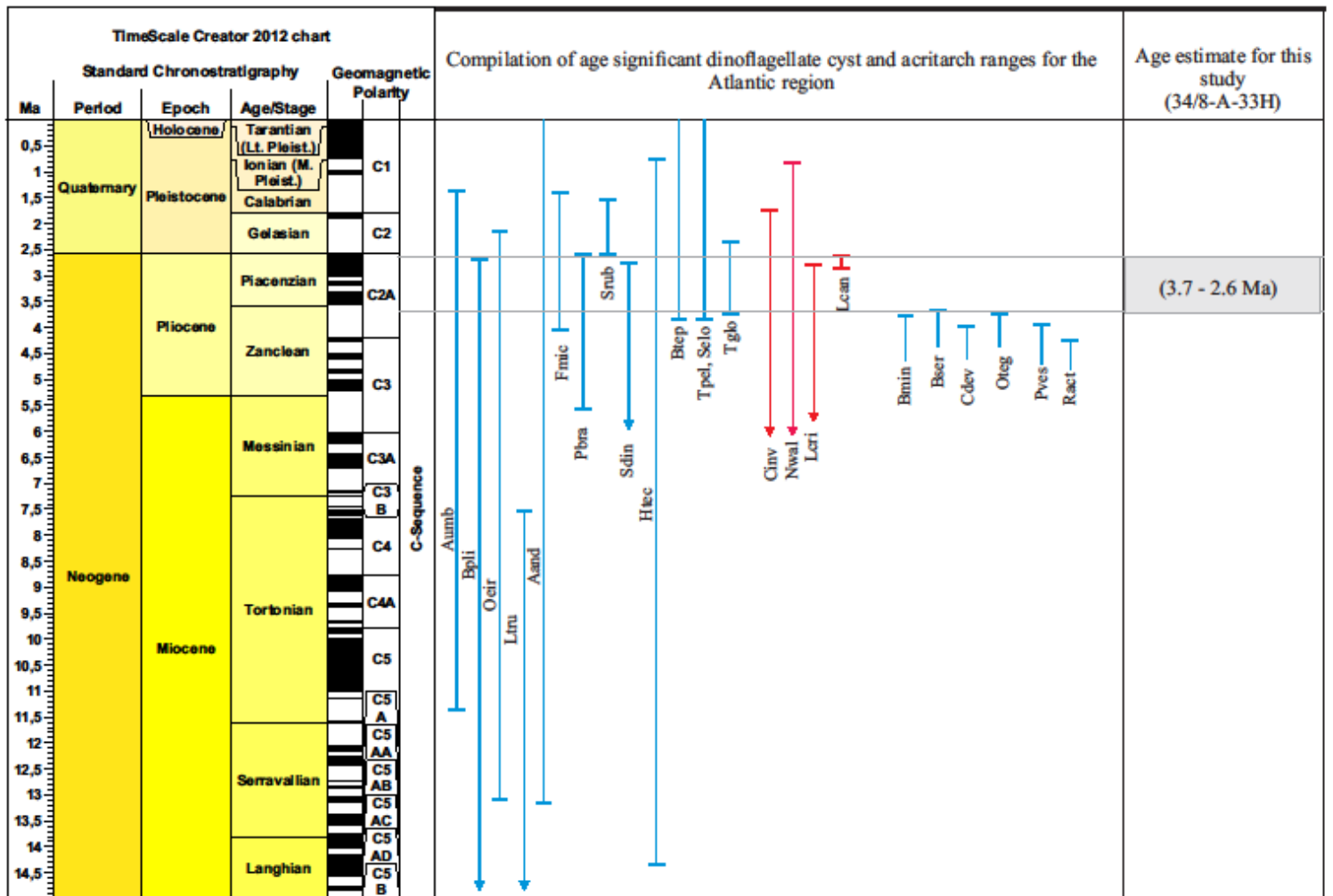


Figure 15. *Bmin*:*Batiacasphaera minuta*, *Bser*:*Bitectatodinium serratum*, *Cder*:*Corrudinium devernalia*, *Oteg*:*Operculodinium tegillatum*, *Pves*:*Pyxidinosia vesiculata*, *Ract*:*Reticulosphaera actinocoronata*. The remaining species are mentioned in figure 14. The compilation of important selected ranges of the extant and extinct useful dinoflagellate cyst species, of acritarchs in the North Atlantic region are put in one figure relative to lowest occurrence (LO) and highest occurrence (HO) and age estimation is considered for the studied interval of this study (34/8-A-33H) based on stratigraphy of dinoflagellate cysts and acritarchs.

6.1.2. Stratigraphic range in the North Atlantic region of significant dinoflagellate cysts

The selected significant dinoflagellate cyst and acritarch stratigraphic ranges in this study (Figure 14) are calibrated to the standard time scale of Gradstein et al., (2014).

Dinoflagellate cysts are an excellent tool for correlation and palaeoenvironmental reconstruction in the mid- to high latitude oceans. Dinoflagellate cyst assemblages in the present study have been correlated to calibrated stratigraphic ranges from reference sections on the Vøring Plateau and in the North Atlantic, in order to estimate the age of the Tampen area “Utsira Formation”.

The DSDP Hole 610A has studied only restricted interval between 0.5 and 4.0 Ma, which includes many useful species which are also common in the present study (34/8-A-33H) and those species could be found in the other ocean drill sites. *Bitectatodinium tepikiense*, *Operculodinium centrocarpum*, *Nematosphaeropsis labyrinthus*, *Impagidinium aculeatum* and *Impagidinium paradoxum* are recorded throughout the Hole 610A, which means these species may have longer stratigraphic ranges. The low occurrence of these species are coincided at the base of the hole (~ 3.8 and 4.0 Ma) and can not be interpreted as a first occurrence. The stratigraphic ranges of dinoflagellate cyst species of the Hole 610A which used in this study are mentioned below:

Achomosphaera andalousiensis is recorded between (3.82-0.64 Ma), *Amiculosphaera umbraculum* (4.0-1.44 Ma), *Barssidinium pliogenicum* (3.4-2.9 Ma), *Bitectatodinium raedwaldii* (4.0-2.9 Ma), *Bitectatodinium tepikiense* (3.83-0.53 Ma), *Filisphaera filifera* (3.98-1.47 Ma), *Filisphaera microornata* (3.67-1.41 Ma), *Habibacysta tectata* (3.92-0.76 Ma), *Lingulodinium machaerophorum* (4.0-0.80 Ma), *Operculodinium ? eirikianum eirikianum* (3.94-2.16 Ma), *Pyxidinospis braboi* (3.15-2.57 Ma), *Selenopemphix dionaeacysta* (3.42-2.69 Ma), *Spiniferites elongatus* (1.35-0.73 Ma), *Spiniferites rubinus* (2.63-1.56 Ma), *Tectatodinium pellitum* (3.83-0.80 Ma) and *Trinovantedinium glorianum* (3.74-2.3 Ma). *Selenopemphix quanta* are recorded in on sample at 3.30 Ma in this hole. and *Selenopemphix quanta* are recordrd in one sample (3.30 Ma) in this Hole.

The examined interval of the ODP Hole 642B are extended from 5.83- to 3.08 Ma. *Amiculosphaera umbraculum*, *Habibacysta tectata*, *Lingulodinium machaerophorum*, *Nematosphaeropsis labyrinthus*, *Operculodinium? eirikianum* and

Spiniferites/Achomosphaera spp. indet. are present in all studied palynological samples and thus represented stratigraphic ranges between (5.83-3.08 Ma). *Operculodinium centrocarpum* (5.44-3.08 Ma), *Impagidinium paradoxum* (5.71-3.35 Ma), *Impagidinium aculeatum* (5.71-3.08 Ma), *Barssidinium pliogenicum* (5.83-3.60 Ma), *Bitectatodinium raedwaldii* (4.84-3.08 Ma), *Filisphaera filifera* (4.91-3.08 Ma), *Filisphaera microornata* (4.08-3.35 Ma), *Pyxidinopsis braboi* (5.53-3.35 Ma), *Spiniferites elongatus* (3.83-3.35 Ma), *Selenopemphix quanta* (5.83-4.81 Ma) and *Selenopemphix dionaeacysta*, *Tectatodinium pellitum*, *Trinovantedinium glorianum* (5.83- 3.35 Ma) and 4 specimens of *Bitectatodinium tepikiense* are present in on sample in age (3.83 Ma). Also the stratigraphic ranges of acritarch as *Cymatiosphaera ?invaginata* and *Nannobarbophora walldalei* play a role in this study whereas they have long ranges in these two sites which are mentioned above.

