

# **Latest Miocene to Late Pliocene Dinoflagellate Cyst Biostratigraphy of the Ocean Drilling Program Hole 642B on the Vøring Plateau**

By

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## Abstract

An updated Late Neogene dinoflagellate cyst biozonation of the Norwegian Sea is needed, as it, together with other recent zonations from the Iceland Sea, the eastern North Atlantic and the eastern North Sea (Denmark), will form a cornerstone for achieving a better age constraint of the Utsira Formation.

In the present study magnetostratigraphically dated palynological samples from the Ocean Drilling Program Hole 642B, on the outer Vøring Plateau, eastern Norwegian Sea, have been studied, and a contribution to an up to date Late Neogene biozonation is made. The studied interval encompasses the Late Messinian to the Early Pliocene, and has been divided into a local zonation scheme of four interval zones (KMB-1–KMB-4). The KMB-1 Interval Zone (>5.82–5.33 Ma) is defined by the highest persistent occurrence of *Selenopemphix brevispinosa*. The base is presently not defined. The KMB-2 Interval Zone (4.91–4.64 Ma) is defined from the highest persistent occurrence of *Selenopemphix brevispinosa* to the highest occurrence of *Reticulatosphaera actinocoronata*. The KMB-3 Interval Zone (4.50–3.60 Ma) is defined from the highest occurrence of *Reticulatosphaera actinocoronata* to the highest occurrence of *Operculodinium? eirikianum* var. *crebrum*. The KMB-4 Interval Zone is defined from the highest occurrence of *Operculodinium? eirikianum* var. *crebrum*, but the top is presently not defined. Within the KMB-1–KMB-3 interval zones, several dinoflagellate cyst and acritarch events have also been described. These zones and events were compared with the zonations from the Iceland Sea, the eastern North Atlantic and the eastern North Sea (Denmark). In general, this comparison revealed differences in the distribution and range of the dinoflagellate cysts and acritarchs, likely due to different latitudinal and oceanographic settings of the investigated locations. However, one good regional event and upper zone boundary, are clearly recognized in both the Icelandic Sea and the Norwegian Sea.



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Bergen, June 2013

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## Table of contents

Abstract .....	I
Acknowledgements .....	III
CHAPTER 1 .....	1
INTRODUCTION .....	1
1.1 Introduction .....	1
1.2 Aims of this study .....	2
1.3 Palynology and Biostratigraphy .....	3
1.4 Dinoflagellates and their cysts .....	4
1.5 Acritarchs .....	8
1.6 The Late Miocene and Pliocene .....	8
1.7 Previous studies .....	8
CHAPTER 2 .....	11
GEOLOGICAL FRAMEWORK .....	11
2.1 Geological setting .....	11
2.2 Tectonic development .....	12
2.3 Regional oceanography .....	13
2.4 Miocene and Pliocene depositions .....	15
CHAPTER 3 .....	19
MATERIAL AND METHODES .....	19
3.1 Sampling site and sample lithology .....	19
3.2 Age model .....	21
3.3 Palynological preparation .....	21
3.4 The <i>Lycopodium</i> marker-grain method .....	24
3.5 Quantitative analysis .....	24
3.6 LO-analysis .....	25
3.7 Systematic palynology .....	26
3.9 Biostratigraphy .....	27
CHAPTER 4 .....	29
RESULTS .....	29
4.1 Palynomorph preservation and sample spacing .....	29
4.2 Taxonomic remarks .....	29

4.3	Palynomorph assemblages.....	30
4.4	Biozonation .....	33
4.6.1	KMB-1 Interval Zone .....	34
4.6.2	KMB-2 Interval Zone .....	36
4.6.3	KMB-3 Interval Zone .....	38
4.6.4	KMB-4 Interval Zone .....	39
CHAPTER 5.....		41
COMPARISON, CORRELATION AND DISCUSSION.....		41
5.1	Comparison with Mudie (1989) .....	41
5.2	Comparison and correlation with other mid- to high-latitude biozonations.....	41
5.2.1	Eastern North Atlantic .....	43
5.2.2	The eastern part of the North Sea (Denmark).....	49
5.2.3	The Iceland Sea .....	51
CHAPTER 6.....		55
CONCLUSIONS .....		55
References .....		58
Appendix .....		640
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# CHAPTER 1

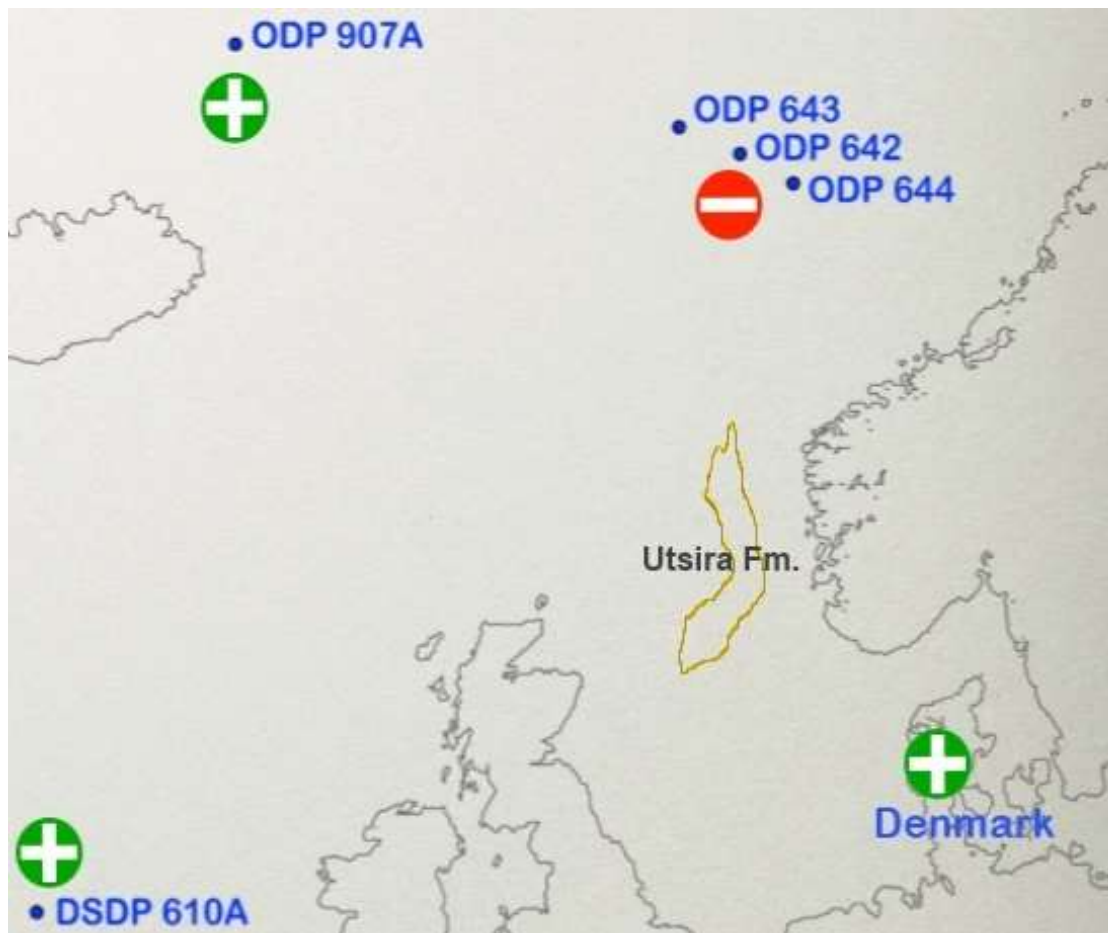
## INTRODUCTION

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### 1.1 Introduction

This master thesis is a part of the project “Dinoflagellate cyst biostratigraphy of the Neogene formations used for carbon dioxide storage in the North Sea”. The project is led by Dr. Stijn De Schepper and Prof. Gunn Mangerud at the Department of Earth Science, University of Bergen. The overall aim of the project is to establish a new stratigraphical framework for the Utsira Formation, provide an age estimate and paleoenvironmental interpretation, evaluate the interpretation of what is called “Utsira Formation” in the Tampen area today, and establish a dinoflagellate cyst zonation for the Neogene North Sea.

The background for this thesis is the conflicting dating of the Utsira Formation, which has been dated as Middle Miocene to Early Pliocene, depending on the method used (Piasecki et al., 2002 and references therein). This is partly caused by the lack of data as only very few industry cores and sidewall cores are available from the Utsira Formation, and cutting samples are not ideal for establishing zonations. Therefore, dating and understanding of the Utsira Formation is dependent on reliable regional Neogene reference sections for comparison. Recent dinoflagellate cyst reference sections are available from the eastern North Atlantic (De Schepper and Head, 2008, 2009), the Iceland Sea (Schreck et al., 2012) and the eastern North Sea (Denmark) (Dybkjær and Piasecki, 2010). However, in the Norwegian Sea a Miocene-Pliocene dinoflagellate cyst biozonation has not been performed since by Mudie (1989). Since then new dinoflagellate cyst taxa have been described, and have caused this zonation to be partly outdated. Thus, an updated reference section for the Norwegian Sea is needed and will together with the other available zonations listed above, form a cornerstone for a mid- to high-latitude biozonation, relevant for gaining a better constrained age for the Utsira Formation (Figure 1).



**Figure 1:** Location map, showing the mid- to high latitude biozonations, relevant for gaining a better age constraint of the Utsira Formation. The locations marked with a green circle with a white cross are available reference sections: ODP Hole 907 in the Iceland Sea (Shreck et al. 2012), DSDP Hole 610A in the eastern North Atlantic (De Schepper and Head, 2008, 2009) and eastern North Sea (Denmark) (Dybkjær and Piasecki, 2010). ODP 642, ODP 643 and ODP 644 in the eastern Norwegian Sea (Mudie, 1989) are marked with a red circle with a white line, indicating that an update is needed. From S. De Schepper (pers. comm., 2013).

## 1.2 Aims of this study

The purpose of the present study is to make a contribution to an up to date Late Neogene dinoflagellate cyst biozonation for the Norwegian Sea, as a basic building block in order to further construct a detailed zonation for the area. Palynological core samples from the Ocean Drilling Program (ODP) Hole 642B is the basis for the present study. ODP Hole 642B is located on the Vøring Plateau in the eastern Norwegian Sea (Figures 1 and 9 [p. 20]), and a rich Miocene–Pliocene dinoflagellate assemblage had previously been identified by Mudie (1989). The hole also has a good age control provided by detailed magnetostratigraphy (Bleil, 1989), which allows for absolute dating of the palynological samples.

- The first aim of this study is, through light microscope analysis, to investigate palynological samples, with a main focus on dinoflagellate cysts and acritarchs, for a time interval encompassing the latest Miocene (dated from 5.83 Ma, late Messinian) to the early Late Pliocene (dated 3.08 Ma, early Piacenzian) in order to find biostratigraphic events.
- The second aim is to divide the studied interval into a local zonation scheme based on the found events.
- The third object is to compare these events and this zonation scheme with the North Atlantic (De Schepper and Head, 2009), Iceland Sea (Schreck et al., 2012) and North Sea (Dybkjær and Piasecki, 2010) areas, to see if a correlation is possible, and get a better understanding whether the found events are only of local importance, or of more regional importance.

### **1.3 Palynology and Biostratigraphy**

Palynology is the study of microfossils made of acid-resistant organic material. These microfossils are termed palynomorphs and include acritarchs, dinoflagellate cysts, chitinozoa, fungal spores, green/blue algae, plant spores, pollen grains and scolecodonts (Jansonius and McGregor, 1996). Palynology is used in a wide array of integrated geological studies from the Proterozoic to the Holocene to provide biostratigraphic and palaeoecologic information. Palynomorphs occurs both in marine and non-marine rocks, and the potential of age correlation between these two environments makes palynology particularly important in biostratigraphy.

Biostratigraphy is defined as “the element of stratigraphy that deals with the distribution of fossils in the stratigraphic record and the organization of strata into units on the basis of their contained fossils” (Murphy and Salvador, 1999). These units are called biostratigraphic zones (abbreviated biozones), and differ from other kinds of stratigraphic units in that evolutionary changes make the fossil assemblages of any one age distinctive from any other (Murphy and Salvador, 1999). Biozones are thereby particularly useful for determining the relative age of

sediments and rocks, and through correlation detect concurrency between geographically separated areas. In addition, the fossil distribution can be used to interpret past geological settings and environments.

The correlation of biozones may be hampered by the fact that their boundaries might be diachronous. The first and last occurrence of fossils is rarely synchronous throughout their total distribution area. Provincial and latitudinal differences clearly indicate pervasive biogeographic controls on the spatial and temporal distribution of many species (e.g. Williams et al., 2004). Other factors, including the effect of diagenesis on fossilization, sediment removal, non-deposition and sample spacing, may also affect the biozone boundaries (Stover et al., 1996).

The value of different fossil species for biostratigraphy, including relative dating, is variable, particularly for long distance correlation. The most applicable species, called index fossils, are easy to identify, widely deposited, abundant, and short lived (rapidly evolving). In the ocean, the best biostratigraphic markers/index fossils are often organisms that live in the upper water column, either as free-floating plankton or as actively swimming nekton.

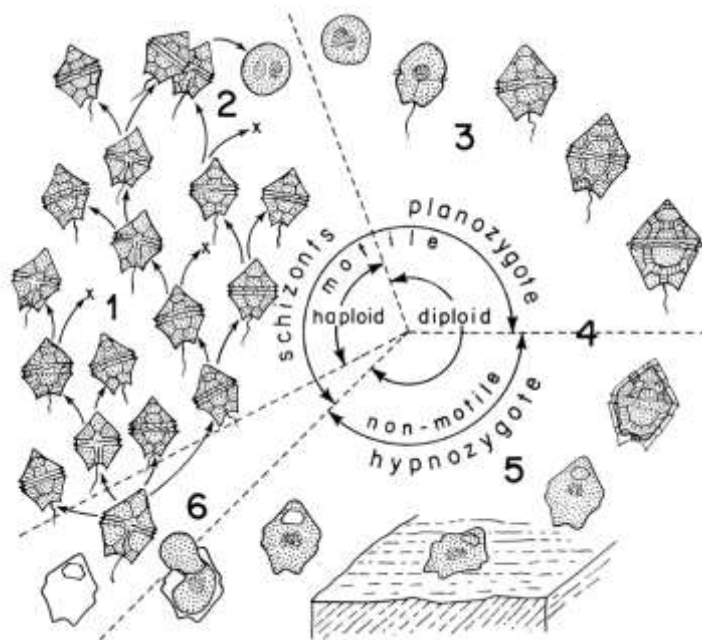
To determine the absolute age of biozones, biostratigraphic events are usually calibrated to magnetostratigraphy, calcareous nannofossil biostratigraphy and/or marine isotope stratigraphy (e.g. De Schepper and Head, 2009; Schreck et al., 2012).

## **1.4 Dinoflagellates and their cysts**

### **Introduction**

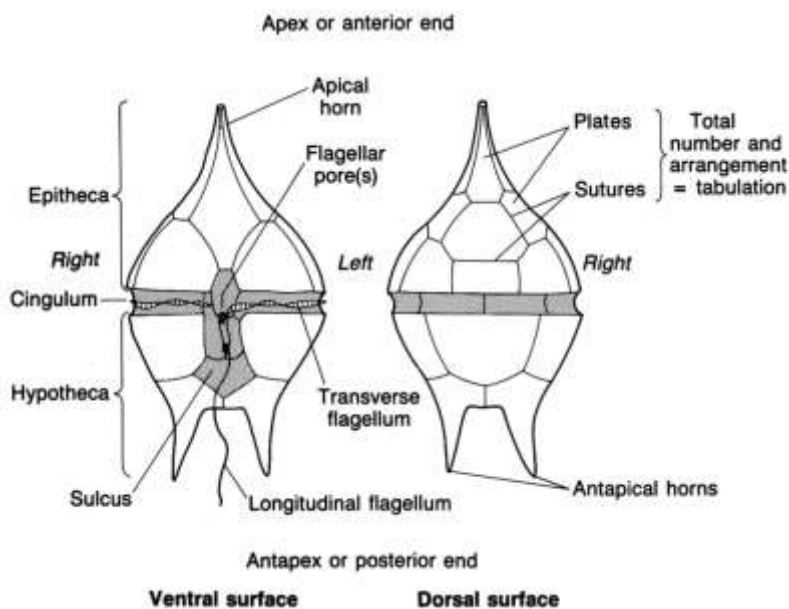
Dinoflagellates are eukaryotic, primarily single-celled protists, found in most aquatic environments (including ocean, coastal and estuarine waters, and rivers and lakes) (Fensome et al., 1993). The majority of dinoflagellates are free-living and have their greatest diversity in the marine plankton, where they are a major component of the phytoplankton and important primary producers. Marine forms occur in all climate regimes, from polar to tropical, but have their highest diversity in the tropics. The distribution of different dinoflagellates is dependent on controlling factors, including nutrient supply, water temperature, water depth and salinity.

Dinoflagellates may have a complex life-cycle with several stages (Figure 2), but for the majority of dinoflagellate species a motile flagellate stage is included (Fensome et al., 1993) (stage 1 in Figure 2). The cell then possesses two dissimilar flagella (the transverse flagellum and the longitudinal flagellum), propelling them through the water in a corkscrew fashion. In most dinoflagellates these two flagella both arise from a single pore that defines the ventral surface (Figure 3). The opposite surface is thus dorsal and left and right is defined conventionally. The transverse flagellum is typically located in a transverse groove, the cingulum, which subdivides the theca into an epitheca and a hypotheca (Figure 3). The longitudinal flagellum is directed posterior and is usually located in a longitudinal furrow, the sulcus (Figure 3).



**Figure 2:** Schematic dinoflagellate life-cycle, involving sexual reproduction and cyst formation. 1) During favorable conditions for rapid growth and population expansion, vegetative reproduction occurs and gives successive generations of motile haploid schizonts. 2) Environmental stress or change causes the haploid schizonts to act as gametes and fuse to form diploid zygotes. A loss of thecae is possible during this process. 3) The diploid, still motile zygote constructs a new theca resembling the vegetative one (if lost). The zygote is in this stage called a planozygote. 4) During this stage a resistant cyst wall forms within the theca (that becomes thicker and larger than during the vegetative stage). The zygote loses its motility and becomes a hypnozygote, and when the cyst wall is fully developed the thecal plates gradually decay. 5) The hypnozygote or resting cyst behaves as a sediment particle and follows currents or sinks through the water column in calmer environments, settling on the sea floor. 6) When conditions become favorable the protoplast excysts through a distinct opening, called the archeopyle, leaving the cyst wall behind on the sea floor. Meiotic division occurs and the life cycle starts over. From Evitt (1985).

The motile cell is usually bounded by an outer complex covering, called the amphiesma, typically including a layer of vesicles, which may contain cellulosic thecal plates (Evitt, 1985; Fensome et al., 1993). Dinoflagellate taxa with such plates are called armored or thecate, while taxa lacking thecal plates are termed athecate, naked or unarmored. In thecate dinoflagellates the thecal plates are fitted tightly together along margins called sutures (Figure 3). The number and arrangements the amphiesmal vesicles, with or without thecal plates, constitute the tabulation. The tabulation is characteristic for a genus or species (Evitt, 1985), and is of prime importance in classification, especially in the groups usually found as fossils (then called paratabulation).