The ODP Hole 907A has 3 important species which are also common in the present study. The stratigraphic range of *Habibacysta tectata* are long and extended from the base of the Hole 907A (14.2 Ma) to Late Pliocene (2.78 Ma). *Operculodinium ? eirikianum* (13.1-4.45 Ma) and the first occurrence of *Labyrinthodinium truncatum* are recorded in this site on its base (14.2 Ma) and extended up to (8.44 Ma).

The ocean drill site in the eastern North Sea Basin (Denmark) are very long as restricted between (25.0 Ma-present day). The stratigraphic ranges of species are very long such as *Amiculosphaera umbraculum*, *Achomosphaera andalousiensis* and *Barssidinium pliogenicum*, their ranges are respectively (11.4-1.82 Ma), (13.2 Ma- present day) and (\geq 25.0-2.6 Ma). *Labyrinthodinium truncatum* (15.97-7.5 Ma) and the low occurrence of *Bitectatodinium tepikiense* on (2.2 Ma) and extends to present day.

(Figure 15) shows the compilation of significant stratigraphic ranges of these all abovementioned species. The principle of this compilation is taking the highest- and lowest occurrence of these recorded species . The figure represents also the compilation of highest occurrence for several extinct dinoflagellate cyst species in the Early Pliocene such as; The highest occurrence of *Batiacasphaera minuta*, *Corrudinium devemaliae*, *Echinidinium euaxum*, *Operculodinium tegillatum* and *Pyxidinopsis vesiculata* have been recorded respectively 3.83, 3.90, 3.98, 3.70 and 3.92 Ma at DSDP Site 610. *Bitectatodinium serratum* has highest occurrence in 3.60 at ODP Site 642 and in Ocean

Drill Site in Denmark, *Reticulatosphaera actinocoronata* has recorded 4.20 Ma as highest occurrence.

6.1.3. Age of the studied interval at Well 34/8-A-33H (1141.65-1125.65 m)

According to the biostratigraphic ranges of selected dinoflagellate cyst and acritarch assemblages, the oldest boundary of this unit is estimated depending upon the lowest occurrence of *Bitectatodinium tepikiense* and *Trinovantidium glorianum*. This age is in addition supported by the absence of typical early Pliocene species such as *Batiacasphaera minuta*, *Corrudinium devernaliae*, *Echinidinium euaxum*, *Operculodinium tegillatum*, *Pyxidinopsis vesiculata* and *Reticulatosphaera actinocoronata*, where the highest occurrences of these species was seen at respectively 3.83, 3.90, 3.98, 3.70, 3.92 and 4.20 Ma.

The highest occurrence of *Barssidinium pliogenicum*, *Pyxidinopsis braboi*, *Selenopemphix dioneacysta* and *Lavradosphaera canalis*, seen at respectively 2.65, 2.60, 2.70 and 2.6 Ma, and the lowest occurrence of *Spiniferites rubinus*, seen at 2.6 Ma, have been utilized to determine the upper boundary of the age of the section.

Based on the dinoflagellate cysts and acritarchs analysis, the age of the sedimentary unit in the Tampen area “Utsira Formation” can be considered to be from 3.7 to 2.6 Ma, i.e. Late Pliocene (Piacenzian).

6.2. Palaeoenvironment

Dinoflagellate cysts are considered to be sensitive palaeoenvironmental indicators (e.g. Downie et al., 1971; Mudie and Harland, 1996 and Wall et al., 1977).

Palaeoenvironmental changes were characterized by Versteegh (1994) & De Schepper (2006), by means of various palaeoecological indices based on the composition of dinocyst assemblages.

Some Pliocene dinoflagellate cyst such as *Achomosphaera andalousiensis*, *Lingulodinium machaerophorum*, *Operculodinium israelianum* are still extant in the present oceans. Knowledge of the ecology of those species and their distribution patterns can be indicative of the palaeoecological conditions for the dinoflagellate cysts in Pliocene sediments. The presence of preserved pollen and spores in the marine sediments, also provide informations about contemporaneous changes in terrestrial environments (Versteegh, 1994).

To acquire better understanding of palaeoenvironments, certain indices were derived from the data (see chapter 4 in methods). Those curves comprise the ratio Sporomorphs / Dinoflagellate cysts (S/D), Gonyaulacoid / Protoperidinioid dinoflagellate cysts (G/P), warm / cold water indicating dinoflagellate cysts (W/C), Inner neritic / Outer neritic dinoflagellate cysts (IN/ON) and Neritic / Oceanic dinoflagellate cysts (N/O).

The S/D index (Figure 16) shows fluctuations between 0.46 and 0.09 throughout the well, initially dropping sharply from the highest value at the deepest part of the core, to 0.23 at depth 1141,18 m, before peaking up again to 0.42 at depth 1140.27 m and then gradually decreasing to lowermost value, halfway up along the core. It then shows further fluctuation, with a couple of peaks, before dropping again to 0.14 at depth 1125,65 m.

The S/D curve indicates therefore major marine influence with little continental influence, reflecting deepening of the environment. The curve decreases from the base to the top of the core (i.e. from proximal towards distal setting), indicating a neritic environment.

The W/C index is an important index describing sea surface temperature (SST). In this context, dinoflagellate cysts provide an interesting avenue for SST reconstruction. A general warming trend is recorded in the W/C curve (Figure 17), with a couple cooler intervals observed at 1138.76 m and at 1132.63 m. The cool intervals are demonstrated in the lower part of the well, by the higher percentage of *Bitectatodinium tepikiense*, and in the middle part of the well, by the presence of *Filisphaera filifera*. The warm species such as *Operculodinium? eirikianum*, *Bitectatodinium raedwaldii*, *Lingulodinium machaerophorum*, are dominant elements throughout the well. The latter increasing in abundance toward the top of the core, with contrasting reduction of *Bitectatodinium*

tepikiense from the base to the top of the core. This leads to the conclusion of temperate to warm conditions for the greater part of the well.

The IN/ON ratio indicates an outer neritic environment throughout the well, interrupted by a peak in the middle of the core, indicating inner neritic influence (Figure 18), due to the abundance of *Operculodinium israelianum* at 1133.67 m. Another single and smaller peak of inner neritic influence is also seen at the base of the core, due to the abundance of *Lingulodinium machaerophorum* at 1140.27 m.

The G/P ratio indicates productivity in distal settings (Figure 19). The abundance of Gonyaulacoids relative to Protoperidinioids, reflects oligotrophic stable marine environment. The curve has predominantly high values, increasing from 0.65 at the base of the core to 0.95 at the top of the core. Proximal influence is observed with values of 0.72 at depth 1139.99 m, 0.65 at depth 1133.28 m and 0.60 at depth 1129.28 m, and can be attributed to the abundance of *Brigantidinium* sp., *Selenopemphix quanta* and *Trinovantidinium* sp.

The sediment section of the studied interval may have been deposited in outer neritic under warm to temperate conditions.

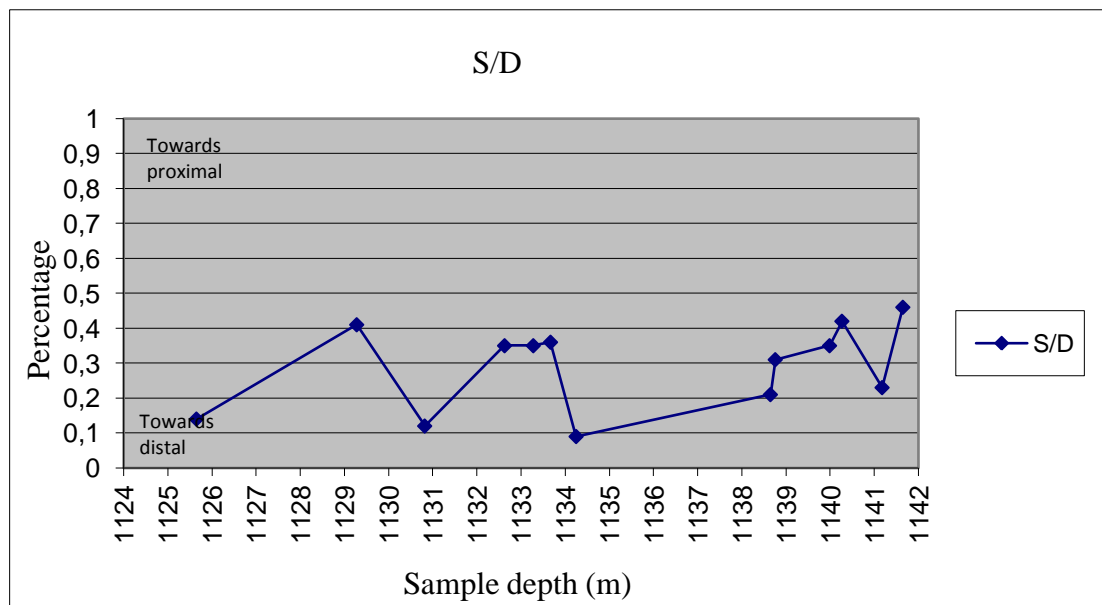


Figure 16. The S/D ratio = $nS/(nS+nD)$, means sporomorphs versus dinoflagellate cysts, reflects continental- and marine influences.

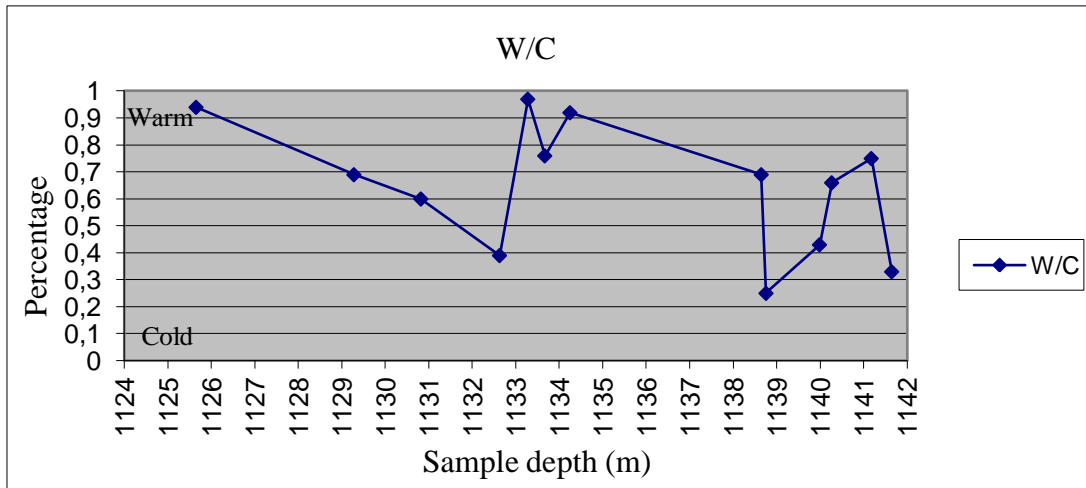


Figure 17. The temperature W/C ratio = $nW/(nW+nC)$, means warm water versus cold water diatom species, indicates sea surface temperature.

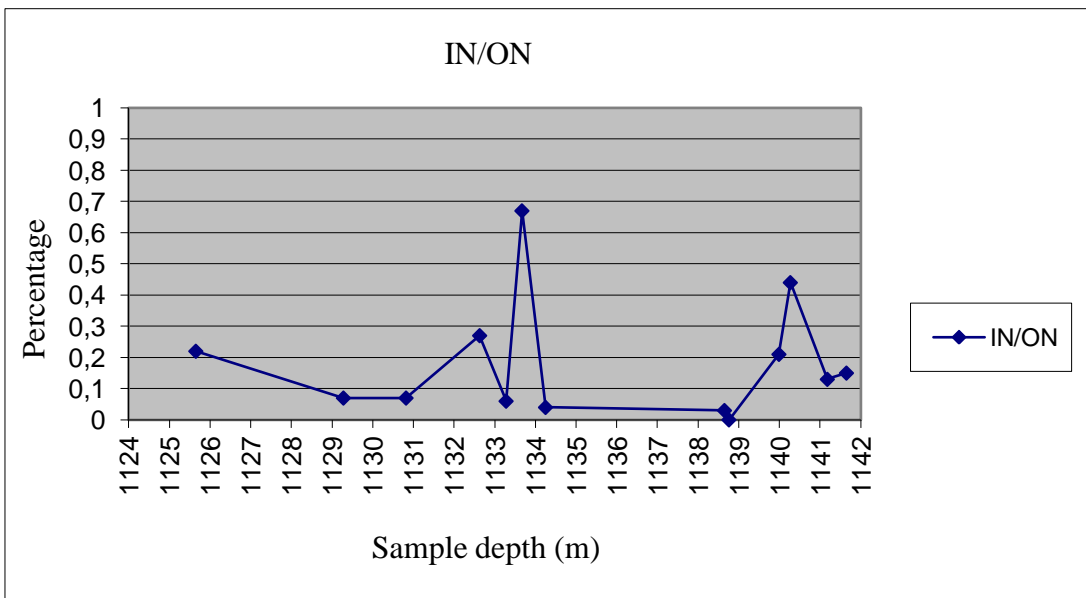


Figure 18. The IN/ON = $nIN/(nIN + nON)$ reflects inner neritic influence versus outer neritic influence.

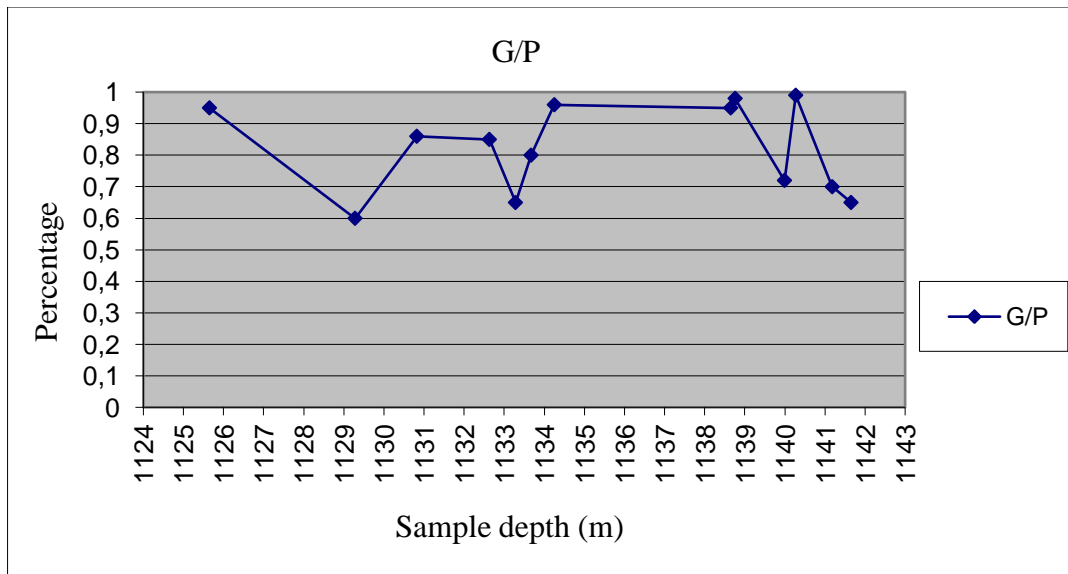


Figure 19. The G/P ratio = $nG/(nG+nP)$ indicates productivity.