**Figure 3:** General morphology of a thecate motile cell. From Evitt (1985).

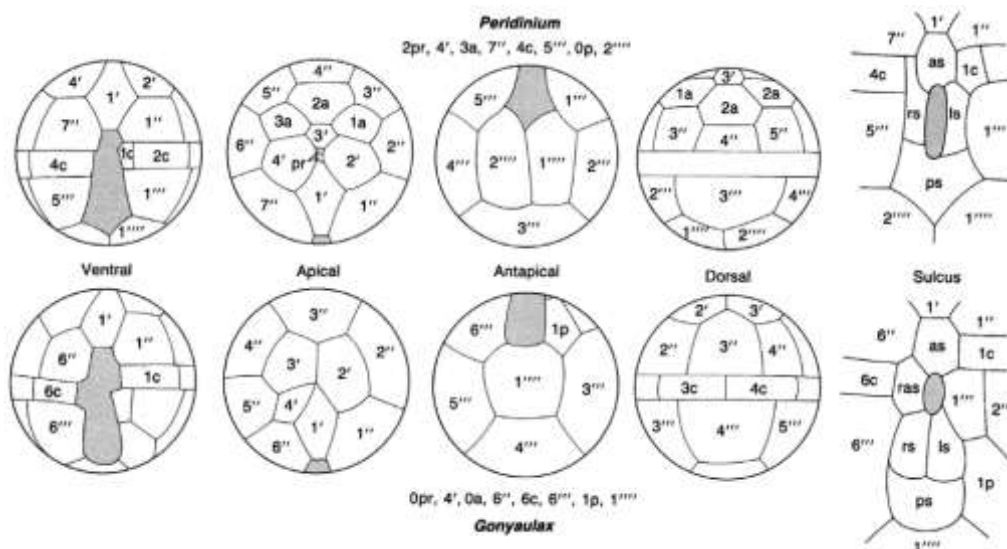
### Fossilizable dinoflagellate cysts

In contrast to the dinoflagellate's biflagellate motile stage, a variety of non-motile cysts may be included in their life cycles (cells with continuous wall and thus devoid of flagella) (Fensome et al., 1993). It is believed that most fossil dinoflagellates are resting cysts, formed from sexual fusion (Figure 2), although sexuality is presently only known for a few living taxa (Fensome et al., 1993). Taxa that form such cysts are predominantly neritic-marine.

The membranes and walls of motile dinoflagellates and the walls of most non-motile cysts are often quickly destroyed by bacterial action after death. In contrast, the resting cyst wall composition of some species is composed of a highly resistant fossilizable organic material, calcium or, rarely, silica (Fensome et al., 1993).

The resting cysts that are most commonly found in the geological record consist of dinosporin. Dinosporein constitute a strongly cross-linked carbohydrate-based polymer, which differ from sporopollenin and algaenan (Versteegh et al., 2012). The dinosporein makes the cysts highly resistant to bacterial degradation, digestion and aggressive mineral acids (e.g. HF), but it may be degraded by oxidation.

Most dinoflagellate cysts are from 25 to 200  $\mu\text{m}$  in overall diameter. The oldest record of dinoflagellate cysts is from Late Triassic sediments (Evitt, 1985), and their rapid evolution, diverse morphologies and abundance in many Mesozoic and Cenozoic marine rocks, makes these fossils ideal for biostratigraphic purpose. Characteristic features used for determination and classification of the dinoflagellate cysts are: wall structure (e.g. psilate or reticulate), surface features (e.g. ridges and processes), general features (e.g. shape and size), indication of paratabulation and the archeopyle.



**Figure 4:** The peridinioid and gonyaulacoid tabulation patterns following Kofoed's tabulation system. From Evitt (1985).

For most dinoflagellate fossils the gonyaulacoid-peridinioid tabulation type is characteristic (Fensome et al., 1993). A widely used tabulation analyzing system for the gonyaulacoid-peridinioid is the Kofoid tabulation system (Fensome et al., 1993), where the latitudinal series of plates are related to the apex, cingulum and antapex and categorizes in seven series parallel to the cingulum. The series and number of plates can then be expressed as a plate formula, using Kofoid's alphanumeric system (Figure 4).

## 1.5 Acritarchs

Acritarchs are fossilized, organic walled, unicellular protists, of unknown biological affinity, that can be found throughout the geological column (Strother, 1996). Most acritarchs are considered to be the resting cysts of marine phytoplankton, and often a simple excystment structure is seen (Strother, 1996). Acritarchs usually consist of a hollow vesicle (or theca) which may show large morphological differences, e.g. projecting spines, or processes, and crests. Most species are 15 - 80  $\mu\text{m}$  in diameter, but they vary in size from less than 10  $\mu\text{m}$  to more than 1 millimeter (Strother, 1996). Like for dinoflagellate cysts, several factors control the acritarchs distribution, including temperature, water depth, salinity and nutrient supply. In the Neogene, acritarchs have mostly been used for paleoenvironmental studies (Jansonius and McGregor, 1996), but in more recent studies they have been noted as important biostratigraphic markers (e.g. Schreck et al., 2012; De Schepper and Head, 2013).

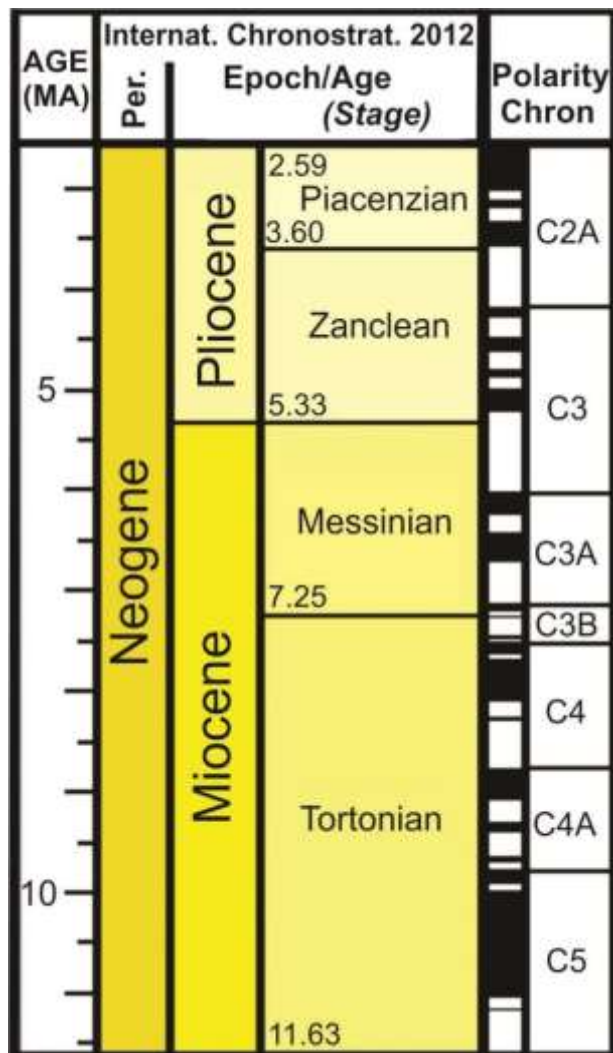
## 1.6 The Late Miocene and Pliocene

The Miocene and Pliocene are epochs of the Neogene period (Figure 5) (Hilgen et al., 2012). The Late Miocene incorporates the Tortonian (11.63 Ma to 7.25 Ma) and Messinian (7.25 Ma to 5.33 Ma) stages, whereof the latter constitutes the latest Late Miocene (Hilgen et al., 2012). The Pliocene epoch includes the Zanclean (5.33 Ma to 3.60 Ma) and Piacenzian (3.60 Ma to 2.58 Ma) stages (Hilgen et al., 2012).

Through the late Miocene a general global climate cooling is evident both on the continents (Pound et al., 2012) and in the oceans (Zachos et al., 2001), and the continental latitudinal temperature gradients appear to gradually become steeper, and for the Messinian the gradients



seemed to be close to the preindustrial conditions (Pound et al., 2012). During the Pliocene the global cooling trend continued and developed further into the high magnitude glacial-interglacial oscillations of the Pleistocene epoch (e.g. Salzmann et al., 2011). Even though a progressive cooling occurred, the Pliocene was a generally warmer epoch compared to the present (e.g. Salzmann et al., 2011).



**Figure 5:** Upper Neogene (latest Miocene through Pliocene) time scale chart. Modified from Hilgen et al. (2012).

## 1.7 Previous studies

Late Neogene Palynological studies and dinoflagellate cysts zonation for Ocean Drilling Program (ODP) 642, were initially done during the drilling of Leg 104 by the Scientific Shipboard Party (1987). However, these zones were only meant as informal and tentative because they were based on core-catcher samples (Scientific Shipboard Party, 1987).

A post-cruise Late Neogene palynological study from ODP 642, also comprising ODP 643 and ODP 644 (Fig. 1) was done by Mudie (1989). A regional dinoflagellate cyst biozonation comprising four biozones, spanning the middle Miocene through the middle Pleistocene, was then established for the Norwegian Sea. Two of these zones (abbreviated PM3 and PM2) encompass the Messinian through Piacenzian (Figure 16, p. 47). The *Achomosphaera andalousiensis* acme–Zone PM3 extends from the early Late Miocene to the middle Lower Pliocene. The zone is characterized by the acme of *Achomosphaera andalousiensis*. The zone top is also recognized by the highest common occurrence of *Amiculosphaera umbracula* just above the base. The *Filisphaera filifera*–Zone PM2 is defined by the range of *Fillisphaera filifera*. The base of the zone is also marked by the LO of *Tectatodinium pellitum*, and the top of the zone by the HO of *Nematosphaeropsis lemniscata*. The zone extends from the middle lower Pliocene to the uppermost of the Lower Pleistocene.

Dinoflagellate cyst zonations for sediments of Eocene to Miocene age on the Vøring Plateau, have been published by Manum (1976) and Manum et al., (1989).

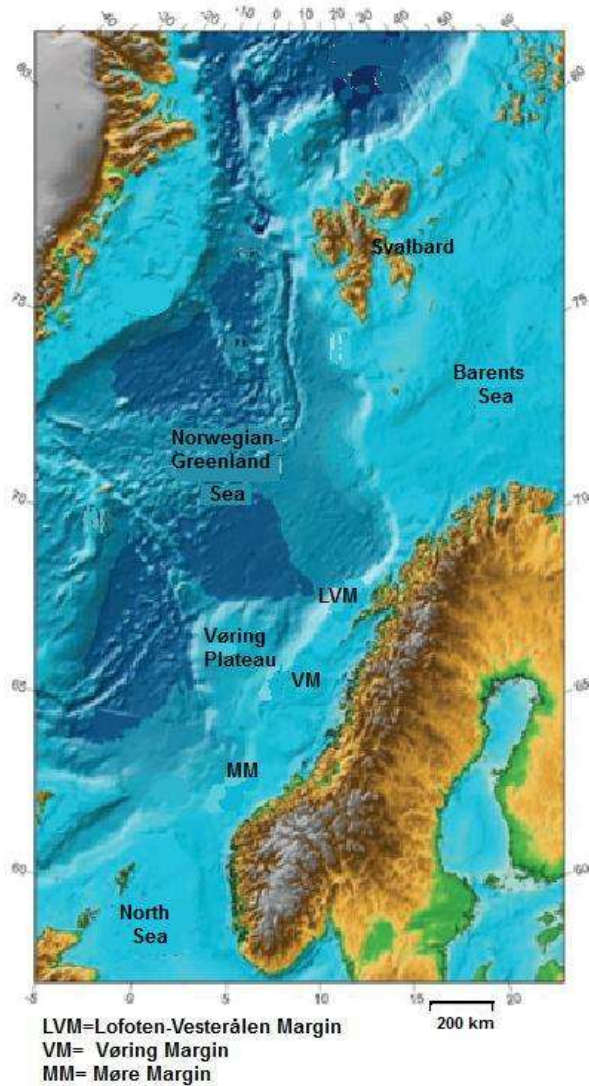
## CHAPTER 2

# GEOLOGICAL FRAMEWORK

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### 2.1 Geological setting

The mid-Norwegian continental margin between 62° and 70° N consists of three main segments: The Møre, Vøring, and Lofoten-Vesterålen margin provinces (Figure 6) (Eldholm et al., 1987; Faleide et al., 2008).



**Figure 6:** The regional setting of the Norwegian continental margin. From Faleide et al. (2008).

The Vøring Margin is about 500 km wide and is the broadest of these segments and it is separated from the Møre Segment to the south by the East Jan Mayen Fracture Zone/Lineament and from the Lofoten-Vesterålen margin to the north by the Bivrost Fracture zone/Lineament (Faleide et al., 2008).

The Vøring margin is a complex continental margin with an up to 200 km wide shelf area, and a gently dipping slope, terminating onto the inner Vøring Plateau (Dahlgren et al., 2002; Laberg et al., 2005). From the outer Vøring Plateau, a more steeply dipping slope is leading down to the more than 3000 m deep abyssal plains of the south-westward underlying Norwegian Basin and the northwards underlying Lofoten Basin (Dahlgren et al., 2002; Laberg et al., 2005).

The Vøring Plateau is a broad marginal plateau with a fairly smooth sea floor. The Plateau covers an area of about 35 000 km<sup>2</sup>, and lies at water depths between 1200–1500 m (Eldholm et al., 1987). The plateau is structurally divided by the Vøring Plateau Escarpment into the Vøring Basin (inner Vøring Plateau) and the Vøring Marginal High (outer Vøring Plateau).

## 2.2 Tectonic development

Between the Devonian collapse of the Caledonian orogeny and the Early Eocene continental breakup, the Vøring Margin was subject to a series of discrete extensional phases, spanning a period of approximately 350 Ma (Lundin and Doré, 2002). The rifting occurred in three main episodes: in the Carboniferous to Permian, in the late Middle Jurassic to Early Cretaceous, and in the Late Cretaceous to Early Eocene (Brekke et al., 1999). During the two first episodes, the extensional tectonics were related to continental rifting, whereas the last episode was more directly influenced by the relative movements along plate boundaries just before and after the continental breakup (Brekke et al., 1999).

The major crustal extension and thinning of the late Middle Jurassic to earliest Cretaceous rifting episode led to formation of the Vøring Basin, which has a thick Cretaceous infill (Faleide et al., 2008; Brekke et al., 1999).

The final lithospheric breakup occurred near the Paleocene–Eocene transition and was accompanied by a few million years of intense magmatic activity (Faleide et al., 2008). During this phase the Vøring Marginal High was formed (Eldholm et al., 1989). It consists of

a westerly or outer part with a thick oceanic crust, and an easterly, landward part of thinned continental crust covered by early Eocene volcanics and underplated by mafic intrusions (Faleide et al., 2008). When the magmatic activity abated and the Norwegian-Greenland Sea basin widened, the basement relief of the Vøring Marginal High was maintained as it subsided at the same rate as the oceanic crust (Eldholm et al., 1989). The relief of the Vøring Plateau was later smoothed out, as the Vøring Basin was filled with a thick sediment package, while the Vøring Marginal High received a relatively thin sediment cover (Eldholm et al., 1987).

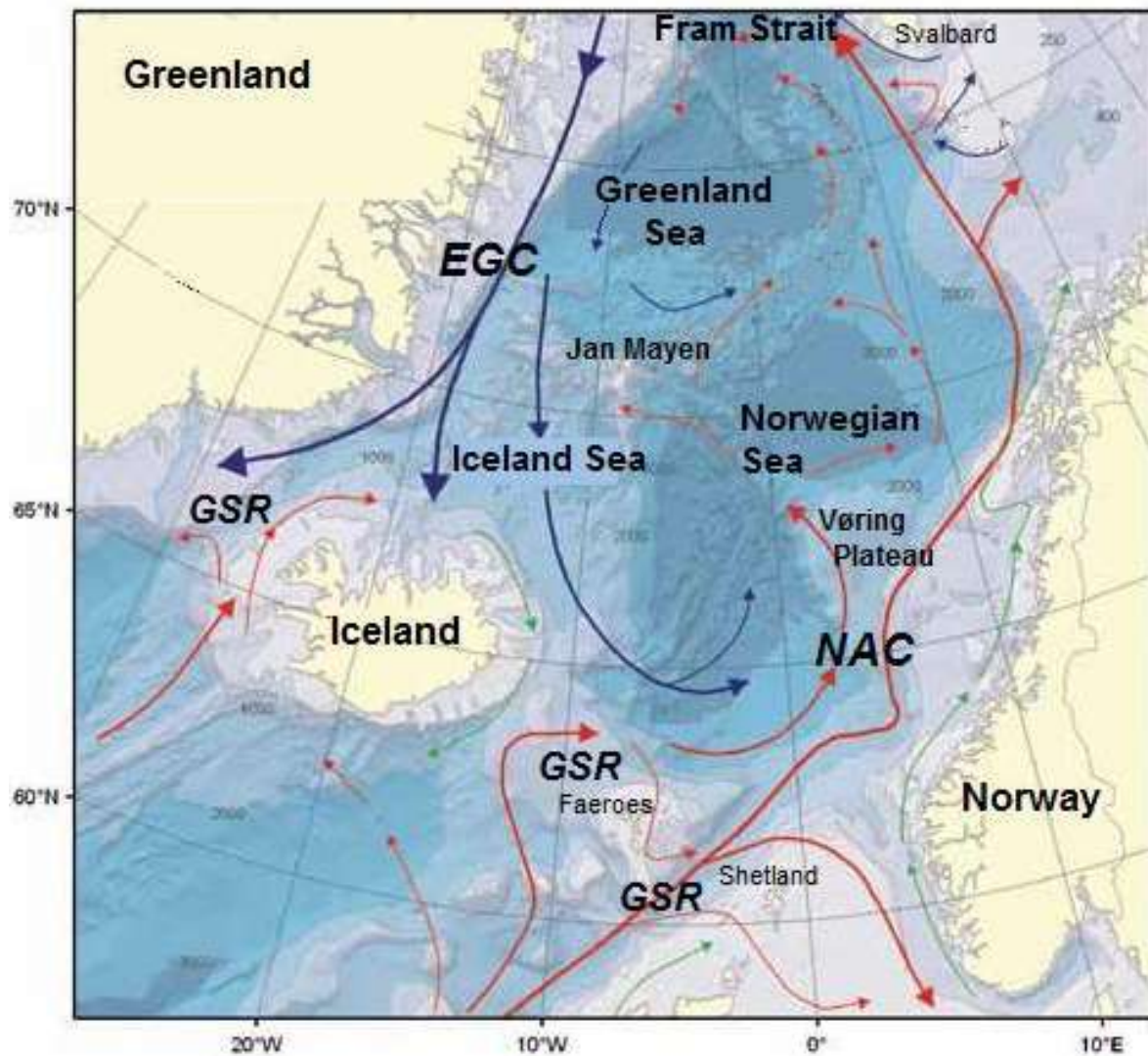
Since the Middle Eocene the mid-Norwegian continental margin experienced regional subsidence together with relatively modest sedimentation, and developed into a passive continental margin (Faleide et al., 2008). In the Mid-Cenozoic the Vøring Margin underwent compressional deformation with formation of structures including domes, anticlines, reverse faults, and broad scale inversion (Faleide et al., 2008). In the Late Miocene Fennoscandia underwent a regional moderate uplift and subsequent outbuilding of the inner shelf (Eidvin et al., 2007).

### **2.3 Regional oceanography**

The present day oceanography of the Norwegian-Greenland Sea is influenced by the Arctic-North Atlantic thermohaline circulation system, where water masses between the Atlantic Ocean, the Norwegian-Greenland Sea and the Arctic Ocean are exchanged, across the Greenland-Scotland Ridge gateway to the south and through the Fram Strait gateway to the north (e.g. Thiede et al., 1998) (Figure 7). A strong surface temperature asymmetry of the Norwegian-Greenland Sea is caused by the Norwegian Atlantic Current (NAC) carrying warm and saline North Atlantic water northward along the Norwegian continental margin, and the East Greenland Current transporting colder and less saline water from the Arctic Ocean southward along the East Greenland continental margin (e.g. Bohrmann et al., 1990).

Along the mid Norwegian margin the NAC has two branches; an eastern branch passing through the Faroe-Shetland region and a western branch entering across the Faroe-Iceland ridge (Figure X) (Orvik and Niiler, 2002; Orvik et al., 2001; Poulain et al., 1996). The eastern branch flows along the inner continental slope towards the arctic, with a bifurcation into the Barents Sea (Orvik and Niiler, 2002; Orvik et al., 2001). The western branch flows along the Vøring Plateau slope and continues past Svalbard into the Fram Strait (Orvik and Niiler,

2002; Orvik et al., 2001; Poulain et al., 1996). Deeper water circulation involves the colder and denser southward flowing Norwegian Sea Arctic Intermediate Water and Norwegian Sea Deep Water (e.g. Hansen and Østerhus, 2000). These water masses form as the North Atlantic water gradually cools and sinks towards the north, and returns to the North Atlantic Ocean across the Greenland-Scotland Ridge (e.g. Hansen and Østerhus, 2000).



**Figure 7:** Main currents of the Norwegian-Greenland Sea. EGC = East Greenland Current, NAC = Norwegian Atlantic Current, GSR = Greenland-Scotland Ridge. From Oug et al. (2010).

## **Regional Paleoceanography**

The present day oceanographic circulation in the Norwegian-Greenland Sea, relates to the tectonic history of the area (e.g. Thiede and Myhre, 1996; Stoker et al., 2005a). The opening of the Fram Strait between Svalbard and Greenland the thermal subsidence of the Greenland-Scotland Ridge probably allowed a thermohaline circulation system to occur in the Middle Miocene (Bohrmann et al., 1990; Bryn et al., 2005; Thiede and Myhre, 1996).

The surface circulation on the Vøring Plateau during the Early Neogene was comparable to that of today, with north-eastward flowing waters entering the area, but the elevation of the Vøring Marginal High prevented the water masses from flowing along the Norwegian Shelf (Laberg et al., 2005). On the Vøring Plateau this period is represented by current controlled sedimentation (contourites) (Laberg et al., 2005). Sometime between the Late Miocene and the Early Pliocene the subsidence of the Vøring Marginal High resulted in reduced topographic control on the ocean currents, and water masses started to flow also nearer to the Norwegian coast, like today, and a change to hemiplegic sedimentation occurred at the Vøring plateau (Laberg et al., 2005).

## **2.4 Miocene and Pliocene depositions**

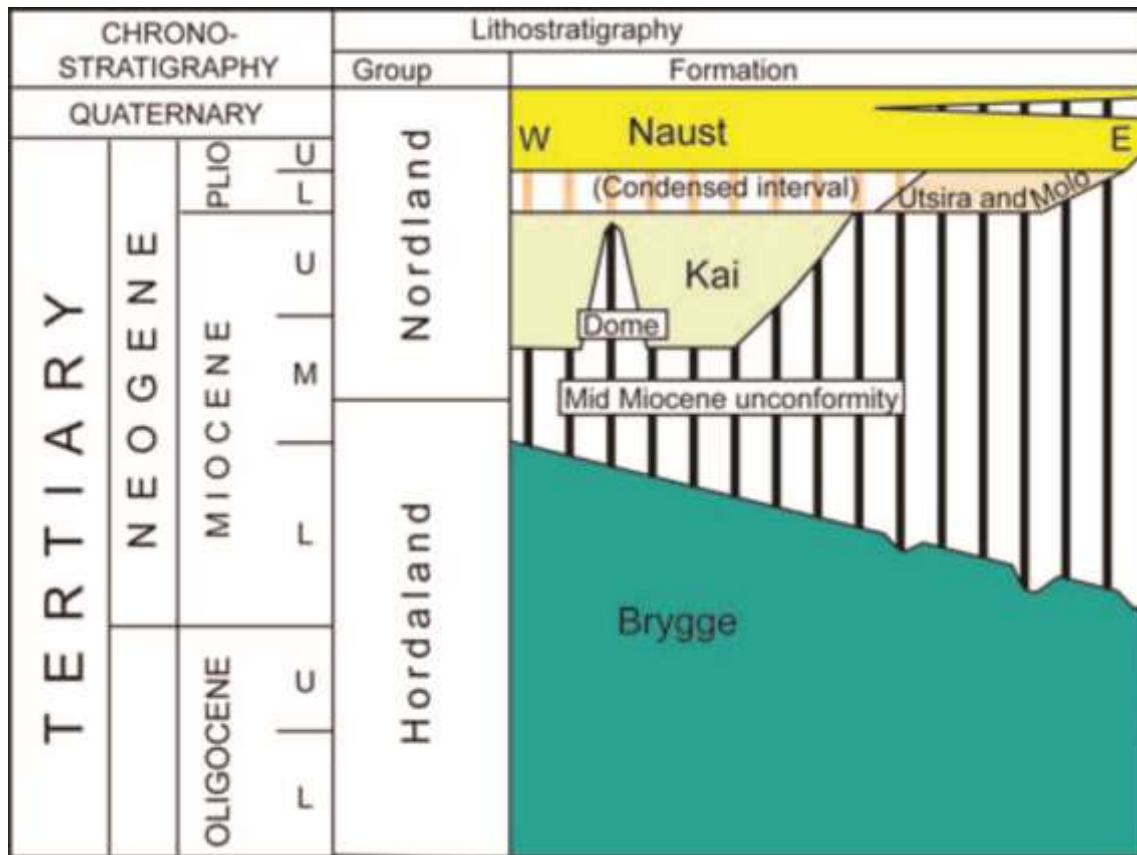
The Late Miocene and Pliocene sediments covering the Vøring continental margin belongs to the Kai and the Naust formations of the Nordland Group, which overlie the Brygge Formation of the Hordaland Group (Dalland et al., 1988) (Figure 8).

### **The Kai Formation**

The Kai Formation consists of alternating sandstone, siltstone and mudstone with some stringers of limestone, and was deposited under marine conditions of varying water depth (Dalland et al., 1988). The formation is of Late/Middle Miocene to Early Pliocene age (Eidvin et al., 1998), and is bounded by the Base Kai and Base Naust unconformities (Stoker et al., 2005b). The formation typically fills in the synclines around inversion structures, and is thin or absent over positive features, such as over the Vøring Marginal High (Løseth and Henriksen, 2005; Stoker et al., 2005b). On the Vøring Plateau Laberg et al. (2005) favored



current controlled sedimentation (contourites) for most of the formation, which may relate to increased water mass exchange in the Norwegian-Greenland Sea during this period (Stoker et al., 2005a).



**Figure 8:** The Oligocene to Quaternary lithostratigraphy of the Vøring continental margin. From Løseth and Henriksen (2005).

A proximal equivalent to the deeper marine Kai Formation and also the Utsira Formation in the North Sea, is the sandy Molo Formation, which is a depositional unit on the inner Mid-Norwegian continental shelf which extends from Møre to Lofoten (Eidvin et al., 2007). These three formations were all deposited as a result of the compression and uplift of mainland Norway in mid Miocene time (Eidvin et al., 2007).



**Naust formation**

The Naust Formation consists of interbedded sandstone, siltstone and claystone, with occasionally very coarse clastics in the upper part, and was deposited in a marine environment with a transition to glaciomarine conditions in the upper part (Dalland et al., 1988). The formation is of Late Pliocene age to the present, and represents the strata between the Base Naust Unconformity and the present day sea bed (Stoker et al., 2005b). The Base Naust Unconformity is an angular unconformity onto which clinoforms of the prograding Naust Formation is downlapping along the Vøring shelf margin (Stoker et al., 2005a). Further west the unconformity becomes a conformable surface, and on the Vøring Plateau no obvious hiatus has been identified at outer part (Bruns et al., 1998).



## CHAPTER 3

### MATERIAL AND METHODES

#### 3.1 Sampling site and sample lithology

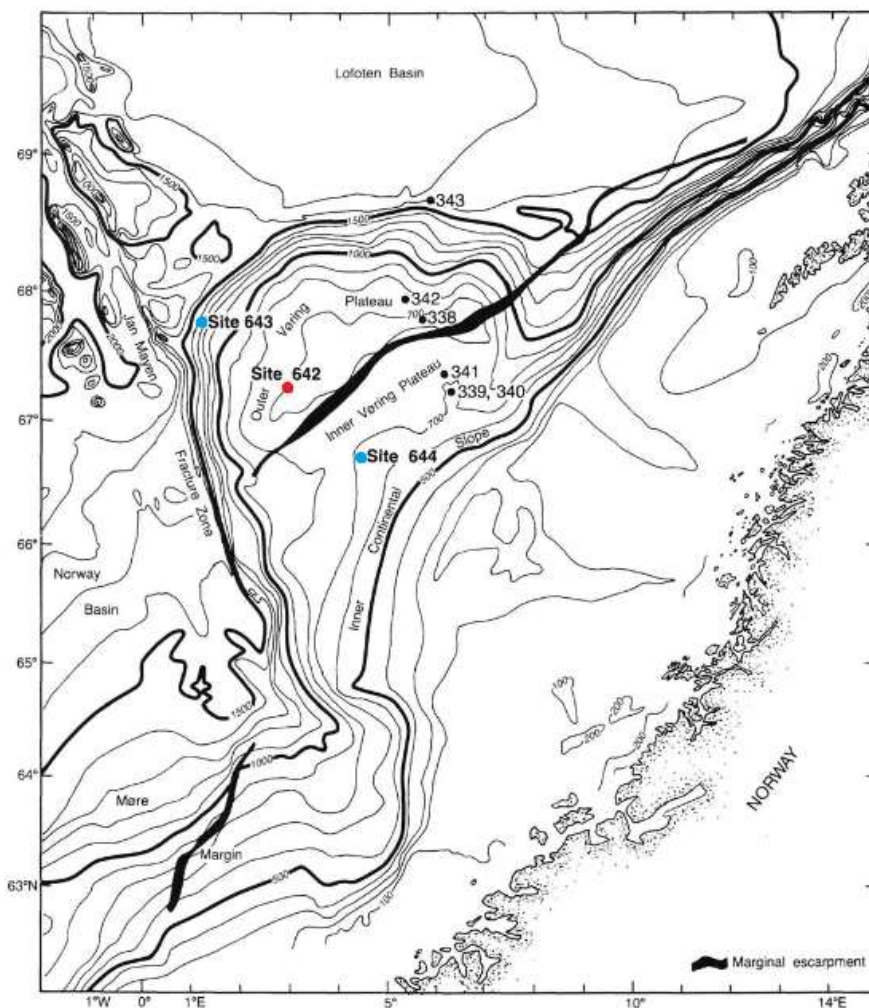
The Ocean Drilling Program (ODP) Hole 642B (67°13.5'N, 2°55.7'E; Water depth 1268 m) located on the outer Vøring Plateau, was drilled with an advanced hydraulic piston corer in the summer of 1985 as a part of the ODP Leg 104 (Shipboard Scientific Party, 1987) (Figure 9). The drill hole reached a depth of 221.1 meter below sea floor (abbreviated hereafter as mbsf), and penetrated a predominantly pelagic-hemipelagic sediment succession of Holocene through Early Miocene age (Shipboard scientific party, 1987). The total core recovered was 215.6 m, giving a core recovery of 97.5% (Shipboard Scientific Party, 1987).

**Table 1:** An overview of the sample information for the samples analyzed in this study. Shallowest/youngest at the top and deepest/oldest sample at the bottom.

ODP drilling site	Palynological sample	Core-section	Depth in section (cm)	Depth (mbsf)	Litological unit	Age (Ma) GTS 2012	Epoch	Stage
642B	12 F401	8H6A	129-130	65.69	I	3.08	Pliocene	Piacenzian
642B	12 F471	9H2A	40-41	68.30	IIA	3.35	Pliocene	Piacenzian
642B	12G10	9H3A	60-61	70.00	IIA	3.60	Pliocene	Zandean
642B	12G72	9H4A	145-146	72.35	IIA	3.83	Pliocene	Zandean
642B	12G98	9H6A	100-101	74.9	IIA	4.08	Pliocene	Zandean
642B	12 G102	10H1A	40-41	76.3	IIA	4.23	Pliocene	Zandean
642B	12G104	10H1A	145-146	77.36	IIA	4.50	Pliocene	Zandean
642B	12G105	10H2A	40-41	77.80	IIA	4.64	Pliocene	Zandean
642B	12G132	10H2A	100-101	78.40	IIA	4.69	Pliocene	Zandean
642B	12G135	10H3A	102-103	79.92	IIA	4.81	Pliocene	Zandean
642B	11J378	10H4	15-16	80.55	IIA	4.84	Pliocene	Zandean
642B	11J381	10H5A	11-12	82.01	IIA	4.91	Pliocene	Zandean
642B	11 J495	11H1A	80-81	86.20	IIA	5.35	Miocene	Messinian
642B	11J498	11H2A	65-66	87.55	IIA	5.44	Miocene	Messinian
642B	11J501	11H3A	65-66	89.05	IIA	5.53	Miocene	Messinian
642B	11J507	11H5A	60-61	92.00	IIB	5.71	Miocene	Messinian
642B	11J511	11H6A	110-111	94.00	IIB	5.83	Miocene	Messinian

Three main lithological units (I, II and III) were distinguished by Shipboard Scientific Party (1987) from the drilled section. Unit II was further divided into four subunits (IIA, IIB, IIC and IID) defined by varying importance of siliceous biogenic, calcareous biogenic and terrigenous components. The samples used in this study are collected from the lower part of Unit I, Subunit IIA and the upper part of IIB (Table 1). Unit I (0–65.7 m sub-bottom to core

sample 104-642B-8H-6, 132 cm) consists of repeated alternations of carbonate poor, dark glacial mud and carbon-rich, light interglacial sandy mud. Bioturbation is common throughout this unit. Subunit IIA (65.7–90.4 m sub bottom to sample 104-642B-11H-4, 50 cm) consists predominantly of nannofossil oozes, with some diatom nannofossil oozes and muds. This subunit is moderately to heavily bioturbated. Subunit IIB (90.4–107.2 m sub bottom to sample 104-642B-13H-2) consists of siliceous oozes and siliceous muds, which is moderately to heavily bioturbated.



**Figure 9:** Bathymetric map of the Norwegian continental margin between 62°–70° N, with 100 m contour interval, and the locations of the three sites drilled during ODP Leg 104. The sampling site ODP 642 is marked with a red dot, while the locations of ODP 643 and ODP 644 are marked with blue dots (from Shipboard Scientific Party, 1987).

### 3.2 Age model

The original paleomagnetic reversal data for ODP Hole 642B is from Bleil (1989), who used the polarity time scale of Berggren et al. (1985). This time scale is now outdated. For this thesis the paleomagnetic reversal data of (Bleil, 1989) was recalibrated to the Astronomically Tuned Neogene Time Scale 2012 (ATNTS 2012) of Hilgen et al. (2012) (Table 2).

**Table 2:** The paleomagnetic tie points and ages. From C. Andersson (pers. comm., 2013).

Chron/Subchron name in Beil, 1989	Chron/Subchron	Comment	Berggren et al., 1985) in Snelling (Ma) (Bleil)	ATNTS 2004/2012 (Ma)	Sample	Upper Depth (mbsf)	Sample	Lower Depth (mbsf)	Mid-depth (mbsf)
C2AN-2/C2AR-2	C2An.2n/ C2An.2r	Top Mammoth	3,08	3,207	9H-1, 41	66,81	9H-1, 71	67,11	66,96
C2AR-2/C2AN-3	C2An.2r / C2An.3n	Base Mammoth	3,18	3,330	9H-2, 11	68,01	9H-2, 41	68,31	68,16
C2AN-3/C2AR-3	C2An.3n/C2Ar	Top Gilbert	3,40	3,596	9H-3, 47	69,87	9H-3,71	70,11	69,99
C2AR-3/C3N-1	C2Ar/C3n.1n	Top Cochiti	3,88	4,187	9H-7, 56	75,96	10H-1, 9	75,99	75,98
C3N-1/C3R-1	C3n.1n/C3n.1r	Base Cochiti	3,97	4,300	10H-1, 70	76,60	10H-1, 101	76,91	76,76
C3R-1/C3N-2	C3n.1r/C3n.2n	Top Nunivak	4,10	4,493	10H-1, 130	77,20	10H-2, 11	77,51	77,36
C3N-2/C3R-2	C3n.2n/C3n.2r	Base Nunivak	4,24	4,631	10H-2, 11	77,51	10H-2, 41	77,81	77,66
C3R-2/C3N-3	C3n.2r/C3n.3n	Top Sidufjall	4,40	4,799	10H-3, 71	79,61	10H-3, 100	79,90	79,76
C3N-3/C3R-3	C3n.3n/C3N.3r	Base Sidufjall	4,47	4,896	10H-4, 126	81,66	10H-5, 11	82,01	81,84
C3R-3/C3N-4	C3N.3r/C3n.4n	Top Thvera	4,57	4,997	10H-5, 130	83,2	10H-6, 10	83,5	83,35
C3N-4/C3R-4(?)	C3n.4n/C3r	Base Thvera	4,77	5,235	10H-6, 71	84,11	10H-6, 100	84,4	84,255
C3R-4 (?) / (C3A) C3AN-1	C3R/C3An.1n		5,35	6,033	12H-2, 71	97,11	12H-2, 101	97, 41	97,26
C3AN-1/C3AR-1	C3An.1n/C3AN.1r		5,53		13H-1, 81	105,01	13H-111	105, 31	105,16
C3AR-1/C3AN-2	C3AN.1r/C3AN.2n		5,68		13H-2, 51	106,21	13H-2, 81	106,51	106,36
C3AN-2/C3AR-2	C3AN.2n/C3AN.2r		5,89		13H-6, 141	113,11	13H-7, 32	113,52	113,32

### 3.3 Palynological preparation

The palynological samples from ODP 642B, used in this thesis, were prepared by Malcolm J. Jones of the company Palynological Laboratory Services in Holyhead, United Kingdom. The samples were processed using standard preparation method (see e.g. Wood et al., 1996), described below and in Figure 10. In addition, *Lycopodium cavatum* spores were added to the samples to enable the determination of the absolute abundance of dinocysts and acritarchs, as described below (subchapter 3.4 The *Lycopodium* marker-grain method).

The specified weight of each sample (Table 3) was crushed with a hammer and bashing plate and placed into a 1 liter Tripour beaker. One *Lycopodium* tablet was then added prior to chemical degradation.

Calcium carbonate was removed by slowly adding 50% Hydrochloric acid (HCl) until the sample had stopped reacting. Subsequently, the beaker was topped up fully with water, stirred

and allowed to settle. The diluted supernatant liquid was then sieved through a 10 µm sieve cloth, and the collected residue returned to the beaker.

To remove silicate from the sample 100 ml of 60% Hydrofluoric acid (HF) was added and left for two days with periodical stirring. The sample was then topped up with water for dilution and the entire residue sieved and collected, before it was placed in a 250 ml Pyrex glass.

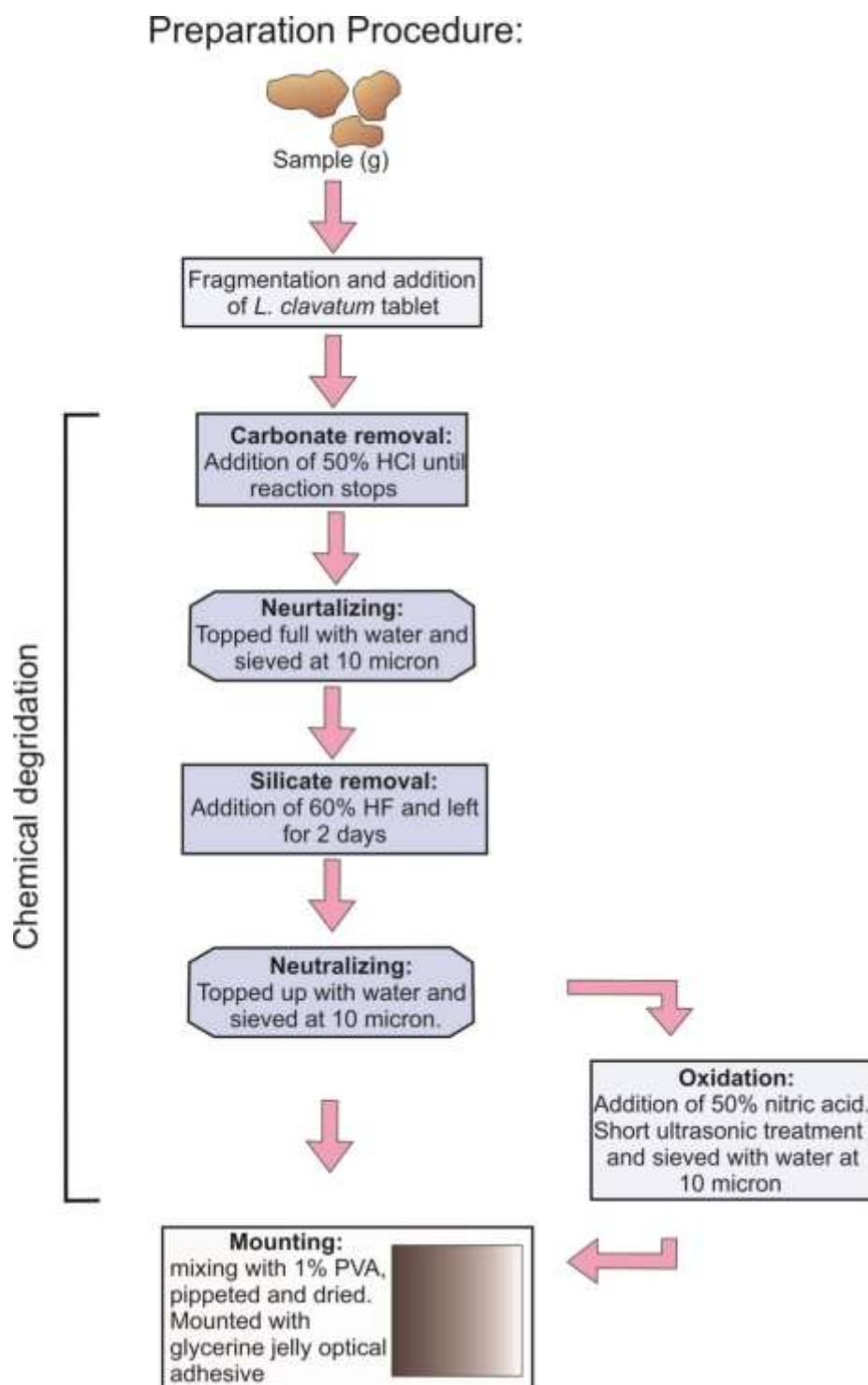
**Tabell 3:** An overview of the palynological preparation of the samples.