6.3. Comparison of the age and palaeoenvironment of the studied Well 34/8-A-33H with the Utsira Formation in the pervious studies

Based on stratigraphical discussion, mentioned above, the age of the sediments of the Utsira Formation in this study is estimated to be Late Pliocene (Piacenzian). This age is younger than previously estimated early Pliocene age for the Utsira Formation in well 15/9-A23 (Piasecki et al., 2002). The estimated age in well 15/9-A23, which is situated in the Sleipner area of the northern North Sea, had depended on the presence of species such as *Hystrichokolpoma rigaudiae* and *Reticulosphaera actinocoronata*, which are reported to range into the Lower Pliocene, whereas the age in this study is considered younger due to the absence of those species in the studied interval. The well 34/8-A-33H indicates that the Tampen area “Utsira Formation” is from higher up in the Utsira Formation compared to the interval studied by Piasecki (well 15/9-A23), possibly near the uppermost boundary of the Utsira Formation. The age of Nordland group mudstone (well 15/9-A-11), which directly overlies the Utsira Formation, was estimated to be early Pleistocene (Gelasian), (Head et al., 2004), depending on dinoflagellate cysts, pollen and spores, foraminiferal and stable isotopic analyses. Our studied interval is older in age than the Nordland group mudstone, and this supports the conclusion that the Tampen area is from higher up in the Utsira Formation.

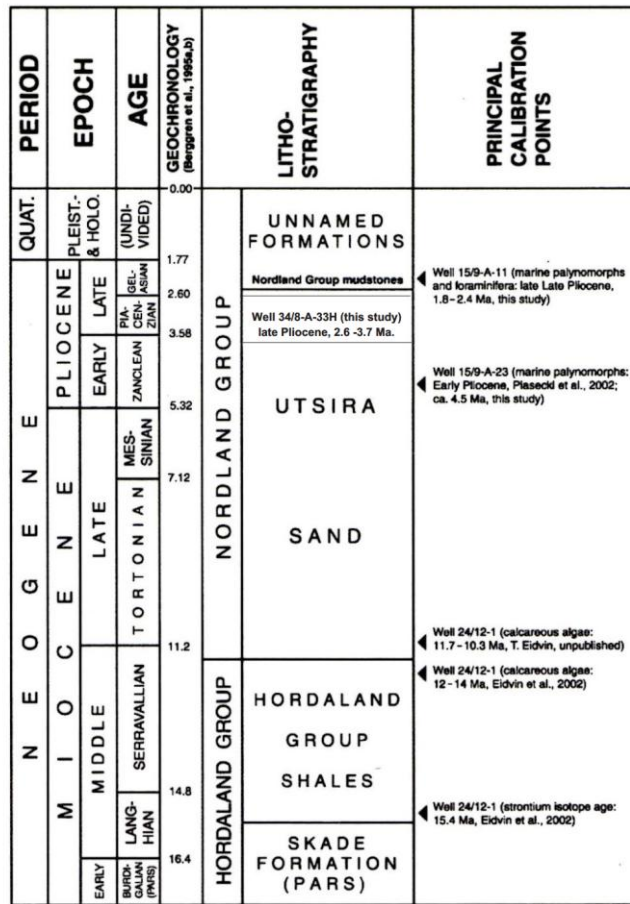


Figure 20. A diagram representing the Nordland Group and the uppermost Hordaland Group in the Viking Graben, northern North Sea. Comparison of the age of the studied well 34/8-A-33H with the Utsira Formation in pervious studies, Well 15/9-A-23 (Piasecki et al., 2002) and Well 15/9-A-11 (Head et al., 2004).

The dinoflagellate cyst assemblages indicate in this study, a warm to temperate outer neritic environment, while the succession in the well 15/9-A23 (Piasecki et al., 2002), is distally deposited with some oceanic influence, possibly during a period of cooling climate and near the transition from temperate to sub-arctic climate. In the well 15/9-A-11, the foraminiferal assemblages at 913.10 m, indicates warm climatic conditions, while abundance of the cool-tolerant dinoflagellate cysts *Filisphaera filifera* and *Habibacysta tectata* at 906.00 m alone with evidence of pollen and foraminifera points to evidence of deposition during a cool phase of the Gelasian, well 15/9-A-11 (Head et al., 2004).

7. CONCLUSIONS

The studied interval between 1125.65 m and 1141.65 m of the Well 34/8-A-33H, is considered to be Late Pliocene, from 3.7 to not higher than 2.6 Ma in age. This study is based mainly on the stratigraphy of the dinoflagellate cyst species and acritarchs, correlated to the stratigraphical range for the reference sections in the North Atlantic region and adjacent seas .

The organic-walled dinoflagellate cysts and the presence of preserved pollen and spores in the marine sediments have attributed considerably to the interpretation of palaeoenvironment. All palaeoecological indices which were utilized in this study indicated distal outer neritic environment, deposited possibly during a period of warm climate in the Late Pliocene, though estimations could be partially affected by the fact that the Pliocene was a generally warmer epoch compared to the present time (Salzmann et al., 2011). The age of this study is younger than the age in the Well 15/9-A 23, (Piasecki et al., 2002), which was estimated as Early Pliocene while older than Gelasian in the Well 15/9-A-11, and this can be explained by the present sedimentary section being located in the uppermost part of Utsira Formation.

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__ <http://nhm2.uio.no/norges/litho/rogaland.php>.

Depth (m)	I125.65	I129.28	I130.82	I132.63	I133.28	I133.67	I134.25	I138.65	I138.76	I139.99	I140.27	I141.18	I141.65
Core	34/8-A-33H	34/8-A-33H	34/8-A-33H	34/8-A-33H	34/8-A-33H	34/8-A-33H	34/8-A-33H	34/8-A-33H	34/8-A-33H	34/8-A-33H	34/8-A-33H	34/8-A-33H	34/8-A-33H
Lycopodium	15	110	78	108	92	68	44	18	20	18	89	44	68
Weight (g)	20	20	20	17	15	20	20	25	11	20	25	20	20
sidew	1708	1708	1708	1708	1708	1708	1708	1708	1708	1708	1708	1708	1708
number of lycop tablets	1	1	1	1	1	1	1	1	1	1	1	1	1
no lycop per tablet	18583	18583	18583	18583	18583	18583	18583	18583	18583	18583	18583	18583	18583
Total dinoflagellate cysts counted	449	253	242	161	401	362	611	507	342	244	342	487	329
Total dinoflagellate cyst species	14	14	19	23	19	23	26	15	15	18	22	22	23
Total acritarchs counted	10			2			14		1	7	45	23	32
Dinoflagellate cyst concentration (cyst/g)	2781	2137	2906	1629	5399	4946	12902	20936	28888	10076	2856	10284	4495
Error bar (cyst/g)	773	313	463	252	797	796	2337	5378	7157	2629	429	1875	727
Acritarch concentration (acritarch/g)	619			20			295		84	289	375	485	437
Error bar (acritarch/g)	259			14			94		86	131	77	133	102
Total pollen and spores counted	74	178	35	87	222	212	66	136	157	151	251	152	289
Pollen spore concentration	2911	541	214	101	2128	2139	880	450	7349	360	2225	880	2405
Error bar (pollen/g)	867	82	48	17	328	357	189	120	1871	96	342	171	392
<i>Achomosphaera andaloustenensis subsp.andaloustenensis</i>		6	12	2	1		19	13	20		5	1	14
<i>Amiculosphaera umbraculum</i>	2		65	7	35	8	23	44	7	1	4	11	82
<i>Barrasidinium plicocenicum</i>						2							1
<i>Bitectatodinium raedwaldii</i>	14		9	13		13	38	6	9	4	74	21	28
<i>Bitectatodinium tepikensi/raedwaldii</i>				1			4				5		
<i>Bitectatodinium tepikense</i>	4	7	18	18		45	22	38	84	54	69	42	73
<i>Brigantidinium cartiaceum</i>							1						
<i>Brigantidinium simplex</i>							2						
<i>Brigantidinium</i> sp.										12		2	1
<i>Filipsphaera filifera</i>			2	9	4	6		6	6	3		1	
<i>Filipsphaera microornata</i>				7	8	12	26	2	2		10	1	
<i>Habibocysta ?tectata</i>							1						
<i>Impagidinium aculeatum</i>												2	
<i>Impagidinium paraolaxum</i>	1												
<i>Imvertocysta/Amiculosphaera</i> spp.indet	1		11	22	13	2		28	15		3		
<i>Labyrinthodinium truncatum</i>			3								3		
<i>Lejeunecysta marieae</i>		1											
<i>Lejeunecysta sabrine</i>													1
<i>Lejeunecysta</i> sp.		2	3	4	4	5	2	1	1	3			
<i>Lingulodinium machaerophorum</i>	68	8	4		2	5	1	2		6	64	1	1
<i>Nematosphaeropsis labyrinthus</i>							3						
<i>Nematosphaeropsis rigida</i>	4						5			2	3	1	
<i>Operculodinium ? eirikianum</i>	9	8	15	+	159	106	216	76	23	33	+	104	+
<i>Operculodinium centrocarpum</i>	78	16	13	35	11	26	22	202	95	45	+	120	+
<i>Operculodinium israelianum/centrocarpum</i>				2		6	124				4		
<i>Pyxidinoopsis israelianum</i>				+	+	40	30			1			2
<i>Pyxidinoopsis braboi</i>						+							