Palynological sample	Sample weight (g)	HCl treatment	HF treatment	Oxidation	Ultrasonic treatment	Stained
12F401	14,20	X	X			X
12F471	10,03	X	X			X
12G10	9,63	X	X			X
12G72	18,76	X	X			X
12G98	16,32	X	X			X
12 G102	10,89	X	X			X
12G104	6,74	X	X			X
12G105	8,50	X	X	X	X	X
12G132	11,92	X	X	X	X	X
12G135	11,84	X	X	X	X	X
11J378	10,15	X	X			
11J381	7,83	X	X			
11 J495	11,85	X	X			
11J498	8,87	X	X			
11J501	7,65	X	X			
11J507	7,42	X	X			
11J511	8,66	X	X			

Oxidation was carried out on three of the samples before mounting (Table 3). 50% cold nitric acid (HNO<sub>3</sub>) was then added to the residue in the beaker (in 25 ml of water) and left for the required time (depending on the preservation of the residue/palynomorphs present). A short 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.

Before mounting, the residue was mixed with a 1% solution of polyvinyl alcohol (PVA) to prevent clotting, and stained if necessary. It was then pipetted onto a 32x22mm cover slip on a low temperature drying plate and allowed to dry. Once dry, the coverslip was mounted onto the glass microscope slide using glycerine jelly optical adhesive. The slide was then cleaned and labeled with the appropriate sample details and lab number (Table 3), and checked under

the microscope to ensure that the residue was free of bubbles and that the distribution on the cover slip was correct.



**Figure 10:** The palynological preparation procedure used for the samples analyzed in the present study.

### 3.4 The *Lycopodium* marker-grain method

The dinoflagellate cyst and acritarch concentrations in this study have been calculated according to the method described by Stockmarr (1971).

A *Lycopodium clavatum* spore tablet (*Lycopodium clavatum* spores imbedded in calcium carbonate), produced by the University of Lund, Sweden, were added to the sample prior to chemical degradation. The tablets used were batch no. 483216 (number of spores  $18583 \pm 1708$ ). Palynological analysis was done, and *Lycopodium clavatum* spores were counted like the other palynomorphs in the samples. The number of dinoflagellate cysts/acritarchs in the samples was then calculated following the equation:

$$C = dc \times Lt \times t / Lc \times w$$

Where C = concentration/number of dinoflagellate cysts/acritarch per gram sediment, dc = number of counted dinoflagellate cysts/acritarchs, Lt = number of *Lycopodium* spores per tablet, t = number of tablets added to the sample, Lc = number of counted *Lycopodium* spores and w = weight of dried sediment (g).

The total error is calculated following the equation:

$$e = \sqrt{(e_1^2 + e_2^2 + e_3^2)}$$

Where  $e_1$  = error on number of *Lycopodium clavatum* spores in marked tablets,  $e_2$  (the square root of cyst/acritarchs counted divided by the cysts/acritarchs counted) = error on dinoflagellate cysts counted, and  $e_3$  (the square root of *Lycopodium clavatum* spores counted divided by the spores counted) = error on the number of *Lycopodium clavatum* spores counted.

### 3.5 Quantitative analysis

The identification of palynomorphs was done with a Zeiss Axiophot microscope in transmitted light. Magnifications used were 20x, 40x, and 100x (oil) on the lenses and a built-in plate in the microscope with magnifications 1.0x, 1.25x, 1.6x and 2.0x. Pictures of selected dinocysts and acritarchs were taken with a Zeiss AxioCam ERc5s on a Zeiss AxioImager.A2



microscope on a 100x objective. To record the location of species chosen for photography, an “England Finder” (abbreviated E.F. for the plates) was used.

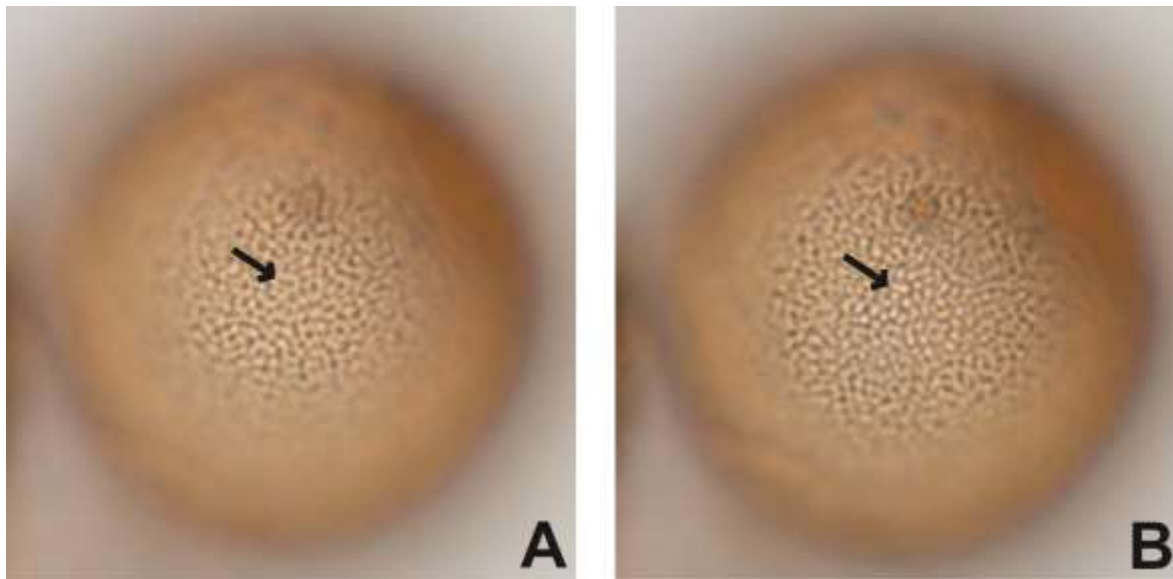
A minimum of 250 dinocysts were counted in each slide, together with acritarchs, spores, pollen, fresh water algae and the added *Lycopodium cavatum* spores. If broken, the palynomorphs were only counted if half or more of the original form was present. Where possible, the dinocysts were identified to species level. The counting was done along non-overlapping transverses with a 40 x objective lens. When at least 250 dinocysts had been counted in a slide, the rest of the slide was scanned with a 20 x objective lens to look for rare taxa/species not seen during the counts. These are included in the range chart (Appendix 1) and in Figure 14 (p. ...) with a “(+)” (present but not counted).

Some of the dinoflagellate cyst species were often difficult to recognize on the 40 x objective lens. This was particularly the case for the genera *Batiacasphaera*, *Pyxidinopsis* and *Bitectatodinium*, where the morphology of the wall and archeopyle is important for species recognition. When this was the case, a 100 x objective lens together with oil was used.

### 3.6 LO-analysis

The LO-analysis (L=lux/light, O=obscuritas/dark) was used to diagnose raised structures and depressions on the dinocyst walls, as described by Erdtman (1956), and was particularly important for distinguishing the genera *Filisphaera*, *Bitectatodinium*, *Pyxidinopsis* and *Habibacysta*.

In the LO-analysis the wall patterns of a palynomorph oriented 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”) if raised, and from dark to light (OL-patterns) if depressed. The method therefore presents an easy and effective way of recognize e.g. a reticulate wall from a scabrate wall (Figure 11).



**Figure 11:** The reticulate wall ornament of *Pyxidinospis braboi* (maximum diameter 35  $\mu\text{m}$ ) at two successive microscope adjustments of the higher focus. Arrow points to a depression, showed by an OL-pattern (dark to light). A: high focus. B: lower focus.

### 3.7 Systematic palynology

The different taxa found in this study were not given a formal description. Only for the taxa that do not fully fit a description, a short remark on the characteristics used for identifying these taxa is given in 4.2 Taxonomic remarks.

The generic names of taxa are abbreviated in the text and figures, but a list with full names is given in Appendix 3. A selection of dinoflagellate cyst and acritarch species considered as important for this thesis, are illustrated on Plate I–IV in Appendix 2.

When the preservation of the dinoflagellate cysts was not good enough for identification down to species level, identification down to genera was done. For some dinocysts even this was not possible and they were only counted as dinocyst spp. indet.

Some species were only grouped down to genera because of low stratigraphic value, e.g. most *Spiniferites* and *Achomosphaera*, which also were lumped together under *Spiniferites/Achomosphaera* spp. indet. Even though *Batiacasphaera minuta* is recognized as an important stratigraphic marker (e.g. De Schepper and Head, 2009), it was in the present study not differentiated from *Batiacasphaera micropapillata* because the species descriptions of the species overlap (Matsuoka and Head, 1992). The genera *Batiacasphaera* and *Pyxidinospis* were only differentiated when the archeopyle was visible, otherwise identification would have

been too time consuming, and these genera were lumped together as *Batiacasphaera/Pyxidinosia* complex.

Dinoflagellate cysts interpreted as reworked were not classified and only counted as reworked dinocysts spp. indet, as these were not important for the purpose of this thesis.

### 3.9 Biostratigraphy

The present study follows the terminology and abbreviation of De Schepper and Head (2008), where the abbreviation HO stands for highest in-situ occurrence, LO stands for lowest occurrence and HPO stands for highest persistent/continuous occurrence, even where the occurrence is marked by a few specimens only. An acme is defined by the highest occurrence of one particular species, and the numbers will therefore differ between different species.

For the establishment of the biostratigraphic zonation, Interval zones are used. An interval zone is defined as “the body of fossiliferous strata between two specified biohorizons” (Murphy and Salvador, 1999), and a biohorizon (full name biostratigraphic horizon) is defined as “a stratigraphic boundary, surface, or interface across which there is a significant change in biostratigraphic character” (Murphy and Salvador, 1999).

The classification of relative abundance of the dinoflagellate cysts and the acritarchs in the present study follows **Rare:** 0–2,9 %, **frequent:** 3–9,9 %, **common:** 10–29,9 %, **abundant:** 30–49,9 %, and **dominant**  $\geq$  50 %.



## CHAPTER 4

### RESULTS

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#### 4.1 Palynomorph preservation and sample spacing

The 17 palynological samples analyzed in this study contained mostly well-preserved palynomorph assemblages, making identification and counting relatively easy. The only exceptions were the samples 11G105 (depth 78.80 mbsf) and 12G135 (79.92 mbsf), where counting was difficult due to a very high concentration of palynomorphs and a large amount of amorphous material, and sample 11J511 (94.00 mbsf), where the color of the palynomorphs was very light and their preservation poor.

The spacing between the sample depths in the present study varies between a maximum of 4.19 meters (between 86.20 mbsf and 82.01 mbsf) and a minimum of 0.44 meters (between 77.36 mbsf and 77.80 mbsf). The average spacing is 1.77 meters. The age spacing between the samples varies between a maximum of 440 kyr (between depth 86.20 mbsf and 82.01 mbsf) and a minimum of 30 kyr (between depth 80.55 mbsf and 79.92 mbsf), with an average of 170 kyr (Figure 14).

#### 4.2 Taxonomic remarks

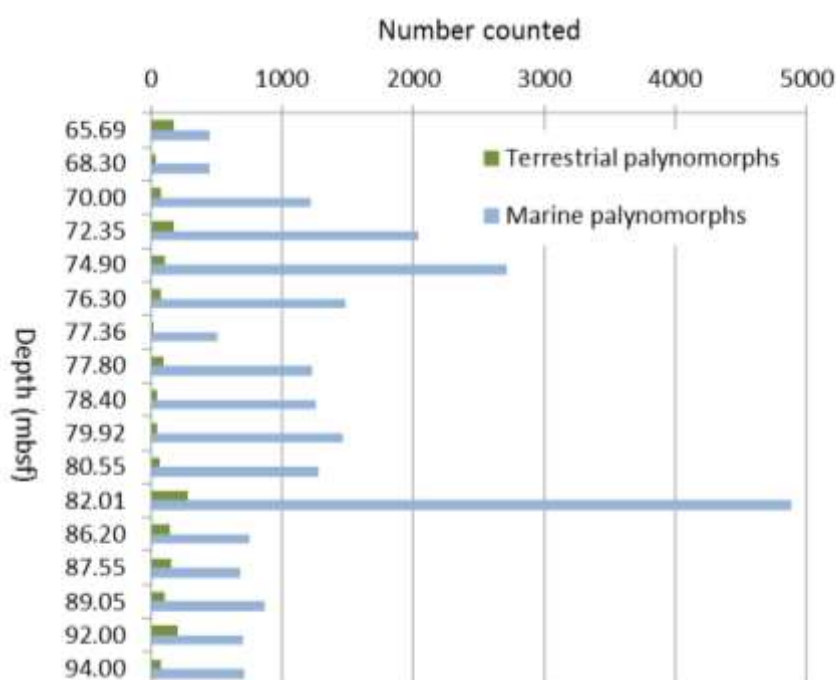
In the present study three informal dinoflagellate cyst taxonomical names are used:

- *Ataxiodinium?* sp. A (plate I, 2–4): This taxon looks similar to the genus *Ataxiodinium* in having a periblast seemingly connected by funnel shaped invaginations to the endoblast. However none of the observed taxa revealed an archeopyle, and the periblast was never clearly seen. This taxon may thus just represent bad preservation, but further studies are needed to confirm this.
- *Bitectatodinium* sp. A: This taxon represents a transitional form, as it shows typical morphological characteristics of both *Bitectatodinium raedwaldii* (circular pili) and *Bitectatodinium tepikiense* (pili fusing together to form irregular ridges).

- Small *Spiniferites/Achomosphaera* (plate II, 15 and 16): This taxon is similar to *Spiniferites/Achomosphaera* in having bifurcating and trifurcating process terminations, but has a maximum diameter of less than 25  $\mu\text{m}$ .

### 4.3 Palynomorph assemblages

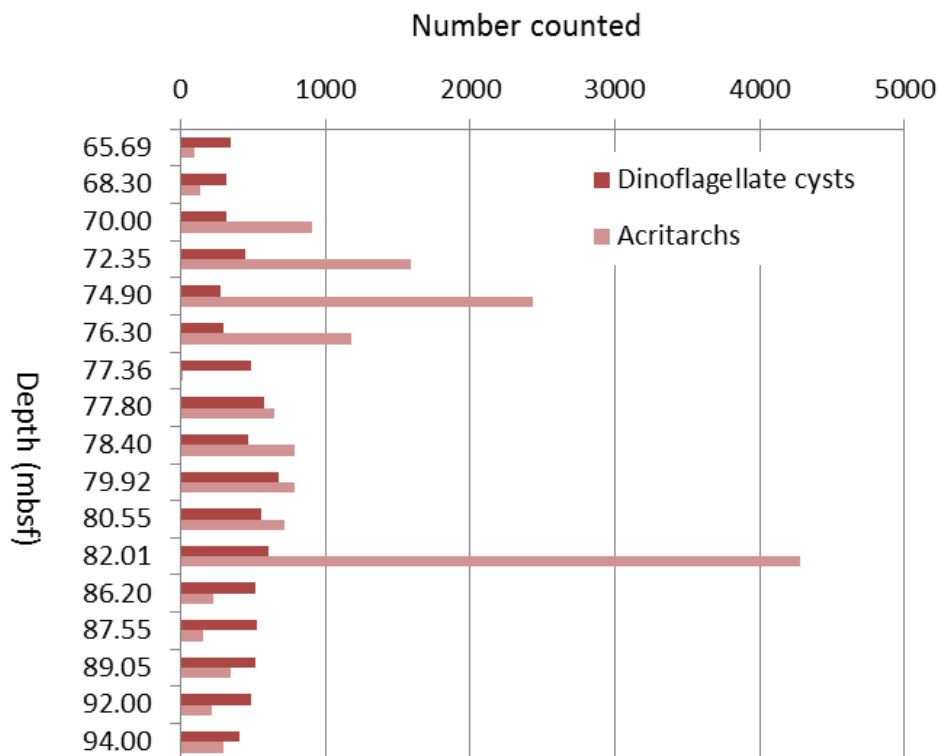
The palynomorph assemblages within the studied interval are dominated by marine taxa (dinoflagellate cysts and acritarchs). Terrestrial material (spores and pollen) occurs with an average of one terrestrial palynomorph per twenty marine palynomorphs. An exception is the youngest sample (depth 65.69 mbsf), where there is one terrestrial palynomorph for every three marine palynomorphs (Figure 12). The fresh water algae *Gelasinicysta vangeelii* is present in most of the samples, but with a low frequency. The palynomorphs reflect a marine environment on the Vøring Plateau during this time interval, with some continental input.



**Figure 12:** The relationship between marine palynomorphs (dinoflagellate cysts and acritarchs) and terrestrial palynomorphs within the studied interval.

## Dinoflagellate cysts

A total of 81 different dinoflagellate cyst taxa are recorded in the studied interval (Appendix 1). On average, there is a rich dinoflagellate cyst assemblage of 30 taxa per sample. The generally high diversity causes most taxa to occur only as rare to frequent, and no mono-specific intervals are recorded. Throughout the counted interval, *Nematosphaeropsis labyrinthus* (on average common), *Operculodinium? eirikianum* var. *eirikianum* (on average frequent) and *Spiniferites/Achomosphaera* spp. indet. (on average frequent), have a persistent occurrence. Other species, e.g. *Achomosphaera andalousiensis* subsp. *andalousiensis*, *Amiculosphaera umbraculum*, *Bitectatodinium* sp. A (this study), *Habibacysta tectata* and *Lingulodinium machaerophorum*, are also recorded throughout the studied interval, but with a more sporadic occurrence. Some species (*Invertocysta tabulata*, *Impagidinium solidum*, *Tuberculodinium vancampoeae*, *Lejeunecysta catomus* and *Pyxidinoopsis tuberculata*) are recorded only outside the regular count, others occur only in one sample (*Ataxiodinium confusum*, *Cerebrocysta namocensis*, *Nematosphaeropsis lativittata* and *Bitectatodinium tepikiense*).



**Figure 13:** The relationship between acritarchs and dinoflagellate cysts within the studied interval.

## Acritarchs

A total of 10 acritarch taxa were recorded for the studied interval, with an average diversity of five taxa per sample (Appendix 1). In some of the counted samples, the taxa *Cymatiosphaera? invaginata*, small spiny acritarchs and *Nannobarbophora walldalei* dominate the acritarchs assemblage. Acritarchs constitute a significant part of the palynological assemblage, and for most of the studied Pliocene interval (depth 82.01 mbsf to 70.00 mbsf) they outnumber the dinoflagellate cysts (Figure 13).

## Concentrations

The concentration of dinoflagellate cysts and acritarchs is high in the studied interval, with an average of 14,833 ( $\pm 3,183$ ) dinocysts/g and 21,211 ( $\pm 4,370$ ) acritarchs/g (Appendix 1). For the Miocene interval, an average concentration of 7,734 ( $\pm 1,072$ ) dinocysts/g and 4,137 ( $\pm 606$ ) acritarchs/g is recorded. For the Pliocene interval, the average is higher with 17,791 ( $\pm 4,062$ ) dinocysts/g and 28,325 ( $\pm 5938$ ) acritarchs/g.

In two Pliocene samples (depth 77.36 mbsf and 65.69 mbsf) a marked decline in dinoflagellate cyst diversity to respectively 17 and 18 is recorded (compared to an average of 30 taxa for the entire studied interval) (Appendix 1). A marked decline in the number of acritarch taxa occurred in the sample at depth 77.36 mbsf, where only one acritarch taxon is recorded (compared to an average of five taxa). The concentration of dinoflagellate cysts is still high for the sample at 77.36 mbsf (12,497 ( $\pm 1761$ ) cysts/g), whereas acritarch concentration is considerably lower (490 ( $\pm 130$ ) acritarchs/g). In addition, the concentration of pollen and spores is also low in this sample. For the sample at 65.69 mbsf, the marked decline in taxon richness is coeval with a low dinoflagellate cyst concentration and an acritarch concentration of 1,006 ( $\pm 117$ ) cysts/g and 271 ( $\pm 40$ ) acritarchs/g, respectively.



## Reworking

Reworking describes the phenomenon where fossils from older rocks are eroded, transported and redeposited in sediments of a younger age. In general, reworked dinoflagellate cysts are more susceptible to uptake of the staining agent safranin-O (used in palynological preparations), and are often broken as a result of the reworking process. Still, it is very problematic to recognize reworked specimens, which can lead to a dislocation of HOs and produce biostratigraphic boundaries that are too high. De Schepper and Head (2008) noted that sporadic occurrences above a species' persistent range might represent reworking.

Based on the concept used by De Schepper and Head (2008), sparse occurrences above the well-defined persistent range tops of *Ataxiodinium?* sp. A (this study), Cyst type 1 of Head and Mudie (1989), *Operculodinium tegillatum* and *Reticulatosphaera actinicornata* are in the present study interpreted as reworked (Figure 14). Reworking of dinoflagellate cysts older than the latest Miocene is also recorded and occurs in all samples. However, the number of reworked cysts constitutes a very small part of the dinoflagellate cyst assemblage, so reworking appears to be quite limited.

## Bioturbation

As mentioned earlier (3.1 Sampling site and sampling lithology), common to heavy bioturbation of the sampled sediments was reported by the Shipboard Scientific Party (1987). Bioturbation may lead to fossils being introduced into younger or older rocks, and can smooth out the signal of a species' HO, HPO and/or LO. However, because of the average sample spacing of 1.77 meters (170 kyr) in the present study, bioturbation is considered to be of limited importance.

## 4.4 Biozonation

Most of the recorded dinoflagellate cyst taxa are long ranging within the studied interval and are therefore of low stratigraphic value (Appendix 1). However, a selection of taxa which show clear trends and appear to be stratigraphically useful is shown in Figure 14. This selection has formed the basis for the biozonation.

The studied interval is, based on one HPO and two HO of the selected dinoflagellate species, divided into four interval biozones, and within each zone, dinoflagellate cyst and acritarch events that might be of local or regional correlative value, are also described. Pictures of the dinoflagellates defining the zone boundaries are shown in Appendix 2, together with most of the dinoflagellates and acritarchs listed as events.

The HOs, HPOs and LOs mentioned in the zonation relate to what has been recorded in the present study. Note that the given ages relate to the sample depth where an event occurs, but the upper and lower boundaries of the zones and events recorded in a sample, may range between this depth and the sample depth above and below, respectively.

#### 4.6.1 KMB-1 Interval Zone

**Definition:** The zone is defined as the body of strata whose uppermost limit is the HPO of *Selenopemphix brevispinosa*. The base of the zone is presently not defined by a biohorizon, and includes the lowermost part of the studied interval.

**Events:** At the top of the zone *Ataxiodinium?* sp. A (this study) and *Impagidinium* “*vermiculatum*” of Simon Petroleum Technology Limited (SPT) (1994) have their HO. The zone top is also marked by the HPO of *Selenopemphix dionaeacysta*, *Selenopemphix* spp. indet., *Tectatodinium pellitum* and *Trinovantedinium glorianum*. Near the top of the zone (depth 86.20 mbsf), *Ataxiodinium zevenboomii* appear to have its LO.

**Dinoflagellate cyst association:** The *Batiacasphaera/Pyxidinosia* complex is rare in this zone, except for the lowermost sample (depth 94.00 mbsf) where it is frequent. *Reticulatosphaera actinocoronata* occurs as frequent, except in the lowermost sample (depth 94.00 mbsf), where it is rare. *Habibacysta tectata*, *Barssidinium graminosum* and *Lejeunecysta* spp. indet occur consistently throughout the zone as rare. *Lingulodinium machaerophorum* (frequent at depth 94.00), *Tectatodinium pellitum* and *Impagidinium patulum* also have a consistent occurrence, but are recorded as rare or even outside the counts. *Invertocysta tabulata* has its only recorded occurrence within this zone, but occur sporadically, and was only registered outside the counts.

Depth (mbsf)		Core		Section		Interval (cm)		Total dinoflagellate cysts counted		Total acritarchs counted		Calibrated ages (Ma)																
65.69	8	6	129-130	349	97	3.08																						
68.30	9	2	40-41	313	137	3.35																						
70.00	9	3	60-61	313	905	3.60																						
72.35	9	4	145-146	444	1596	3.83																						
74.90	9	6	100-101	279	2432	4.08																						
76.30	10	1	40-41	301	1184	4.23																						
77.36	10	1	145-146	485	19	4.50																						
77.80	10	2	40-41	578	651	4.64																						
78.40	10	2	100-101	472	788	4.69																						
79.92	10	3	102-103	676	788	4.81																						
80.55	10	4	15-16	562	719	4.84																						
82.01	10	5	11-12	604	4283	4.91																						
86.20	11	1	80-81	522	225	5.35																						
87.55	11	2	65-66	527	157	5.44																						
89.05	11	3	65-66	518	353	5.53																						
92.00	11	5	60-61	492	213	5.71																						
94.00	11	6	110-111	412	307	5.83																						
Selenopemphix brevispinosa																												
Ataxiodinium? Sp. A																												
Impagidinium vermiculata SPT																												
Selenopemphix dioneacysta																												
Selenopemphix spp. indet																												
Tectatodinium pellitum																												
Trinovantedinium glorianum																												
Ataxiodinium zevenboomii																												
Reticulatosphaera actionocoronata																												
Operculodinium tegillatum																												
Cyst type 1 of Head and Mudi (1989)																												
Lejeunecysta spp. indet																												
Bitectatodinium raedwaldii																												
Filisphaera filifera subsp. filifera																												
Corrudinium harlandii																												
Impagidinium sp. 2 of De Schepper and Head (2009)																												
Round Brown Cyst																												
Operculodinium? eirikianum var. crebrum																												
Bitectatodinium? Serratum																												
Barssidinium pliocenicum																												
Filisphaera filifera subsp. pilosa																												
Operculodinium centrocarpum s.s.																												
Operculodinium centrocarpum sensu Wall and Dale (1966)																												
Impagidinium sp. 1 of De Schepper and Head (2009)																												
Small spinifirites/Achomosphaera spp. indet																												
Baticasphaera micropapillata																												
Corrudinium devermalie																												
Spinifirites elongatus																												
Filisphaera microornata																												
Ataxiodinium choane																												
Barssidinium graminosum																												
Corrudinium? Labradori																												
Invertocysta lacrymosa																												
Melitisphaeridium choanophorum																												
Cymatiosphaera? Invaginata																												
Cymatiosphaera? aegirii																												
Cymatiosphaera iecenorum																												
Lavradosphaera crista																												
Nannobarbophora walldalei																												
Biozonation																												

**Acritarch association:** Small spiny acritarchs dominate the acritarch assemblage for most of the zone and *Cymatiosphaera? invaginata* occurs as abundant, but at the zone top *Cymatiosphaera? invaginata* becomes slightly more abundant than small spiny acritarchs. *Cymatiosphaera? aegirii*, *Cymatiosphaera? icenorum* and *Nannobarbophora walldalei* are present within the zone, but with a low and sporadic occurrence.

**Reference section:** The reference section for the KMB-1 Interval Zone is in Hole ODP 642B, from 86.20 mbsf in core section 642B-11H-1A to 94.00 mbsf in core section 642B-11H-6A. Five samples were counted for the interval.

**Age:** Late Messinian, from >5.83 Ma to 5.35 Ma, giving the zone a duration of at least 480 kyr.

**Remarks:** Dinoflagellate cysts are the dominant palynomorphs within the zone, with an average concentration of 7,734 ( $\pm$  1,072) cysts/g. Acritarchs have an average concentration of 4,136 ( $\pm$  606) acritarchs/g. The relationship between marine and terrestrial palynomorphs is on average twenty-one marine palynomorphs for every terrestrial palynomorph.

Whether *Ataxiodinium? sp. A* (this study) is a new species or represents a poorly preserved *Ataxiodinium* species is still unclear. In the case of a new species this can be used to identify the top of the zone in areas where *Selenopemphix brevispinosa* is missing or is poorly preserved.

#### 4.6.2 KMB-2 Interval Zone

**Definition:** This zone is defined from the HPO of *Selenopemphix brevispinosa* to the HO of *Reticulatosphaera actinocoronata*.

**Events:** The zone also represents the concurrent range of *Operculodinium tegillatum*, which has its LO near the base of the zone (depth 82.01 mbsf) and HO at the top of the zone. At the zone top, Cyst type 1 of Head and Mudie (1989) is abundant and has its HO. The top of the zone is also marked by the HO of *Lejeunecysta* spp. indet. Within the zone *Bitectatodinium raedwaldii* (depth 80.55 mbsf) has a LO. At the base of the zone (depth 82.01 mbsf) is the first recorded occurrence (LO) of *Filisphaera filifera* subsp. *filifera*, *Corrudinium harlandii*

and *Impagidinium* sp. 2 of De Schepper and Head (2009). The zone base is also marked by a high abundance of Round Brown Cysts.

**Dinoflagellate cyst association:** The *Batiacasphaera*/*Pyxidinosphaera* complex occurs as frequent in the zone, except in the uppermost part (depth 77.80 mbsf) where it is rare. *Corrudinium?* *labradori*, *Corrudinium devernaliae*, *Impagidinium pallidum* and *Reticulosphaera actinocoronata* all have a consistent occurrence as rare throughout the zone. *Barssidinium graminosum* and *Lejeunecysta* spp. indet, are also recorded with an consistent occurrence within the zone. *Operculodinium tegillatum* occurs as frequent within the zone, except in one sample (depth 79.92 mbsf) where it occurs as common. An increase of *Nematosphaeropsis labyrinthus* to common also occurs within the zone (depth 80.55 mbsf). *Bitectatodinium raedwaldii* occurs sporadically.

**Acritarch associations:** The zone represents the acme of *Cymatiosphaera?* *invaginata* which has an influx at the base (depth 82.01 mbsf) and dominates the acritarch assemblage throughout the zone. Small spiny acritarchs occur as common in the lowermost part (depth 82.01 mbsf) and as abundant throughout the rest of the zone. *Cymatiosphaera?* *aegirii* is not observed in the zone, while *Cymatiosphaera icenorum* occurs as rare throughout the zone. *Nannobarbophora walldalei* has a more consistent occurrence compared to in the KMB-1 zone.

**Reference section:** The KMB-2 Interval Zone reference section is in ODP Hole 642B, from 82.01 mbsf in core section 642B-10H-5A to 77.80 mbsf in core section 642B-10H-2A. Five samples were counted for this interval.

**Age:** The zone is of Zanclean age, from 4.91 Ma to 4.64 Ma, giving the zone a duration of 270 kyr.

**Remarks:** Acritarchs are the dominant palynomorph group within the zone with an average concentration of 51,635 ( $\pm$  11,939) acritarchs/g. Dinoflagellate cysts also occur in higher numbers within this zone compared to the KMB-1 zone, with an average of 35,873 ( $\pm$  8,777) cysts/g. The average marine versus terrestrial palynomorph relationship is 23 marine palynomorphs for every terrestrial palynomorph.

*Reticulatosphaera actinocoronata* was by Mudie (1989) recorded with a HO in ODP 642B-14-CC (core catcher) and was for ODP Hole 642B not recorded for the time interval counted in the present study. However in ODP Hole 642C this species was recorded to range higher, to an age of 4.2 Ma (Mudie, 1989, Schreck et al., 2012).

The LO of *Filisphaera filifera* was also recorded by Mudie (1989), but in younger sediments (sample ODP 642B-9-CC).

#### 4.6.3 KMB-3 Interval Zone

**Definition:** The zone is defined from the HO of *Reticulatosphaera actinocoronata* to the HO of *Operculodinium? eirikianum* var. *crebrum*.

**Events:** *Bitectatodinium? serratum* and *Barssidinium pliogenicum*, and *Filisphaera filifera* subsp. *pilosa* appear to have their HO at the top of the zone. Within the zone *Ataxiodinium zevenboomii* (depth 76.30 mbsf), *Baticasphaera micropapillata* (depth 72.35 mbsf), *Operculodinium centrocarpum* s.s (depth 76.30 mbsf), *Impagidinium* sp. 1 of De Schepper and Head (2009) (depth 76.30 mbsf) and small *Spiniferites/Achomosphaera* spp. indet (depth 74.90 mbsf) have their HO. *Spiniferites elongatus* (depth 72.35 mbsf), *Operculodinium? eirikianum* var. *crebrum* (depth 72.35 mbsf) and *Filifera microornata* (depth 74.90 mbsf) are recorded for the first time (LO) within the zone. At the zone base, *Operculodinium centrocarpum* s.s and *Operculodinium centrocarpum* sensu Wall and Dale (1996) increase in abundance and become common, and *Corrudinium devernaliae* has its HO.

**Dinoflagellate cyst association:** The occurrence of *Achomosphaera andalousiensis suttonensis* (depth 70.00 mbsf and 72.35 mbsf), *Ataxiodinium confusum* (depth 70.00 mbsf), *Cerebrocysta namocensis* (depth 72.35 mbsf) and *Impagidinium solidum* (depth 72.35 mbsf) is restricted to this zone. *Corrudinium? labradori*, *Impagidinium pallidum* (frequent at 74.90 mbsf) and *Impagidinium paradoxum* are rare but consistently present. At the base of the zone there is a marked decrease in species diversity. In the sample above (depth 76.30) diversity again increases, and *Ataxiodinium choane* (rare), *Bitectatodinium raedwaldii* (rare), *Bitectatodinium* sp. A (rare to frequent), *Corrudinium harlandii* (rare), *Impagidinium* sp. 2 of De Shepper and Head (2009) (rare), Cyst of *Pentapharsidinium dalei* (rare) and *Pyxidropsis*

*braboi* (rare to frequent) occur as persistent throughout the zone. *Operculodinium centrocarpum* sensu Wall and Dale (1996) occurs as common to abundant.

**Acritarch assemblage:** At the zone base, a species decline also affects the acritarchs. After the decline the zone represents the acme of *Cymatiosphaera? Icenorum* (abundant at 72.35 mbsf), and *Lavradosphaera crista* (frequent at 72.35 mbsf) which on average occur as common. After being absent in the zone below, *Cymatiosphaera? aegirii* is again occurring (depth 76.30 mbsf), with a persistent range throughout the rest of the zone. Small spiny acritarchs are the most common acritarchs within the zone.

**Reference section:** The reference section of the KMB-3 Interval Zone is in ODP Hole 642B from 77.36 mbsf in core section 642B-10H-1A to 70.00 mbsf in core section 642B-9H-3A. Five samples were counted for the interval.

**Age:** The age of the zone is Zanclean, from between 4.50 to 3.60 Ma, giving a duration of 900 kyr.

**Remarks:** Acritarchs are the dominant palynomorphs within the zone with an average concentration of 15,990 ( $\pm$  2,261) acritarchs/g. Dinoflagellate cysts occur with an average of 5,939 ( $\pm$  856) cysts/g. The relationship between marine versus terrestrial palynomorphs are twenty-two marine palynomorphs for every terrestrial palynomorph.

#### 4.6.4 KMB-4 Interval Zone

**Definition:** The zone is defined from the HO of *Operculodinium? eirikianum* var. *crebrum*. The top of the zone is presently undefined and includes the uppermost part of the studied interval.

**Events:** No certain events are recorded for the KMB-4 Interval Zone. However, at the base of the zone several species (e.g. *Ataxiodinium choane*, *Barssidinium graminosum*, *Corrudinium harlandii*, *Corrudinium? labradori*, *Invertocysta lacrymosa*, *Melitasphaeridium choanophorum*, *Filisphaera microornata*, and *Spiniferites elongatus*) seem to have HOs. But this is the second uppermost sample counted, and younger palynological samples need to be investigated before this can be concluded. Mudie (1989) did record *Corrudinium harlandii*,

*Ataxiodinium choane* and *Spiniferites elongatus* in the early Pleistocene of ODP Hole 642B, illustrating that these events are not HOs.

**Dinoflagellate cyst association:** *Habibacysta tectata*, which has been rare in the deeper zones, becomes frequent within this zone. *Operculodinium centrocarpum* Wall and Dale (1966) is the dominant species in the zone and occurs as abundant. *Bitectatodinium raedwaldii*, *Bitectatodinium* sp. A (frequent at depth 65.69 mbsf) and *Impagidinium pallidum* have a consistent occurrence as rare.

**Acritarch association:** *Cymatiosphaera?* *invaginata* occurs as rare to common, *Cymatiosphaera?* *aegirii* as frequent, *Cymatiosphaera?* *icenorum* as common to rare, and small spiny acritarchs as abundant to common. *Lavradosphaera crista* is absent in the uppermost part (depth 65.69 mbsf). The uppermost part is also marked by an influx of *Nannobarbophora walldalei* which becomes the dominant species

**Reference section:** The reference section for the KMB-4 interval zone is from 68.30 mbsf in core section 642B-9H2A to 65.90 mbsf in core section 642B-8H6A. Two samples were counted for the interval.

**Age:** The age of the zone within the counted interval is Piacenzian, from between 3.60 Ma to <3.08 Ma, indicating a duration of at least 520 kyr.

**Remarks:** Dinoflagellate cysts again become the dominant palynomorph group within this zone (as in the KMB-1 Interval Zone) with an average concentration of 2,219 ( $\pm$  286) cysts/g. Acritarchs have a low concentration of 887 ( $\pm$  131) acritarchs/g. The average relationship between marine and terrestrial palynomorphs is eight marine for every terrestrial.