<i>Reworked dimorflagellate</i>	19	7	+	3	76	35	5	14	5	32	3	9	48	
<i>Round brown cyst</i>		86		14			10		3			86	1	
<i>Selenopemphix armata</i>		4	11	4	18	3	2	7		11		3	14	
<i>Selenopemphix diomeacysta</i>		8			3									
<i>Selenopemphix quanta</i>					5	10		2				33	3	
<i>Selenopemphix septum</i> sp.			9	1										
<i>Selenopemphix</i> sp.	2			2			1				3			
<i>Spiniferites elongatus</i>														
<i>Spiniferites ramsons</i>		2	5	7	21	10	12	58	21		5	4	10	
<i>Spiniferites rubinus</i>		48	56		21	9	24	8	15	13	50	28	21	
<i>Spiniferites</i> spp.	216	50	3	5		3	14	8	9	13	24		5	
<i>Spiniferites/Achomosphaera</i> spp. indet.	29		2	2	1			1		1	1	4	6	
<i>Tectatodinium pellitum</i>	2													
<i>Trinovantedinium glorianum</i>			1		14	8	2			1		7	1	
<i>Trinovantedinium papulum</i> sp.				2	5	1			9			3	6	
<i>Trinovantedinium</i> sp.				1		7						1	1	
<i>Trinovantedinium variabile</i>							2							
<i>Tuberculodinium vancamppoe</i>														
<i>Acritarchs</i>														
<i>Cymatiosphaera ? invaginata</i>	8			2			14						15	
<i>Nannobarbophora walldalei</i>										7	33	17	13	
<i>Lavradosphaera canalis/crista</i> spp.											12	1	4	
<i>Cyclospiella</i> sp.									1			4		
<i>Small spiny acritarch</i>	2													
<i>Other Palynomorphs</i>														
<i>Microforaminifera lining</i>	159		30	80	125	8	312	14	20	80	14	199	218	
<i>Lycopodium</i>	15	110	78	108	92	68	44	18	20	18	89	44	68	
<i>Bistacate</i>	47	50			137	91		73	85	117	159	88	170	
<i>Monolete spore</i>	20	107	16	53	14	13	38	42	50	9	16	19	59	
<i>Trilete spore</i>	4			24	44	44	21	8	7	14	19	13	29	
<i>Fern spore</i>	1							8	11	2				
<i>Anemataceous fern spore</i>		7	1		6	8		2		2	14	9	8	
<i>Schizaeaceous fern spore</i>						2								
<i>Invertebrate egg (long process)</i>		6	8	5	6	22	7		1	3	6	7	3	
<i>Tetrad pollen</i>		6		2										
<i>Triporate pollen</i>					1									
<i>Tricolpate pollen</i>														
<i>Scolecodont fern</i>								3	2	3	1	6	17	
<i>Tsuga</i>		2	8	3	14	31					20	7	3	
<i>Monoporate pollen</i>			2			1					6	3		
<i>Neogenispore</i>											6	7		
<i>Invertebrate egg (long process)</i>	2		2			1					6	3		

plate 1.

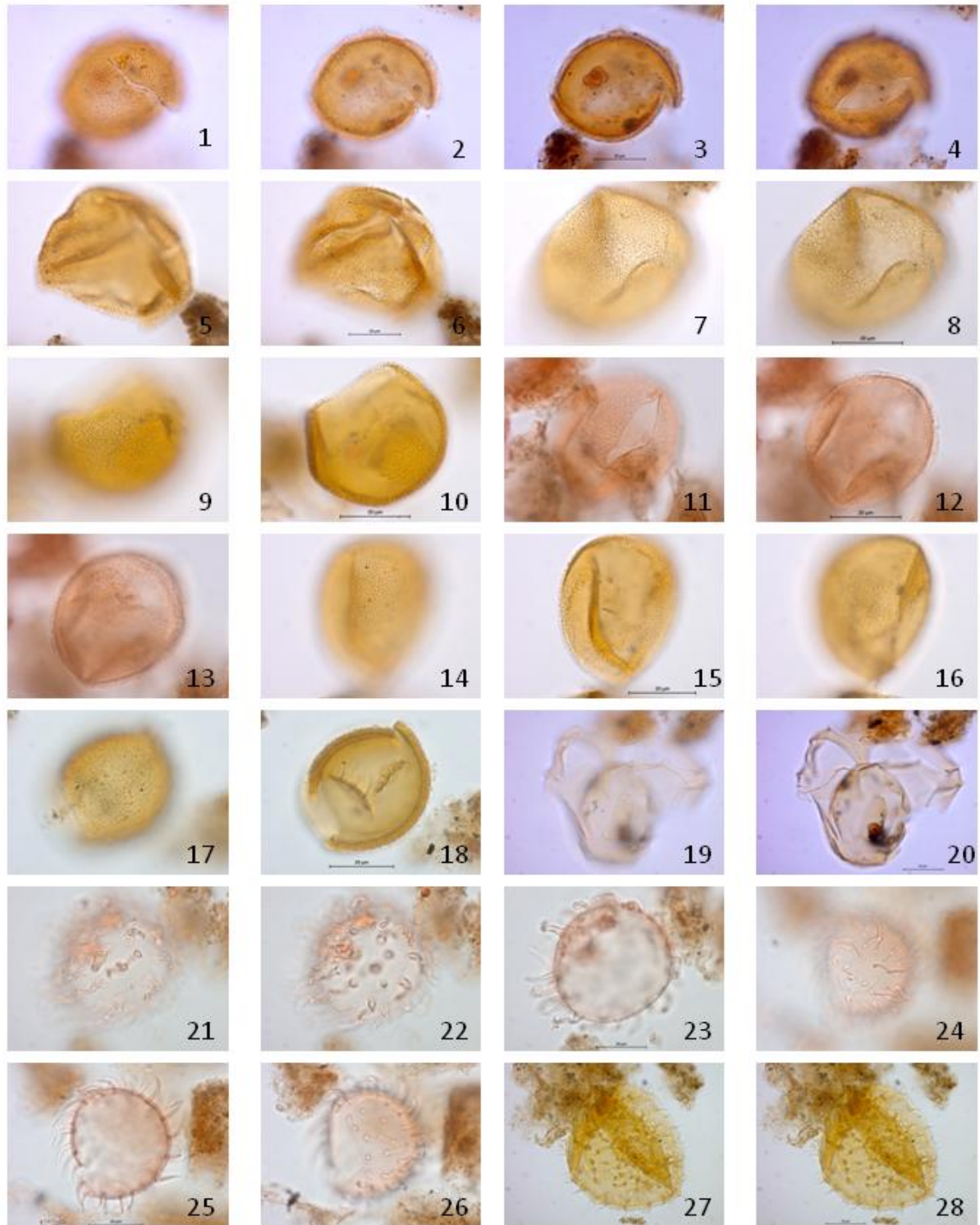


Plate 1.