## CHAPTER 5

### COMPARISON, CORRELATION AND DISCUSSION

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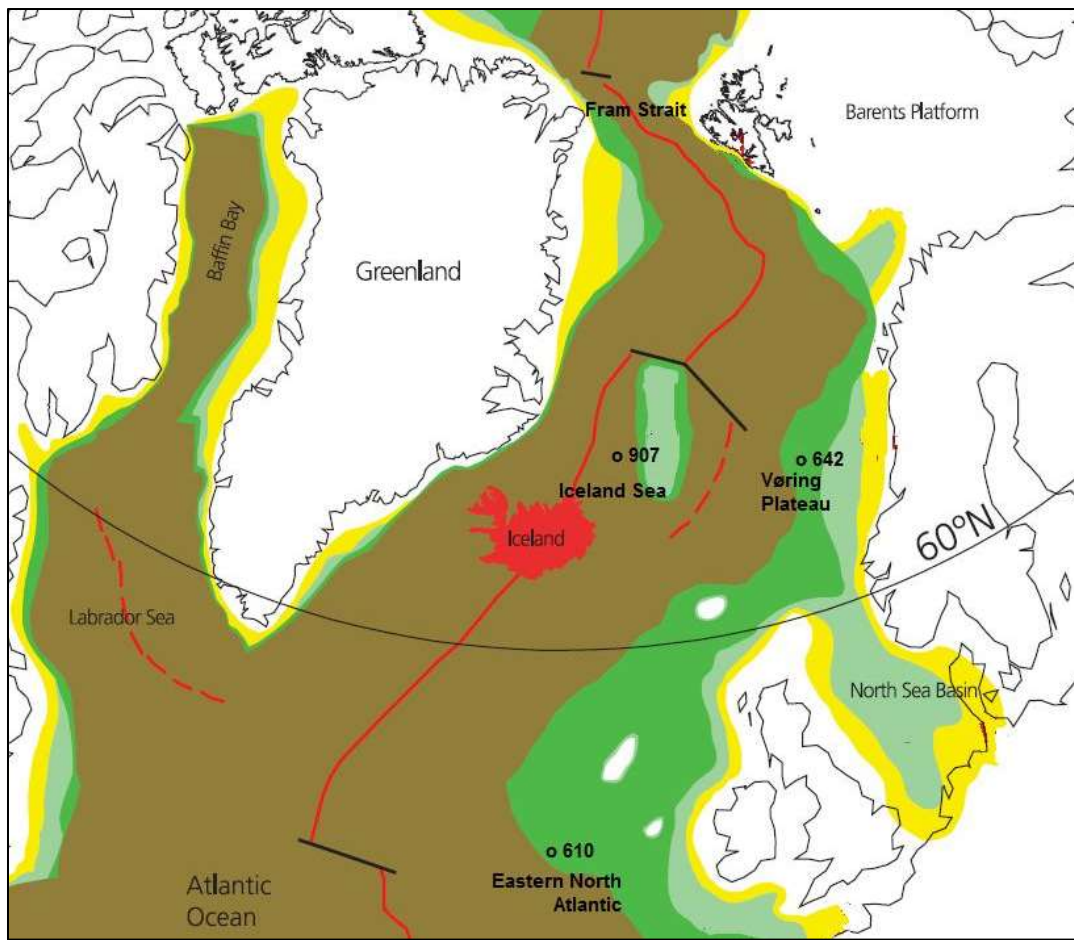
#### 5.1 Comparison with Mudie (1989)

As noted by Mudie (1989) many of the dinoflagellate cysts and acritarchs she recorded had not yet been described and given formal names, and in her report informal taxonomy was thus frequently used. During the twenty-four years that have elapsed since then, new taxonomical studies on dinoflagellate cysts and acritarchs have been done and new species have been defined (e.g. Head, 1997; Head and Norris, 2003; De Schepper et al., 2008). This has caused the work by Mudie (1989) (see 1.6 Previous studies and Figure 16) to be partially outdated, as species defined later than 1989 are now used in biozonations (e.g. De Schepper and Head, 2009).

The reinvestigation of ODP Hole 642B in the present study has successfully recorded several species described after 1989, notably *Operculodinium tegillatum* and *Corrudinium devernaliae* (see Appendix 3 for more). This has now allowed a more detailed late Messinian to early Piacenzian comparison between ODP Hole 642B and more recent studies.

#### 5.2 Comparison and correlation with other mid- to high-latitude biozonations

In this chapter the late Messinian to early Piacenzian biostratigraphic zones of the eastern North Atlantic (De Schepper and Head, 2009), eastern part of the North Sea (Denmark) (Dybkjær and Piasecki, 2010), and the Iceland Sea (Schreck et al., 2012) are briefly described one by one. The zones in each of these works are compared to, and where possible, correlated with the biostratigraphic zones and events defined in the present study.



**Figure 15:** Pliocene (3 Ma) paleogeographic map of Europe with an approximate location of the biozonations compared to the present study. 907 = ODP Hole 907A (Schreck et al., 2012), 642 = ODP Hole 642B (the present study), North Sea (Denmark) (Dybkjær and Piasecki, 2010), and 610 = DSDP Hole 610A (De Schepper and Head, 2009). The colors on the map shows as followed: Yellow = deltaic-shallow marine, pale green = shallow marine, dark green = deeper marine, and brown = basins formed by oceanic crust. Modified from Torsvik et al. (2002).

When comparing events between different sites, there is always an age uncertainty. Notably, inaccuracies are associated with constructions of age models and sample spacing, which may lead to a too large or too low age difference between the occurrences of species. In the present study, and in the studies by De Schepper and Head (2009) and Schreck et al. (2012), the zone boundaries and events are tied to magnetostratigraphy, while the zonation in eastern part of the North Sea (Denmark) (Dybkjær and Piasecki, 2010) is tied to biostratigraphically derived ages. In the following discussion the ages recorded by the above authors are used in the comparison.

### 5.2.1 Eastern North Atlantic

De Schepper and Head (2008) presented an Early Pliocene through Early Pleistocene age calibration of dinocysts and acritarch events for Rockall Trough DSDP Hole 610A in the eastern North Atlantic. Based on species' HO, HCO, LO and HPO, a total of 32 dinoflagellate and acritarch biostratigraphic events were defined. Based on these events, De Schepper and Head (2009) established 8 biozones, of which 5 (abbreviated RT1 to RT5) are of Zanclean to Piacenzian age (Figures 16 and 17).

In Hole ODP 642B, several of the species recorded as important events within the RT1 to RT5 zones and also species used to define the zone boundaries are not recorded (*Pyxidínopsis vesiculata*, *Lavradosphaera lucifer*, *Leiosphaera rockhallensis*, Algal cyst type 1 of Head (1996) and *Edwardsiella sexispinosa*), or only registered in one sample or outside counts (*Ataxiodinium confusum*, *Impagidinium solidum*, *Pyxidínopsis tuberculata* and *Nematosphaeropsis lativittata*). A comparison and correlation with these species to the present study is thus not possible, and they will only be included in the discussion below when they define zone boundaries.

**The *Corrudinium devernaliae* Assemblage Biozone (RT1)** of De Schepper and Head (2009) has currently an undefined base. The top is defined by the HO of *Corrudinium devernaliae* and the zone is of Zanclean age ( $\geq 4.00$ –3.90 Ma). Within the zone the acritarch *Lavradosphaera crista* (3.98 Ma) has LO.

In the present study the HO of *Corrudinium devernaliae* is recorded as an event in the basal part of the KMB-3 interval Zone. The HO is in ODP Hole 642B recorded at 4.50 Ma, which implies a 600 kyr earlier HO than in the eastern North Atlantic. The HO of *Corrudinium devernaliae* can be considered as a Zanclean event in the eastern Norwegian Sea and the eastern North Atlantic, but the large diachronicity of the events in the two basins does not make it useful for detailed high-resolution correlation. The age difference of its HO suggests different environmental control on both basins (see below in the comparison with the Iceland Sea).

The LO of the acritarch *Lavradosphaera crista* registered for the eastern North Atlantic (De Schepper and Head, 2009), is not registered for ODP Hole 642B, where this species ranges throughout the studied interval. The LO of this acritarch is thus older than or equal to 5.83 Ma. This could be caused by different oceanographic settings in the two basins. The

distribution of the acritarch genus *Lavradosphaera*, suggests an affinity for cool-temperate waters (De Schepper and Head, 2013), which could explain an earlier occurrence in the eastern Norwegian Sea.

**The *Batiacasphaera minuta* Interval Zone (RT2)** of De Schepper and Head (2009) is defined from the HO of *Corrudinium devernaliae* to the HO of *Batiacasphaera minuta*. The age of the zone is Late Zanclean (3.87–3.83 Ma).

In the present study *Batiacasphaera minuta* was not differentiated from *Batiacasphaera micropapillata* (see 3.5 Quantitative analysis), hampering the comparison. However in ODP Hole 642B the HO of *Batiacasphaera micropapillata* is recorded within the KMB-3 Zone at the same age (3.83 Ma) as the HO of *Batiacasphaera minuta* in the eastern North Atlantic. Based on the genus *Batiacasphaera*, a correlation between the KMB-3 Zone and the RT2 Zone thus seems possible, and suggests a good correlative event between the two basins, despite differences in oceanography.

**The *Operculodinium tegillatum* Interval Zone (RT3)** of De Schepper and Head (2009) is of Late Zanclean age (3.82–3.71 Ma), and extends from the HO of *Batiacasphaera minuta* to the HO of *Operculodinium tegillatum*.

In ODP Hole 642B the HO of *Operculodinium tegillatum* is recorded at 4.64 Ma, and marks the upper boundary of the KMB-2 Interval Zone. A Zanclean correlation between the upper boundary of the RT3 Interval Zone and KMB-2 Interval Zone, based on the HO of *Operculodinium tegillatum*, is thus possible. However, the large diachronicity of 930 kyr between the events in the two basins does not make this a good correlation. *Operculodinium tegillatum* is regarded as a warm-temperate species (Head, 1997), which supports an earlier HO in the eastern Norwegian Sea, as a response to differential cooling and/or oceanographic changes (See below in the comparison with the Iceland Sea).

**The *Impagidinium solidum* Interval Zone (RT4)** of De Schepper and Head (2009) covers the strata between the HO of *Operculodinium tegillatum* and the HO of *Impagidinium solidum*. The zone age ranges from the late Zanclean to the early Piacenzian (3.70–3.15 Ma). The top of the zone is also marked by the LO of *Pyxidinospis braboi* (3.15 Ma), and within the zone *Filisphaera microornata* (3.67 Ma) and *Operculodinium? erikianum* var. *crebrum* (3.33 Ma) have their LOs.

In the present study *Impagidinium solidum* was only recorded in one sample, outside counts. A comparison and correlation between the eastern North Atlantic and the eastern Norwegian Sea based on this species is therefore not possible. *Impagidinium solidum* is considered a warm water species (De Schepper et al., 2011), which probably explains its lower representation in the eastern Norwegian Sea compared to the eastern North Atlantic. The first record of *Pyxidinosia braboi* in the present study is at 5.53 Ma, implying a 2.38 Ma earlier occurrence in the eastern Norwegian Sea. This large LO age difference between the two basins does not suggest a good correlative event, and proposes a paleoclimatic control on the species.

The events recorded within the RT4 Interval Zone of De Schepper and Head (2009) are also recorded for ODP Hole 642B, as events within the KMB-3 Interval Zone (4.64–3.60 Ma). In ODP Hole 642B *Filisphaera microornata* has LO at 4.08 Ma (410 kyr earlier than in the eastern North Atlantic) and *Operculodinium?* *erikianum* var. *crebrum* has LO at 3.83 Ma (500 kyr earlier than in the eastern North Atlantic). The age difference of the species' LOs between the two basins, again suggests paleoenvironmental control. *Operculodinium?* *erikianum* var. *crebrum* is considered to prefer a sea surface temperature range of 12.5–18.5 degrees Celsius in the North Atlantic (De Schepper et al., 2011), but whether this is the cause of the diachronicity needs to be looked more into.

A correlation between the RT4 Interval Zone and the KMB-3 Interval Zone based on the LOs of *Operculodinium?* *erikianum* var. *crebrum* and *Filisphaera microornata* is possible, but the large age difference between these events in the RT4 and KMB-3 zones does not suggest a good correlation.

**The *Invertocysta lacrymosa* Interval Zone (RT5)** of De Schepper and Head (2009) stretches from the middle to the late Piacenzian (3.15–2.74 Ma) and is defined from the HO of *Impagidinium solidum* to the HO of *Invertocysta lacrymosa*. Within the zone *Operculodinium janduchenei* (2.90 Ma), *Operculodinium eirikianum* var. *crebrum* (2.82 Ma) and *Barssidinium graminosum* (2.74 Ma) have their HO.

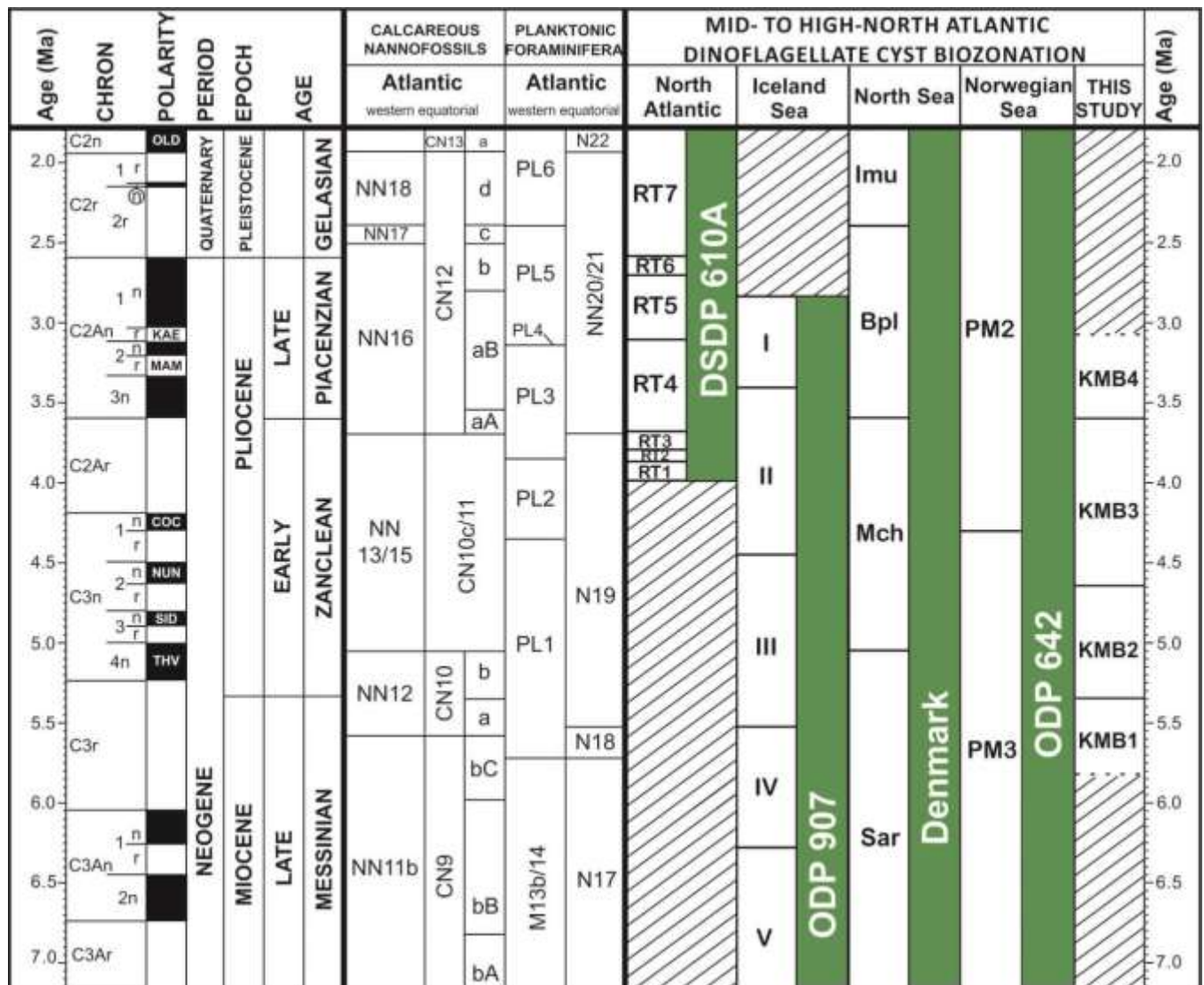
In the present study *Invertocysta lacrymosa* is only recorded as rare or outside counts. This species is considered to have an affinity for warmer waters (De Schepper et al., 2011; Versteegh and Zonneveld, 1994), which could explain why it is less common in the eastern Norwegian Sea than in the eastern North Atlantic. In the uppermost sample investigated for

ODP Hole 642B, this species is no longer observed. However, whether this represents its HO in the second uppermost sample at 3.35 Ma in the eastern Norwegian Sea is currently not concluded, and a correlation is therefore difficult. But its warmer water affinity would suggest an earlier HO in the eastern Norwegian Sea than in the eastern North Atlantic.

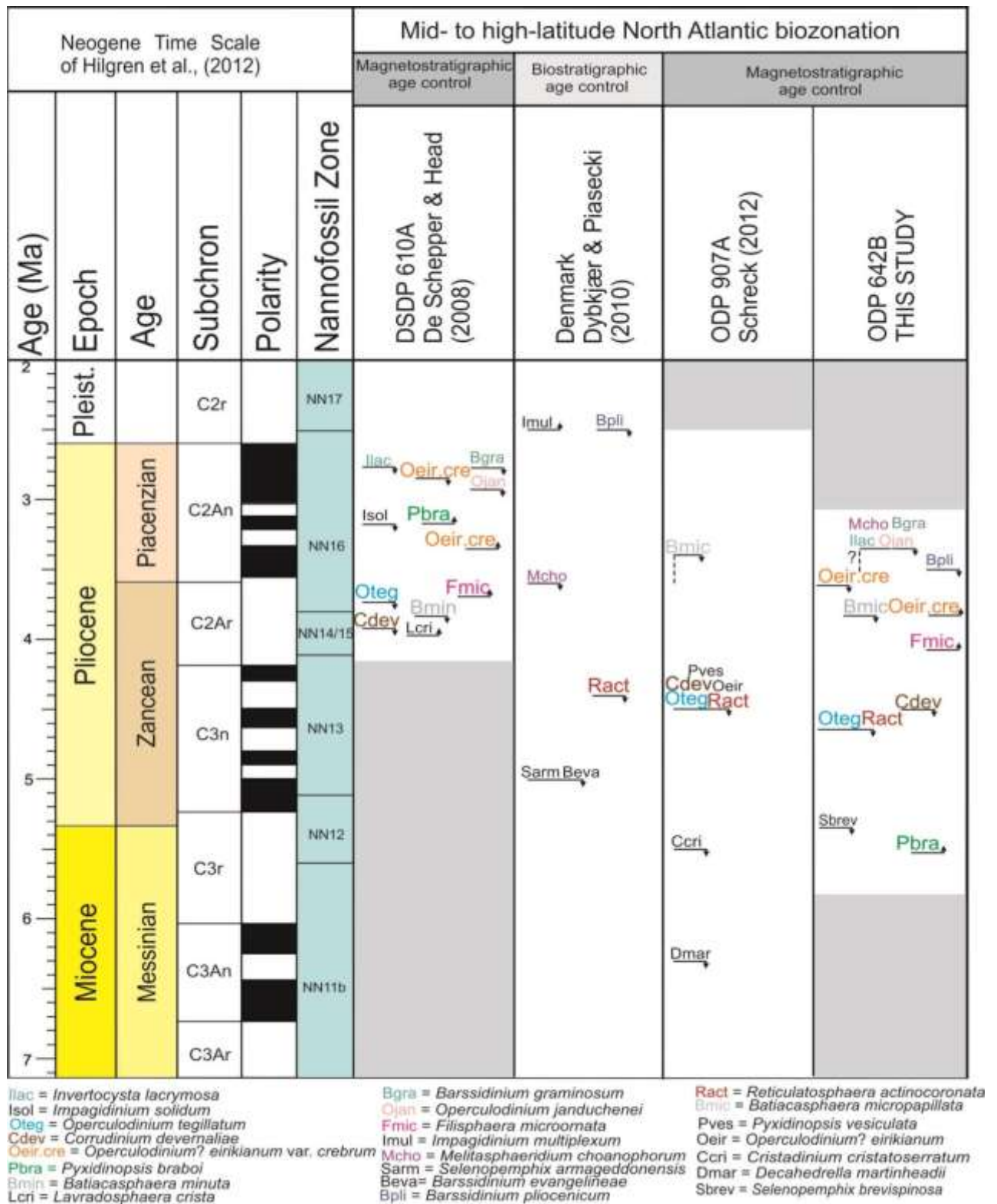
The HOs of *Barssidinium graminosum* and *Operculodinium janduchenei* recorded in the eastern North Atlantic (De Schepper and Head, 2009), is difficult to correlate to the present study. In the present study these species are, like *Invertocysta lacrymosa*, not recorded in the uppermost sample, and whether these three species have HOs in the second uppermost sample cannot currently be concluded.

A HO of *Operculodinium eirikianum* var. *cerebrum*, recorded as an event within the RT5 Interval Zone of De Schepper and Head (2009) is also recorded in the present study, where it defines the upper boundary of the KMB-3 Interval Zone (at 3.60 Ma). This suggests a 780 kyr older HO of this species within the eastern Norwegian Sea, than in the eastern North Atlantic, and is not considered a good correlative event. The temperature range (12.5–18.5 degrees Celsius) recorded for *Operculodinium eirikianum* var. *crebrum* (De Schepper et al., 2011), could explain an earlier HO in the eastern Norwegian Sea than in the eastern North Atlantic.





**Figure 16:** Mid- to high latitude dinoflagellate cyst biozonations. Eastern North Atlantic DSDP Hole 610A (De Schepper and Head, 2009), Iceland Sea ODP Hole 907A (Schreck et al., 2012; De Schepper, pers. comm. 2013), Eastern North Sea (Denmark) (Dybkjær and Piasecki, 2010), and (Mudie, 1989). Modified from S. De Schepper (pers. comm. 2013).



**Figure 17:** Comparison of the important dinoflagellate cyst and acritarch events of DSDP Hole 610A (De Schepper and Head, 2009), Denmark (Dybckjær and Piasecki, 2010) and ODP Hole 907A (Schreck et al., 2012) and comparable events of this study. The species suggesting correlation are marked with color, whereas the species of the above listed studies, not recorded in the present study, are black. Events defining zone boundaries are shown on the left, whereas events within the zones are on the right. Arrows pointing down indicate HO, arrows pointing up indicate LO, and dashed vertical lines attached to arrows indicate uncertainty. Modified from Schreck et al. (2013).



### 5.2.2 The eastern part of the North Sea (Denmark)

In the eastern part of the North Sea (Denmark) Dybkjær and Piasecki (2010) established a dinoflagellate cyst zonation for the late Oligocene through the early Pleistocene. Ten new zones were defined and nine previously defined zones were included. Three of these zones (abbreviated herein as Sar, Mch and Bpl) encompass the Messinian and Piacenzian (Figures 16 and 17).

**The *Selenopempix armageddonensis* Zone (Sar)**, originally defined by de Verteuil and Norris, (1996) (Dybkjær and Piasecki, 2010), is of latest Tortonian to earliest Zanclean age (7.6–5.0 Ma). The zone extends from the HO of *Hystrichosphaeropsis obscura* (zone base) to the HO of *Barssidinium evangelinae* (zone top), and the range of *Selenopempix armageddonensis* is assumed to approximate the range of the zone.

The youngest part of the *Selenopempix armageddonensis* Zone should in theory (based on age) be comparable with the KMB-1 Interval Zone (>5.83–5.35 Ma) and the oldest part of the KMB-2 Interval Zone (5.35–4.64 Ma) (Figure 16). However, a correlation of the zones based on biostratigraphic events is impossible as the species used for defining the *Selenopempix armageddonensis* Zone are not recorded in ODP Hole 642B. The reason why *Selenopempix armageddonensis* and *Barssidinium evangelinae* are not present may be caused by different oceanographic settings in the North Sea and eastern Norwegian Sea, as the North Sea was an epicontinental basin throughout most of the Neogene, restricted by land masses, and the only connection to the North Atlantic Ocean was a narrow strait between the Shetland Isles and Norway (Figure 15), while the Vøring Plateau in the Neogene was under fully open marine conditions (see chapter 2.3 Oceanography).

**The *Melitasphaeridium choanophorum* Zone (Mch)**, originally defined by Powell (1992) (Dybkjær and Piasecki, 2010), is of Zanclean age (5.0–3.6 Ma) and is defined from the HO of *Barssidinium evangelinae* to the HO of *Melitasphaeridium choanophorum*. Within the zone *Reticulatosphaera actinocoronata* has a HO, set to 4.4 Ma based on North Atlantic deep sea drillings by Louwye et al. (2004) (Dybkjær and Piasecki, 2010).

The age set to the upper boundary of the *Melitasphaeridium choanophorum* Zone corresponds with the age of the upper boundary of the KMB-3 interval zone (also 3.6), but the events defining these boundaries differ.

*Melitasphaeridium choanophorum* is recorded in the present study, but occurs as rare or outside counts. In the uppermost sample (at depth 65.69 mbsf) this species is missing in the present study. The absence in this sample may reflect the HO of *Melitasphaeridium choanophorum* in the sample below (depth 68.30 mbsf), proposing an age of 3.35 Ma, but may also be caused by the species' sporadic occurrence. Younger palynological samples from ODP Hole 642B need to be investigated before this can be concluded and a valid comparison done. However, if the absence actually represents the HO of this species, the upper zone boundary of the *Melitasphaeridium choanophorum* Zone can be correlated with the basal part of the KMB-4 Interval Zone, and suggests a 250 kyr younger HO of *Melitasphaeridium choanophorum* at ODP Hole 642B than in the eastern part of the North Sea (Denmark).

The HO of *Reticulatosphaera actinocoronata*, recorded as an event within the *Melitasphaeridium choanophorum* Zone, is in the present study used to define the upper boundary of the KMB-3 Interval Zone. The HO of *Reticulatosphaera actinocoronata* is for ODP Hole 642B recorded at 4.64 Ma, proposing a 240 kyr older HO compared with the age given in Dybkjær and Piasecki (2010). A Zanclean correlation between the eastern part of the North Sea and the eastern Norwegian Sea based on this event is thus possible, but the time difference does not allow for a more accurate correlation. However, as the age of the HO of *Reticulatosphaera actinocoronata* in the North Sea is based on data from the North Atlantic, the big diachronicity cannot be fully explained.

**The *Barssidinium pliogenicum* Zone (Bpl)** of Dybkjær and Piasecki (2010) extends from the HO of *Melitasphaeridium choanophorum* to the LO of *Impagidinium multiplexum* and ranges from the Piacenzian to the earliest Gelasian (3.6 Ma to ~2.6–2.4 Ma). The HO of *Invertocysta lacrymosa* occurs in the zone's basal part, followed by *Barssidinium graminosum* and *Bitectatodinium raedwaldii*. At the upper boundary *Barssidinium pliogenicum* has HO.

All the above mentioned species are recorded in the present study, except *Impagidinium multiplexum*. The age of the basal part of the *Barssidinium pliogenicum* Zone (Dybkjær and Piasecki, 2010) corresponds to the KMB-4 Interval Zone. However, a correlation with this

zone is difficult due to the fact that it is not clear whether the HO of *Melitasphaeridium choanophorum* is recorded in the present study and the youngest sample investigated is of early Piacenzian age (3.08 Ma). However, if the uppermost recorded absence of *Melitasphaeridium choanophorum*, and also the absence of *Invertocysta lacrymosa* and *Barssidinium graminosum* really represent their HOs in the sample below, this would fit well with the zonal base description of the *Barssidinium pliogenicum* Zone of Dybkjær and Piasecki (2010). And the fact that these species “disappear” at the same time in the present study may be caused by e.g. wider sample spacing (270 kyr) than used in Dybkjær and Piasecki (2010). But again, this is highly speculative, and further investigation of ODP Hole 642B needs to be done before a valid correlation is possible. A HO of *Bitectatodinium raedwaldii*, which also disappear close to the *Barssidinium pliogenicum* Zone base (Dybkjær and Piasecki’s, 2010) is not recorded within the studied time interval of ODP Hole 642B.

*Barssidinium pliogenicum*, which in the eastern North Sea has HO in the Pleistocene (Dybkjær and Piasecki, 2010), has in ODP Hole 642B a recorded HO as early as 3.50 Ma. In the present study *Barssidinium pliogenicum* has a sporadic occurrence and is, in many instances, only recorded outside counts. Consequently, if this actually shows the species’ HO, or if it is just coincidental due to sporadic occurrence, needs to be more looked into.

### 5.2.3 The Iceland Sea

Schreck et al. (2012) investigated dinoflagellate cyst and acritarch biostratigraphic events of the Middle Miocene through Pliocene from ODP Hole 907A in the Iceland Sea. Twenty-six bioevents based on HOs, LOs and HCOs (highest common occurrence) were recorded. Based on these events seven biozones were defined, S. De Schepper (pers. comm. 2013), which of four (zones IV-I) range from the Messinian to the Piacenzian (Figures 16 and 17).

**Zone IV** (Schreck et al., 2012; S. De Schepper (pers. comm. 2013) is of Messinian age (6.3–5.5 Ma), and is defined as the strata between the HO of the acritarch *Decahedrella martinheadii* and the HO of *Cristadinium cristatoserratum*.

The youngest part of this zone should correspond with the KMB-1 Interval Zone, defined from >5.83 to 5.35 Ma. However, *Cristadinium cristatoserratum* has not been recorded from

ODP Hole 642B in the present study and a comparison based on this species is thus not possible.

**Zone III** (Schreck et al., 2012; S. De Schepper (pers. comm. 2013) ranges from the HO of *Cristadinium cristatoserratum* to the HO of *Pyxidnopsis vesiculata*, *Operculodinium?* *eirikianum*, *Operculodinium tegillatum*, *Reticulatosphaera actinocornata* and *Corrudinium devernaliae*, and has a Messinian to Zanclean age (5.5–4.5 Ma).

In the present study *Pyxidnopsis vesiculata* is not recorded, and *Operculodinium?* *eirikianum* var. *eirikianum* ranges throughout the counted interval, reflecting a HO younger than 3.08 Ma. However, in the present study the HOs of both *Operculodinium tegillatum* and *Reticulatosphaera actinocornata* are recorded at 4.46 Ma (77.80 mbsf), marking the upper boundary of the KMB-2 Interval Zone, and the HO of *Corrudinium devernaliae* is recorded in the next sample counted, at 4.50 Ma (77.36 mbsf). These HOs suggests a strong correlative event between the Iceland Sea and the eastern Norwegian Sea, where the 140 kyr age difference between the HOs of *Operculodinium tegillatum* and *Reticulatosphaera actinocornata* in the present study and the Iceland Sea is likely related to sample spacing.

In Schreck et al. (2013) the highest occurrences marking Zone III (Schreck et al., 2012; S. De Schepper (pers. comm. 2013) in the Iceland Sea are interpreted to reflect a cooling event due to the establishment of the modern East Greenland Current, between 4.5 and 4.3 Ma. *Operculodinium tegillatum* is considered a warm water species (Head, 1997), and its disappearance in the eastern Norwegian Sea (the present study) thus seems likely to reflect cooling. However, if this is related to the same event, the persistent occurrence of *Operculodinium?* *eirikianum* var. *eirikianum* in ODP Hole 642B indicates less cooling of the eastern Norwegian Sea than of the Iceland Sea, as *Operculodinium?* *eirikianum* var. *eirikianum* is also considered a cold intolerant species (Head, 1993).

Anyway, based on the HOs of *Operculodinium tegillatum* and *Reticulatosphaera actinocornata*, the upper boundary of Zone III can be correlated to the upper boundary of the KMB-2 Interval Zone.

**Zone II** (Schreck et al., 2012; S. De Schepper (pers. comm. 2013) is defined from the HO of *Pyxidnopsis vesiculata*, *Operculodinium?* *eirikianum*, *Operculodinium tegillatum*, *Reticulatosphaera actinocornata* and *Corrudinium devernaliae* to the HO of *Batiacasphaera micropapillata*, and is of late Piacenzian to Zanclean age (4.5–3.4 Ma).

In ODP Hole 642B *Batiacasphaera micropapillata* has its HO at 3.83 Ma, which implies a 430 kyrs younger HO in the eastern Norwegian Sea. The HO of *Batiacasphaera micropapillata* can be correlated as an event between the eastern Norwegian Sea and the Iceland Sea. However, due to this large age difference, this is not considered as a good correlative event.

**Zone I** (Schreck et al., 2012; S. De Schepper (pers. comm. 2013) is of Piacenzian age (3.4–2.6 Ma) and is the interval between the HO of *Batiacasphaera micropapillata* the top of the studied interval.

The age of this zone corresponds to the KMB-4 Interval Zone, but since none of these zones have a recorded upper boundary, a correlation is not possible.



## CHAPTER 6

### CONCLUSIONS

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The palynology of Ocean Drilling Program Hole 642B on the outer Vøring Plateau, eastern Norwegian Sea, has been investigated. Seventeen magnetostratigraphically dated core samples from the latest Late Miocene (Messinian, 5.83 Ma), to the early Late Pliocene (Piacenzian, 3.08 Ma) containing a mostly well preserved palynomorph assemblage, were studied. The main results are:

- Several dinoflagellate cyst species, defined after the original study of Mudie (1989), were recorded in ODP Hole 642B, and a contribution to an updated Late Neogene reference section for the Norwegian Sea has been made
- Based on the HPO of *Selenopemphix brevispinosa* and the HOs of *Reticulatosphaera actinocoronata* and *Operculodinium? eirikianum crebrum* the studied interval was divided into a local zonation scheme of four Interval Zones
- These zones were compared to biostratigraphic zones and events defined in the Late Messinian to Early Piacenzian zones of three other higher latitude oceanic sites from the North Atlantic region in order to evaluate their utility for correlations
- The KMB-3 Interval Zone strongly correlates with the Iceland Sea Zone II, revealing a useful regional event. Otherwise, the comparison mostly revealed differences in the composition and ranges of the dinoflagellate cysts and acritarchs, most likely resulting from latitudinal and oceanographic control
- Several dinoflagellate cyst and acritarch events were recorded. These events can probably be used for correlation within a more restricted area with similar environmental conditions

## Future work

- A higher sample resolution is recommended in order to provide a more accurate age of the recorded event, particularly between sample depth 77.80 mbsf and 77.36 mbsf, to check if the spacing between the HOs of *Reticulosphaera actinocoronata* and *Operculodinium tegillatum* and the HO of *Corrudinium devernaliae* could be less than 140 kyr, and thus possibly strengthen the correlation between the Iceland Sea and the Norwegian Sea.
- Study samples above and below the interval investigated in the present study in order to define the upper and lower boundary of the KMB-1 Interval Zone and the KMB-4 Interval Zone, respectively.
- Compare the zonation and events to other dinoflagellate cyst zonations of the Norwegian Sea to see if these can be related.





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## **Appendix**

<b>Appendix 1</b> Range chart.....	1-6
<b>Appendix 2</b> Plates.....	8-15
<b>Appendix 3</b> Full species names.....	17-20



ODP Hole 642B							DINOFLAGELLATE CYST														
Depth (mbsf)	Core	Section	Interval (cm)	Total dinoflagellate cysts counted	Total acritarchs counted	Calibrated ages (Ma)	Achomosphaera andalousiensis subsp. andalousiensis	Achomosphaera andalousiensis subsp. suttonensis	Amiculosphaera umbraculum	Ataxiodinium choane	Ataxiodinium confusum	Ataxiodinium ? s.p. A (this study)	Ataxiodinium spp. indet	Ataxiodinium zevenboomii	Barssidinium graminosum	Barssidinium pliocenicum	Barssidinium spp. indet	Batiacasphaera micropapillata	Batiacasphaera /Pyxidiniopsis complex	Bitectatodinium raedwaldii	Bitectatodinium? serratum
65.69	8	6	129-130	349	94	3.08	1	8												8	
68.30	9	2	40-41	313	137	3.35	5	3	2					2						2	
70.00	9	3	60-61	313	905	3.60		1	3	1	1			(+)	1					2	1
72.35	9	4	145-146	446	1596	3.83	1	(+)	15	(+)				(+)	1	1	2			5	3
74.90	9	6	100-101	279	2432	4.08	2		(+)	1										5	1
76.30	10	1	40-41	301	1184	4.23	2			2		1		1	2	(+)			5	3	
77.36	10	1	145-146	485	19	4.50	1		1												1
77.80	10	2	40-41	578	651	4.64	3		1					1	15	(+)		3	9		(+)
78.40	10	2	100-101	472	788	4.69	(+)		2	2		1		2	(+)	(+)		9	45		1
79.92	10	3	102-103	675	788	4.81			1			(+)		1	1	1			64	2	6
80.55	10	4	15-16	562	719	4.84	2		1					2	9	(+)		1	28	1	
82.01	10	5	11-12	604	4283	4.91									5			4	45		
86.20	11	1	80-81	522	225	5.35			(+)			59		2	(+)	6			1		
87.55	11	2	65-66	527	156	5.44						23			13	1			9		
89.05	11	3	65-66	518	352	5.53	4		1			21			(+)	(+)		12	3		
92.00	11	5	60-61	492	213	5.71						68	1		1			1	5		1
94.00	11	6	110-111	412	300	5.83	1		1	(+)		4			(+)	(+)		15	32		2
65.69	8	6	129-130	349	94	3.08	0,29 %		2,29 %											2,29 %	
68.30	9	2	40-41	313	137	3.35	1,60 %		0,96 %	0,64 %				0,64 %						0,64 %	
70.00	9	3	60-61	313	905	3.60		0,32 %	0,96 %	0,32 %	0,32 %					0,32 %			0,64 %	0,32 %	
72.35	9	4	145-146	446	1596	3.83	0,22 %		3,36 %							0,22 %	0,22 %	0,45 %	1,12 %	0,67 %	
74.90	9	6	100-101	279	2432	4.08	0,72 %			0,36 %									1,79 %	0,36 %	
76.30	10	1	40-41	301	1184	4.23	0,66 %			0,66 %		0,33 %		0,33 %	0,66 %			1,66 %	1,00 %		
77.36	10	1	145-146	485	19	4.50	0,21 %		0,21 %											0,21 %	
77.80	10	2	40-41	578	651	4.64	0,52 %		0,17 %					0,17 %	2,60 %			0,52 %	1,56 %		
78.40	10	2	100-101	472	788	4.69			0,42 %	0,42 %		0,21 %		0,42 %				1,91 %	9,53 %	0,21 %	
79.92	10	3	102-103	675	788	4.81			0,15 %					0,15 %	0,15 %	0,15 %			9,48 %	0,30 %	0,89 %
80.55	10	4	15-16	562	719	4.84	0,36 %		0,18 %					0,36 %	1,60 %			0,18 %	4,98 %	0,18 %	
82.01	10	5	11-12	604	4283	4.91									0,83 %			0,66 %	7,45 %		
86.20	11	1	80-81	522	225	5.35						11,30 %		0,38 %		1,15 %			0,19 %		
87.55	11	2	65-66	527	156	5.44						4,36 %			2,47 %	0,19 %			1,71 %		
89.05	11	3	65-66	518	352	5.53	0,77 %		0,19 %			4,05 %						2,32 %	0,58 %		
92.00	11	5	60-61	492	213	5.71						13,82 %	0,20 %		0,20 %			0,20 %	1,02 %	0,20 %	
94.00	11	6	110-111	412	300	5.83	0,24 %		0,24 %			0,97 %						3,64 %	7,77 %	0,49 %	