(1-4) *Bitectatodinium raedwaldii* Head 1997. Sample: 1141.65, England finder reference: Q40/3. High focus on ventral surface shows characteristic wall structure (1). Upper to lower focus showing long luxuria (2). Maximam diameter at mid focus (3). Low focus on dorsal surface showing 2p archeopyle (4).

(4-6) *Bitectatodinium tepikiense* Wilson 1973. Sample: 1133.28, England finder reference: O45/0. High focus shows erect, suberect or branched luxuria and characteristic wall structure (5). Mid focus, maximam diameter (6).

(7-8) *Filisphaera microornata* Head et al., 1989; Head, 1994. Sample: 1133.28, England finder reference: V53/2. High focus shows apical view (7). Mid focus (8).

(9-10) *Filisphaera filifera* Bujak 1984, Head, 1994. Sample: 1133.28, England finder reference: R48/0. High focus on ventral surface shows a polygonal microreticulum (9). Lower focus showing high luxuria, archeopyle at lower right of cyst and maximam diameter (10).

(11-13) *Habibacysta tectata* Head, Norris and Mudie 1989. Sample: 1140.27, England finder reference: P43/4. High focus on uncertain surface (11). Mid focus (12). Low focus showing archeopyle at upper left of cyst (dorsal surface) (13).

(14-16) *Pyxidinosopsis braboi* De Schepper et al., 2004. sample: 1133.28, England finder reference: S56/3. High focus (14). Upper to lower focus (mid focus), maximam diameter (15). Low focus (16).

(17-18) *Tectatodinium pellitum* Wall, 1967. Sample: 1141.65, England finder reference: V46/4. High focus (17). Upper to lower focus showing something, probably a part of another dinoflagellate in the middle of the cyst and showing very thick irregular perforate lamellae (18).

(19-20) *Amiculosphaera umbraculum* Harland, 1979b. Sample: 1141.18, England finder reference: P45/3. Dorsal view at high focus (19). Mid focus showing a characteristic fanel shape on the apex of cyst (20).

(21-23) *Lingulodinium machaerophorum* Deflandre and Cookson, 1955. Sample: 1140.27, England finder reference: B36/3. Uncertain view at high focus showing hollow type processes (21). Mid focus (22). Low focus, maximam diameter, hollow processes with granulate ends (23).

(24-26) *Operculodinium? eirikianum* Head et al., 1989b; Head 1997. Sample: 1140.27, England finder reference: C43/3. High focus (24). Mid focus with maximam diameter

(25). Low focus on right dorso-ventral view, showing archeopyle in the left of the cyst
(26).

(27-28) *Operculodinium centrocarpum/israelianum* Deflandre and Cookson, 1955; Wall, 1967/ Rossignol, 1962; Wall, 1967. Sample: 1134.25, England finder reference: C57/2. High focus with maximum diameter (27, 28).

Plate 2.

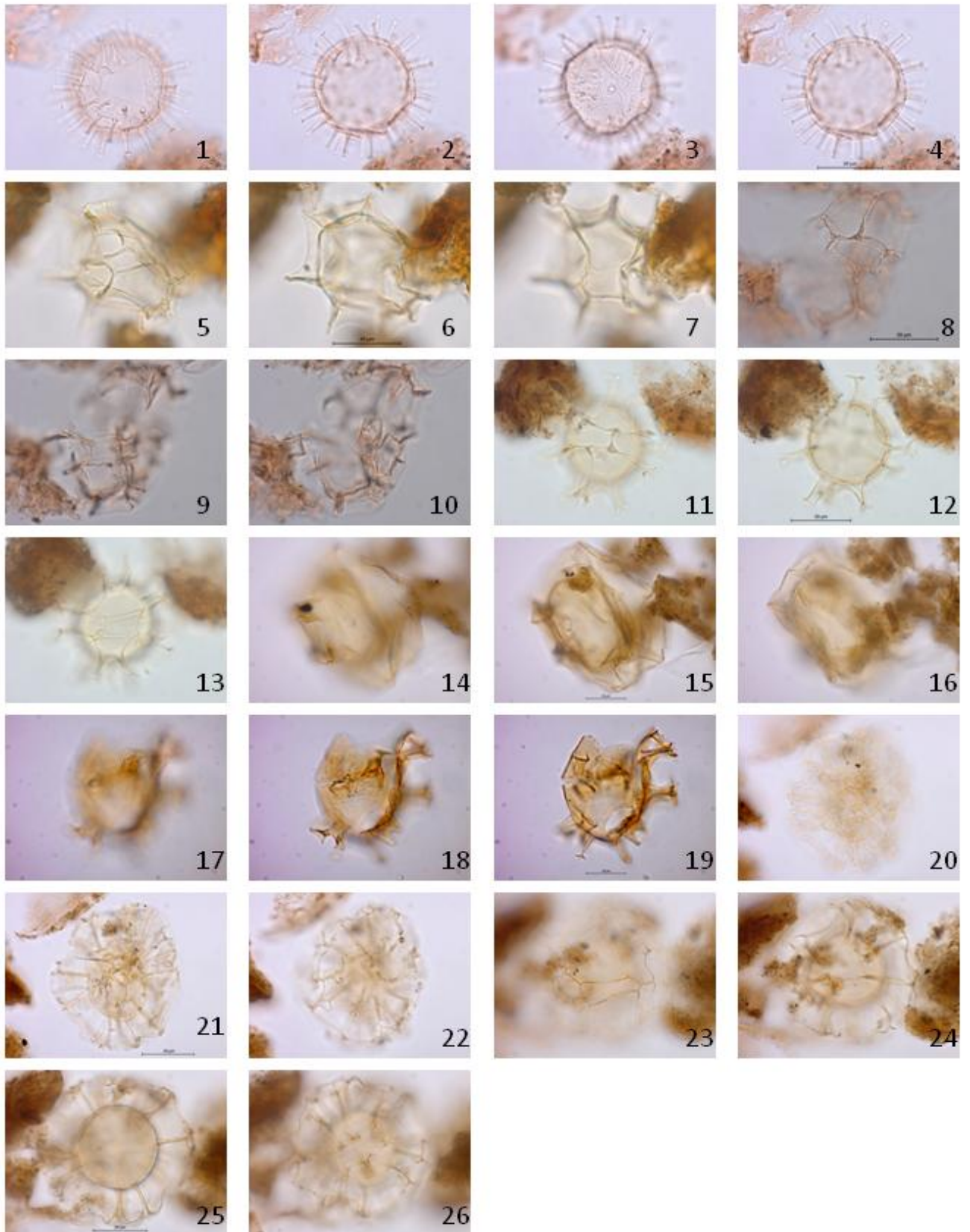


Plate 2.

(1-4) *Operculodinium centrocarpum* Deflandre and Cookson, 1955; Wall, 1967. Sample: 1140.27, England finder reference: C57/2. Dorsal view at high focus (1). Mid to lower focus showing solid processes (2,4). Low focus on ventral view(3).

(5-7) *Impagidinium aculeatum* Wall, 1967; Lentin and Williams, 1981. Sample: 1141.18, England finder reference: S37/0. High focus (5). Mid focus showing sharp edges of cyst (6). Low focus (7).

(8-10) *Impagidinium paradoxum* Wall, 1967; Stover and Evitt, 1978. Sample: 1140.27, England finder reference: O54/0. High focus showing tabulation (8). Mid focus showing short edges (9). Mid to lower focus (10).

(11-13) *Spiniferites spp.* (*mirabilis*)(*bentori*) Rossignol, 1964; (*rhizophorus*) Head and Westphal 1999. Sample: 1141.65, England finder reference: J51/0. High focus on right lateral- dorsal view (11). Mid focus (12). Low focus on lateral-ventral view (13).

(14-16) *Spiniferites rubinus* Rossignol, 1962, 1964. Sample: 1134.25, England finder reference: J59/0. High focus (14). Upper to lower focus (15). Dorsal view at low focus (16).

(17-19) *Achomosphaera andalouisiensis subsp.andalouisiensis* Jan du Chéne, 1977, Jan du Chéne and Londeix, 1988. Sample: 1134.25, England finder reference: M39/0. High focus (17). Mid focus (18). Low focus on lateral-dorsal view (19).

(20-22) *Nematosphaeropsis labyrinthus* Ostenfeld, 1903 and Reid, 1974. Sample: 1125.65, England finder reference: D54/0. High focus on (20). Mid focus (21). Low focus on (22).

(23-26) *Nematosphaeropsis rigida* Wrenn, 1988; Head and Westphal, 1999. Sample: 1125.65, England finder reference: M44/3. High focus on trabeculae (23). Upper to lower focus on dorsal view (24). Mid focus (25). Low focus on ventral view, focus on solid processes(26).

Plate 3.

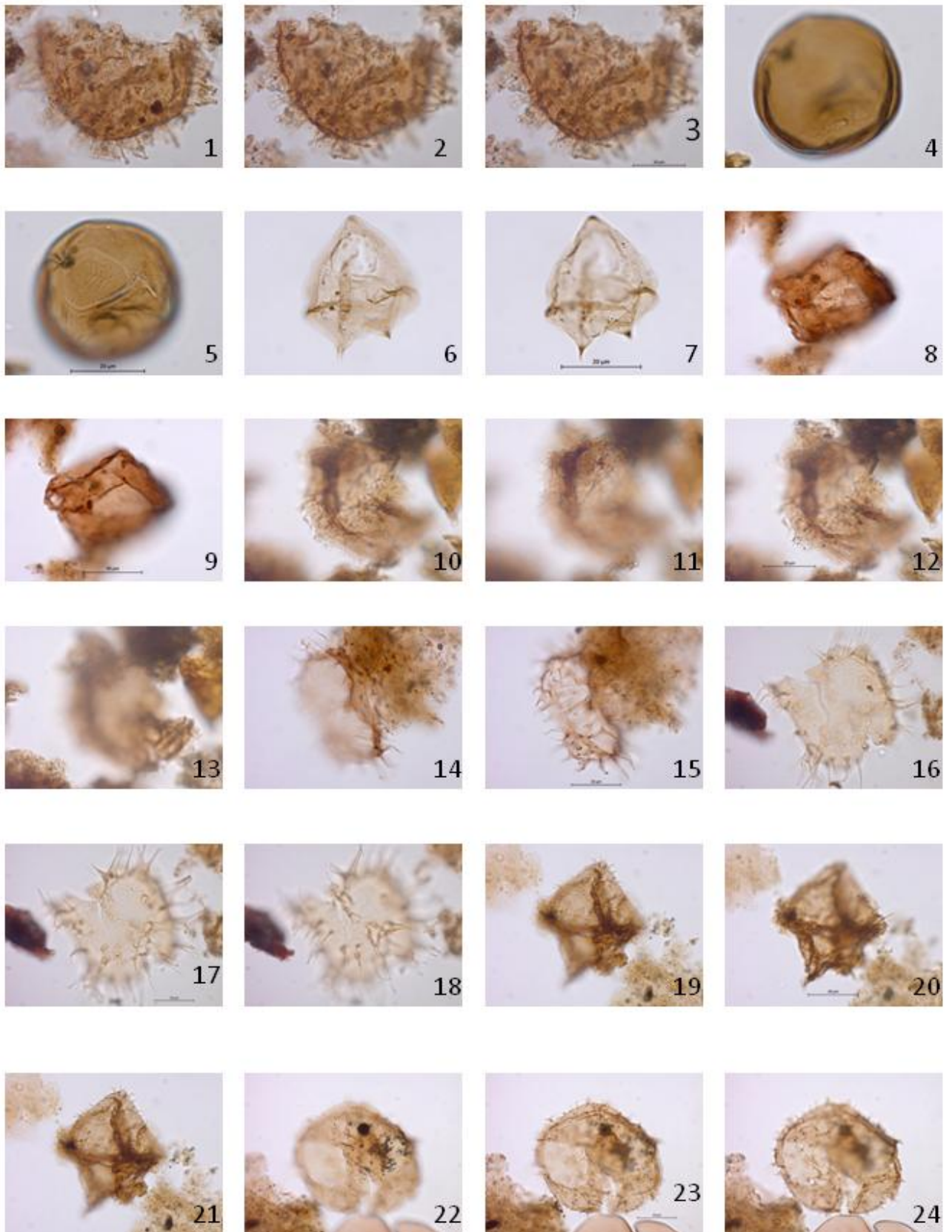


Plate 3.

(1-3) *Barssidinium pliogenicum* Head, 1993; Head, 1994. Sample: 1141.65, England finder reference: F58/3. High focus on uncertain surface of big brown cyst (1). Mid focus showing hollow, closed distally, generally unbranched processes with annular thickening (2,3).

(4-5) *Brigantidium simplex* Wall, 1965b; Lentin and Williams, 1993. Sample: 1134.25, England finder reference: T46/4. High focus on ventral smooth surface (4). Mid to lower focus showing dorsal surface with one monoplacoid archeopyle (5).

(6-7) *Lejeunecysta marieae* Harland et al., 1991; Lentin and Williams, 1993. Sample: 1129.28, England finder reference: G41/1. High focus on dorsal view, showing 2a archeopyle with antapical horns (6). Mid focus (7).

(8-9) *Lejeunecysta Sabrina* Reid, 1977; Bujak, 1984. Sample: 1141.65, England finder reference: W49/3. High focus on dorsal surface (8). Mid focus (9).

(10-13) *Selenopemphix brevispinosa* Head et al., 1989c. Sample: 1133.67, England finder reference: N61/0. High focus (10,12). Mid focus (11). Low focus (13).

(14-15) *Selenopemphix quanta* Bradford, 1975. Sample: 1141.65, England finder reference: D42/0. High focus (14). Upper to lower focus (15).

(16-18) *Trinovantedinium variabile* Bujak, 1984. Sample: 1141.65, England finder reference: F37/3. High focus showing some processes branched (16). Upper to lower focus showing granular surface(17). Mid to low focus (18).

(19-21) *Trinovantedinium glorianum* Head et al., 1989b. Sample: 1139.33, England finder reference: U35/0. High focus, dorsal to lateral view (19,21). Mid focus (20).

(22-24) *Trinovantedinium papula* Verteuil and Norris, 1992. Sample: 1141.18, England finder reference: S56/3. High focus, dorsal to lateral view (22). Mid focus showing archeopyle (23). Mid to lower focus (24).

Plate 4.

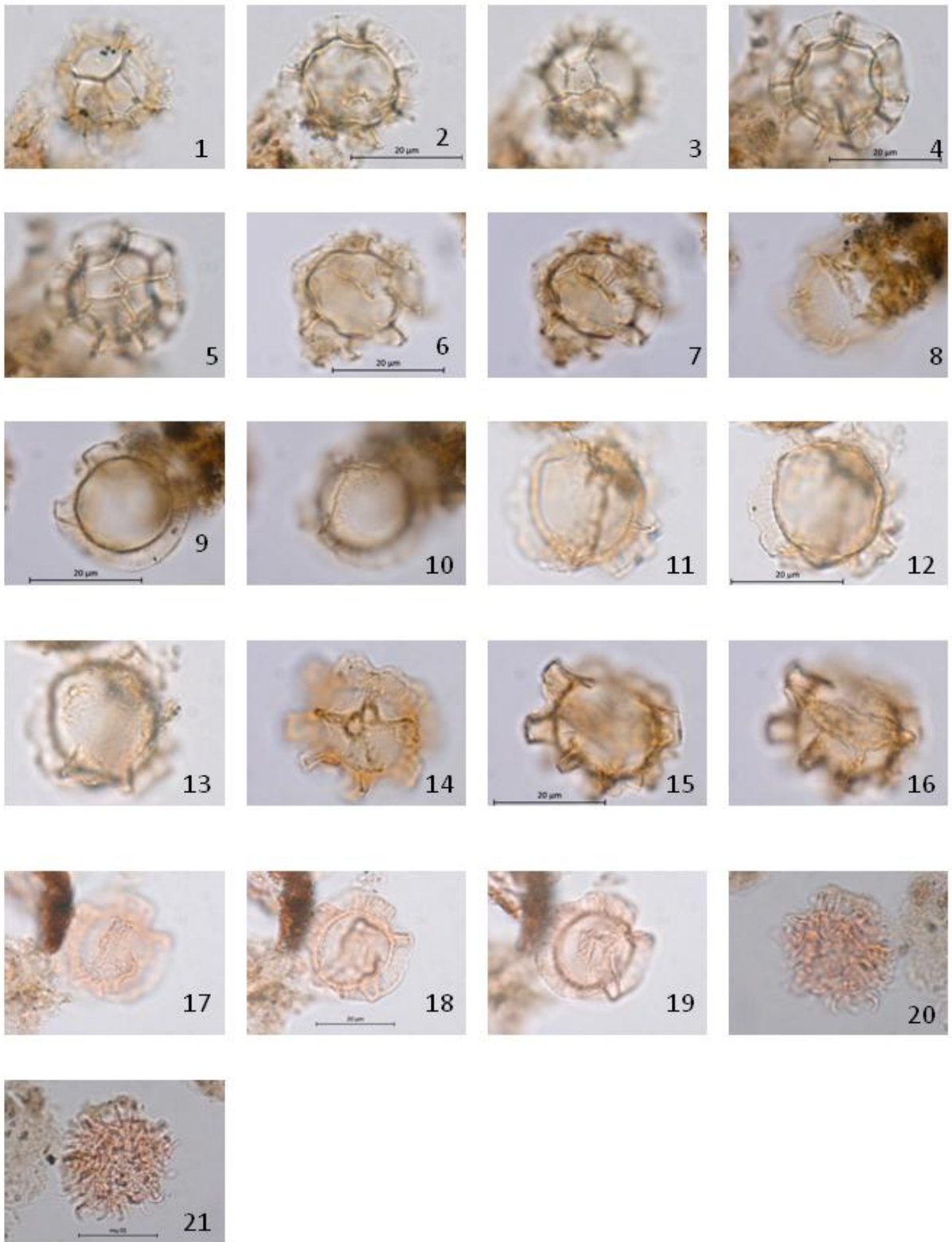


Plate 4.

(1-7) *Cymatiosphaera? invaginata* Head et al., 1989. (1-3) sample: 1141.65, England finder reference: D48/4. High focus (1). Mid focus (2). Low focus (3). (4-5) Sample: 1141.65, England finder reference: F52/4. High focus (4). Upper to lower focus showing polygonal tabulation (5). (6-7) Sample: 1134.63, England finder reference: H60/4. High focus (6). Lower focus (7).

(8-10) *Lavradosphaera crista* De Schepper and Head 2008b. Sample: 1134.63, England finder reference: L60/0. High focus shows straight intersecting crests (8). Mid focus, maximum diameter (9). Low focus on apical field shows polygonal pylome (10).

(11-13) *Lavradosphaera crista* De Schepper and Head 2008b. Sample: 1141.65, England finder reference: X37/1. High focus, apical surface showing rounded to polygonal pylome (11). Mid focus (12). Low focus (13). The focus showing the outer layer which are formed crest (12, 13).

(14-16) *Lavradosphaera crista/canalis* Sample: 1141.65, England finder reference: Q42/3. High focus (14). Mid focus (15). Low focus (16).

(17-19) *Lavradosphaera cf. canalis* De Schepper and Head, 2013; De Schepper and Head, (2008a). Sample: 1140.27, England finder reference: H59/2. High focus, apical view showing operculum within vesicle (17). Mid focus showing U-shaped to V-shaped channels at the cross section (18). Low focus (19).

(20-21) *Nannobrabophora walldalei* Head, 1996. Sample: 1140.27, England finder reference: B64/3. Uncertain view at high focus (20), upper to lower focus (21).

Listing of all recorded and mentioned dinoflagellate cyst species

- Achomosphaera andalouisiensis* subsp. *andalouisiensis* Jan du Chêne, 1977
- Amiculosphaera umbraculum* Harland, 1979
- Barssidinium pliocenicum* (Head, 1993) Head, 1994
- Bitectatodinium raedwaldii* Head, 1997
- Bitectatodinium tepikiense* Wilson, 1973
- Brigantedinium* (Reid 1977) Lentin and Williams 1993
- Filisphaera filifera* subsp. *filifera* (Bujak, 1984) Head, 1994
- Filisphaera microornata* (Head et al., 1989) Head, 1994
- Habibacysta tectata* Head, Norris and Mudie, 1989
- Impagidinium aculeatum* (Wall, 1967) Lentin and Williams, 1981.
- Impagidinium paradoxum* (Wall, 1967) Stover and Evitt, 1978
- Labyrinthus* (Ostenfeld, 1903) Reid, 1974
- machaerophorum* (Deflandre and Cookson, 1955) Wall, 1967
- Operculodinium centrocarpum* sensu Wall and Dale, 1966
- Operculodinium israelianum* Rossignol, 1962
- Operculodinium? eirikianum* Head et al., 1989
- Pyxidopsis braboi* De Schepper et al., 2004
- Selenopemphix armata* Bujak et al., 1980
- Selenopemphix dionaeacysta* Head et al., 1989
- Selenopemphix quanta* (Bradford, 1975) Matsouka, 1985
- Spiniferites ramsous* (Ehrenberg, 1838) Mantell, 1854
- Spiniferites rubinus* (Rossignol, 1962, 1964)
- Spiniferitus elongatus* Reid, 1974
- Tectatodinium pellitum* Wall, 1967
- Trinovantedinium glorianum* (Head et al., 1989) DeVerteuil and Norris, 1992
- Tuberculodinium vancampoae* (Rossignol, 1962) Wall, 1967
- Lejeunecysta marieae* (Harland in Harland et al., 1991)
- Lejeunecysta sabrine* Reid, 1977
- Lingulodinium machaerophorum* (Deflandre and Cookson, 1955) Wall, 1967
- Nematosphaeropsis labyrinthus* (Ostenfeld, 1903) Reid, 1974

Nematosphaeropsis rigida Wrenn, 1988

Trinovantedinium papula DeVerteuil and Norris, 1992

Trinovantedinium variabile (Bujak, 1984)

Trionvantedinium Sabrina Reid, 1977

Recorded acritarchs

Cymatiosphaera? invaginata Head, Norris and Mudie, 1989

Nannobarbophora walldalei Head, 1996

Lavradosphaera cf. canalis De Schepper and Head, 2013

Lavradosphaera crista De Schepper and Head, 2008

Dinoflagellate cysts mentioned in the text but not recorded in this study

Batiacasphaera minuta (Matsuoka, 1983b) Matsuoka and Head, 1992

Bitectatodinium serratum (Head et al., 1989b) Lentin and Williams, 1993

Corrudinium devemaliae Head and Norris, 2003

Echinidinium euaxum (Head, 1993) Head et al., 2001

Hystrichokolpoma rigaudiae Deflandre and Cookson, 1955

Operculodinium tegillatum Head, 1997

Pyxidinospis vesiculata Head and Norris, 2003

Reticulosphaera actinocoronata (Benedek, 1972) Bujak and Matsuoka, 1986