ODP 642B		DINOFLAGELLATE CYST																		
Depth (mbsf)	Calibrated ages (Ma)	<i>Bitectatodinium</i> sp. A (this study)	<i>Bitectatodinium</i> spp. indet	<i>Bitectatodinium tepikense</i>	<i>Brigantedinium</i> spp. indet	<i>Cerebrocysta?</i> <i>namocensis</i>	<i>Corrudinium devernaliae</i>	<i>Corrudinium harlandii</i>	<i>Corrudinium?</i> <i>labradori</i>	Cyst of <i>Pentapharsodinium dalei</i>	Cyst type 1 of Head and Mudi (1989)	<i>Dapsilidinium pseudocolligerum</i>	<i>Echinidinium</i> spp. indet	<i>Filipsphaera filifera</i> subsp. <i>filifera</i>	<i>Filipsphaera filifera</i> subsp . <i>pilosa</i>	<i>Filipsphaera microornata</i>	<i>Filipsphaera</i> spp. indet	<i>Habibacysta tectata</i>	<i>Heteraulacacysta</i> sp. A Costa & Dowie, 1979	<i>Hystricholpoma rigaudiae</i>
65.69	3.08	12												19			1	14		1
68.30	3.35	1	1		(+)			(+)	2	2		1		24		1		2	(+)	(+)
70.00	3.60	(+)			2			(+)	1	6				2	(+)		(+)	1	4	(+)
72.35	3.83	22	1	4	8	1		2	3	3		(+)	(+)	34	1	10				
74.90	4.08	9			1			1	1	15	(+)			33		2				
76.30	4.23	5			(+)			2	1	4		1	(+)	3	7					
77.36	4.50						14		1									(+)		
77.80	4.64	3					4	1	7		174			(+)						(+)
78.40	4.69	2					10		4	10	47		3	3				1	(+)	
79.92	4.81						1		18	28	(+)		1	2				(+)		
80.55	4.84				14		9		16				5	7	3			6		
82.01	4.91	14			7		1	1	8	4			5	45	2					
86.20	5.35				2				(+)		(+)	1	9					13		
87.55	5.44	1			2						4	1	10					5		
89.05	5.53				2		(+)			2	5	(+)	28		1			14		(+)
92.00	5.71	1							(+)		(+)		4					5		(+)
94.00	5.83	3			8					2								9		
65.69	3.08	3,44 %												5,44 %			0,29 %	4,01 %		0,29 %
68.30	3.35	0,32 %	0,32 %						0,64 %	0,64 %		0,32 %		7,67 %		0,32 %		0,64 %		
70.00	3.60				0,64 %				0,32 %	1,92 %				0,64 %				0,32 %	1,28 %	
72.35	3.83	4,93 %	0,22 %	0,90 %	1,79 %	0,22 %		0,45 %	0,67 %	0,67 %				7,62 %	0,22 %	2,24 %				
74.90	4.08	3,23 %			0,36 %			0,36 %	0,36 %	5,38 %				11,83 %		0,72 %				
76.30	4.23	1,66 %						0,66 %	0,33 %	1,33 %		0,33 %		1,00 %	2,33 %					
77.36	4.50						2,89 %		0,21 %											
77.80	4.64	0,52 %					0,69 %	0,17 %	1,21 %	30,10 %										
78.40	4.69	0,42 %					2,12 %		0,85 %	2,12 %	9,96 %		0,64 %	0,64 %				0,21 %		
79.92	4.81						0,15 %		2,67 %	4,15 %			0,15 %	0,30 %						
80.55	4.84				2,49 %		1,60 %		2,85 %				0,89 %	1,25 %	0,53 %			1,07 %		
82.01	4.91	2,32 %			1,16 %		0,17 %	0,17 %	1,32 %	0,66 %			0,83 %	7,45 %	0,33 %					
86.20	5.35				0,38 %							0,19 %	1,72 %					2,49 %		
87.55	5.44	0,19 %			0,38 %						0,76 %	0,19 %	1,90 %					0,95 %		
89.05	5.53				0,39 %					0,39 %	0,97 %		5,41 %		0,19 %			2,70 %		
92.00	5.71	0,20 %			0,00 %								0,81 %					1,02 %		
94.00	5.83	0,73 %			1,94 %					0,49 %								2,18 %		

ODP 642B		DINOFLAGELLATE CYST																			
Depth (mbsf)	Calibrated ages (Ma)	<i>Impagidinium aculeatum</i>	<i>Impagidinium pallidum</i>	<i>Impagidinium paradoxum</i>	<i>Impagidinium patulum</i>	<i>Impagidinium solidum</i>	<i>Impagidinium</i> sp. 1 of De Schepper and Head (2009)	<i>Impagidinium</i> sp. 2 of De Schepper and Head (2009)	<i>Impagidinium</i> spp. indet	<i>Impagidinium vermiculatum</i> SPT (1994)	<i>Invertocysta lacrymosa</i>	<i>Invertocysta tabulata</i>	<i>Invertocysta/Amiculosphaera</i>	<i>Lejeunecysta catomus</i>	<i>Lejeunecysta hatterasensis</i>	<i>Lejeunecysta</i> spp. indet	<i>Lingulodinium machaerophorum</i>	<i>Melittasphaeridium</i> cf. <i>choanophorum</i>	<i>Melittasphaeridium choanophorum</i>	<i>Nematosphaeropsis labyrinthus</i>	<i>Nematosphaeropsis lativittata</i>
65.69	3.08	4	6					2									4			5	
68.30	3.35	(+)	7	5					2		(+)						2	1	3	29	
70.00	3.60	3	8	3	1			2			(+)						3		(+)	19	
72.35	3.83	5	5	3		(+)		7			(+)		4						3	73	
74.90	4.08	3	9	3	1			1			(+)						(+)		1	23	
76.30	4.23	(+)	2	7	(+)		(+)	2			(+)		1				1		(+)	24	
77.36	4.50		(+)	7	14		2				(+)		6				8		(+)	29	
77.80	4.64	1	4	1	(+)				4		2		6			2	2	4		37	
78.40	4.69	1	2				5				1				2	5	(+)		1	44	
79.92	4.81	3	1	(+)	(+)		4		2		(+)					(+)			4	93	
80.55	4.84	1	4	2	(+)						(+)		2			5	1		1	162	
82.01	4.91		2		(+)			2	1				1			14			4	14	
86.20	5.35		3	5	11				3	4	8	(+)	7			4	(+)		4	13	1
87.55	5.44			6	2				1	1	(+)		8			1	(+)		3	52	
89.05	5.53	1	1	(+)	5				1	2	1	(+)		(+)	2	10	3		1	34	
92.00	5.71	(+)		6	1				4	3	2			(+)		3	1		3	37	
94.00	5.83				(+)		2			2	1		4			13	13		4	10	
65.69	3.08	1,15 %	1,72 %					0,57 %									1,15 %			1,43 %	
68.30	3.35		2,24 %	1,60 %				0,00 %	0,64 %								0,64 %	0,32 %	0,96 %	9,27 %	
70.00	3.60	0,96 %	2,56 %	0,96 %	0,32 %			0,64 %									0,96 %			6,07 %	
72.35	3.83	1,12 %	1,12 %	0,67 %				1,57 %					0,90 %						0,67 %	16,37 %	
74.90	4.08	1,08 %	3,23 %	1,08 %	0,36 %			0,36 %											0,36 %	8,24 %	
76.30	4.23		0,66 %	2,33 %				0,66 %					0,33 %				0,33 %			7,97 %	
77.36	4.50			1,44 %	2,89 %		0,41 %						1,24 %				1,65 %			5,98 %	
77.80	4.64	0,17 %	0,69 %	0,17 %					0,69 %	0,35 %		1,04 %				0,35 %	0,35 %	0,69 %		6,40 %	
78.40	4.69	0,21 %	0,42 %				1,06 %				0,21 %				0,42 %	1,06 %			0,21 %	9,32 %	
79.92	4.81	0,44 %	0,15 %				0,59 %		0,30 %										0,59 %	13,78 %	
80.55	4.84	0,18 %	0,71 %	0,36 %									0,36 %			0,89 %	0,18 %		0,18 %	28,83 %	
82.01	4.91		0,33 %					0,33 %	0,17 %				0,17 %			2,32 %			0,66 %	2,32 %	
86.20	5.35		0,57 %	0,96 %	2,11 %				0,57 %	0,77 %	1,53 %		1,34 %			0,77 %			0,77 %	2,49 %	0,19 %
87.55	5.44			1,14 %	0,38 %				0,19 %	0,19 %			1,52 %			0,19 %			0,57 %	9,87 %	
89.05	5.53	0,19 %	0,19 %		0,97 %				0,19 %	0,39 %	0,19 %				0,39 %	1,93 %	0,58 %		0,19 %	6,56 %	
92.00	5.71			1,22 %	0,20 %				0,81 %	0,61 %	0,41 %					0,61 %	0,20 %		0,61 %	7,52 %	
94.00	5.83						0,49 %		0,00 %	0,49 %	0,24 %		0,97 %			3,16 %	3,16 %		0,97 %	2,43 %	

ODP 642B		DINOFLAGELLATE CYST																		
Depth (mbsf)	Calibrated ages (Ma)	<i>Nematosphaeropsis</i> spp. indet.	<i>Operculodinium centrocarpum</i> s.s.	<i>Operculodinium centrocarpum</i> sensu Wall & Dale, 1966	<i>Operculodinium centrocarpum</i> /israelianum	<i>Operculodinium</i> ? eirikianum var. <i>crebrum</i>	<i>Operculodinium</i> ? eirikianum var. <i>eirikianum</i>	<i>Operculodinium</i> <i>janduchenei</i>	<i>Operculodinium</i> sp. 1 of Louwye et al. (2004)	<i>Operculodinium</i> <i>tegillatum</i>	<i>Pyxidinospis</i> <i>braboi</i>	<i>Pyxidinospis</i> <i>pastilliformis</i>	<i>Pyxidinospis</i> <i>tuberculata</i>	<i>Reticulatosphaera</i> <i>actinocoronata</i>	Round brown cyst	<i>Selenopemphix</i> <i>brevispinosa</i>	<i>Selenopemphix</i> <i>dionaeocysta</i>	<i>Selenopemphix</i> <i>nephroides</i>	<i>Selenopemphix</i> <i>quanta</i>	<i>Selenopemphix</i> spp. indet.
65.69	3.08		131				43		3											
68.30	3.35	1	126	3		(+)	(+)			5	1		(+)	(+)	(+)	1				(+)
70.00	3.60		136	(+)	2	21	(+)	1		9				5		2	(+)			4
72.35	3.83		118	4	6	3	2	(+)	1	15			(+)	16		2	1			
74.90	4.08		80	1		6				2				7						
76.30	4.23	1	125			21	1	(+)		(+)				11	(+)		(+)			
77.36	4.50	138	120			32														
77.80	4.64	5	19	1		33				36	(+)			7	18	2	1	(+)		
78.40	4.69		10	1		32				22	(+)	4		(+)	26		1			2
79.92	4.81	53		3		81		(+)		91		1		15	4			(+)		2
80.55	4.84	20		2		36				22	1	1		7	89		2	(+)		2
82.01	4.91	5				26				20		8		17	288					
86.20	5.35	16	21	7		68	(+)						(+)	19	29	4	5	10		29
87.55	5.44	16	2			26								19	4	11	5		6	10
89.05	5.53	17		6		17				1	8			26	70	14	41		8	11
92.00	5.71	4				35					8			21	12	2	34		2	13
94.00	5.83	15	10	4		25	2				20			8	46	3	13		1	1
65.69	3.08		37,54 %			12,32 %	0,86 %													
68.30	3.35	0,32 %	40,26 %	0,96 %						1,60 %	0,32 %					0,32 %				
70.00	3.60		43,45 %	0,64 %	6,71 %	0,32 %	2,88 %							1,60 %		0,64 %			1,28 %	
72.35	3.83		26,46 %	0,90 %	1,35 %	0,67 %	0,45 %		0,22 %	3,36 %				3,59 %		0,45 %	0,22 %			
74.90	4.08		28,67 %	0,36 %	2,15 %					0,72 %				2,51 %						
76.30	4.23	0,33 %	41,53 %		6,98 %	0,33 %								3,65 %						
77.36	4.50	28,45 %	24,74 %		6,60 %															
77.80	4.64	0,87 %	3,29 %	0,17 %	5,71 %				6,23 %				1,21 %	3,11 %	0,35 %	0,17 %				
78.40	4.69		2,12 %	0,21 %	6,78 %				4,66 %	0,85 %				5,51 %		0,21 %			0,42 %	
79.92	4.81	7,85 %		0,44 %	12,00 %				13,48 %				2,22 %	0,59 %					0,30 %	
80.55	4.84	3,56 %		0,36 %	6,41 %				3,91 %	0,18 %	0,18 %		1,25 %	15,84 %		0,36 %			0,36 %	
82.01	4.91	0,83 %			4,30 %				3,31 %	1,32 %			2,81 %	47,68 %						
86.20	5.35	3,07 %	4,02 %	1,34 %	13,03 %									3,64 %	5,56 %	0,77 %	0,96 %	1,92 %	5,56 %	
87.55	5.44	3,04 %	0,38 %		4,93 %									3,61 %	0,76 %	2,09 %	0,95 %	1,14 %	1,90 %	
89.05	5.53	3,28 %		1,16 %	3,28 %				0,19 %	1,54 %			5,02 %	13,51 %	2,70 %	7,92 %		1,54 %	2,12 %	
92.00	5.71	0,81 %			7,11 %					1,63 %			4,27 %	2,44 %	0,41 %	6,91 %		0,41 %	2,64 %	
94.00	5.83	3,64 %	2,43 %	0,97 %	6,07 %	0,49 %				4,85 %			1,94 %	11,17 %	0,73 %	3,16 %		0,24 %	0,24 %	

ODP 642B		DINOFLAGELLATE CYST										ACRITARCHS									
Depth (mbsf)	Calibrated ages (Ma)	Small <i>Spiniferites</i> / <i>Achomosphaera</i> (this study)	<i>Spiniferites elongatus</i>	<i>Spiniferites membranaceus</i>	<i>Spiniferites mirabilis</i> / <i>hyperacanthus</i>	<i>Spiniferites</i> / <i>Achomosphaera</i> spp. indet.	<i>Spiniferitus</i> sp. A of Louwye and De Schepper, 2010	<i>Tectatodinium pellitum</i>	<i>Trinovantedinium glorianum</i>	<i>Tuberculodinium vancampoeae</i>	Dinocyst spp. indet.	Number of dinoflagellate taxa counted	<i>Cymatiosphaera?</i> <i>aegirii</i>	<i>Cymatiosphaera ? icenorum</i>	<i>Cymatiosphaera ? invaginata</i>	<i>Cymatiosphaera</i> spp. indet.	<i>Lavradosphaera</i> cf. <i>canalis</i>	<i>Lavradosphaera</i> cf. <i>crista</i>	<i>Lavradosphaera crista</i>	<i>Nannobarbophora walldalei</i>	
65.69	3.08					48					39	18	3	1	10	4				53	
68.30	3.35		1	1	1	62	(+)	2			12	32		23	11				12	17	
70.00	3.60		(+)	(+)	(+)	60	(+)		2		6	31	28	256	277	1			228	15	
72.35	3.83		1		(+)	42	(+)	2	(+)		16	39	19	768	128	2	1		158	20	
74.90	4.08			4		51	2	(+)			14	27	18	459	590		2		341	27	
76.30	4.23	19			(+)	43		(+)			4	28	7	245	184				223	31	
77.36	4.50	19				91		(+)			1	17									
77.80	4.64	40				130		(+)			2	33		8	453				7	3	
78.40	4.69	97			1	70	(+)				3	35		9	485				16	23	
79.92	4.81	22				168		(+)			3	28		3	378				15	19	
80.55	4.84	29				68	1		(+)			35		16	338	2			42	16	
82.01	4.91	29				32						27		5	3615			171	11		
86.20	5.35	49		(+)		107		2	(+)			32			100				30		
87.55	5.44	139				137		3	(+)		6	31	2		19						
89.05	5.53	31		(+)		105	(+)	1	4		4	38	1	(+)	128				12	15	
92.00	5.71	119			(+)	93		(+)	2			30			68	(+)			24		
94.00	5.83	38				84	2	3	1	(+)	10	36			104		7		1	19	
65.69	3.08					13,75 %					11,17 %		3,19 %	1,06 %	10,64 %	4,26 %			0,00 %	56,38 %	
68.30	3.35		0,32 %	0,32 %	0,32 %	19,81 %		0,64 %			3,83 %			16,79 %	8,03 %				8,76 %	12,41 %	
70.00	3.60					19,17 %			0,64 %		1,92 %		3,09 %	28,29 %	30,61 %	0,11 %			25,19 %	1,66 %	
72.35	3.83		0,22 %			9,42 %		0,45 %			3,59 %		1,19 %	48,12 %	8,02 %	0,13 %	0,06 %		9,90 %	1,25 %	
74.90	4.08			1,43 %		18,28 %	0,72 %				5,02 %		0,74 %	18,87 %	24,26 %		0,08 %		14,02 %	1,11 %	
76.30	4.23	6,31 %				14,29 %					1,33 %		0,59 %	20,69 %	15,54 %				18,83 %	2,62 %	
77.36	4.50	3,92 %				18,76 %					0,21 %										
77.80	4.64	6,92 %				22,49 %					0,35 %			1,23 %	69,59 %				1,08 %	0,46 %	
78.40	4.69	20,55 %			0,21 %	14,83 %					0,64 %			1,14 %	61,55 %				2,03 %	2,92 %	
79.92	4.81	3,26 %				24,89 %					0,44 %			0,38 %	47,97 %				1,90 %	2,41 %	
80.55	4.84	5,16 %				12,10 %	0,18 %							2,23 %	47,01 %	0,28 %			5,84 %	2,23 %	
82.01	4.91	4,80 %				5,30 %								0,12 %	84,40 %		3,99 %		0,26 %		
86.20	5.35	9,39 %				20,50 %		0,38 %							44,44 %				13,33 %		
87.55	5.44	26,38 %				26,00 %		0,57 %			1,14 %		1,28 %		12,18 %						
89.05	5.53	5,98 %				20,27 %		0,19 %	0,77 %		0,77 %		0,28 %		36,36 %				3,41 %	4,26 %	
92.00	5.71	24,19 %				18,90 %			0,41 %						31,92 %				11,27 %		
94.00	5.83	9,22 %				20,39 %	0,49 %	0,73 %	0,24 %		2,43 %				34,67 %		2,33 %		0,33 %	6,33 %	

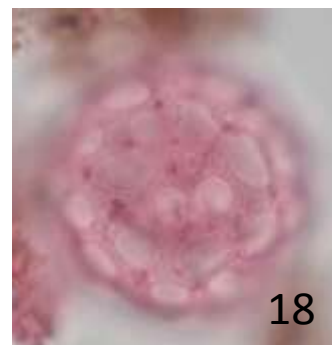
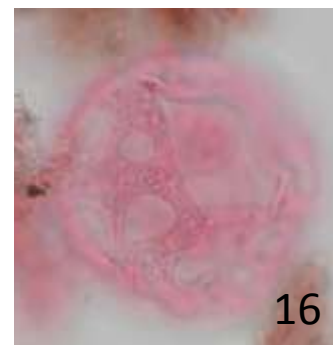
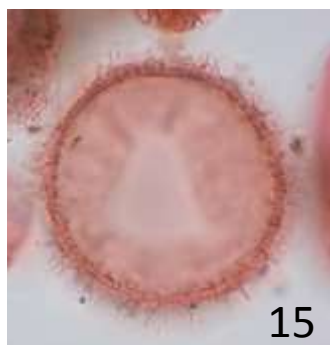
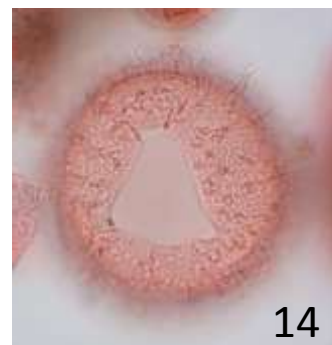
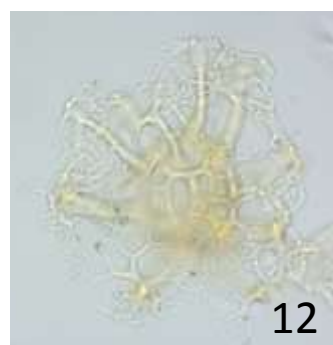
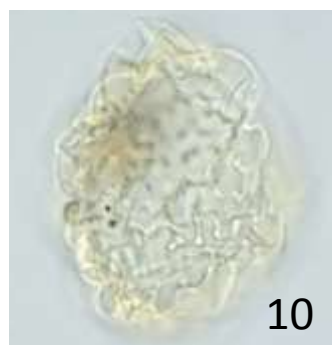
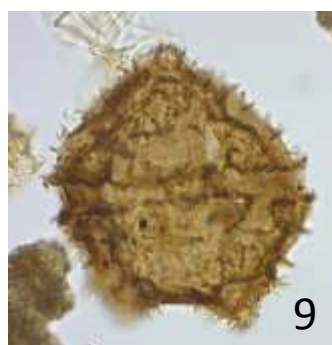
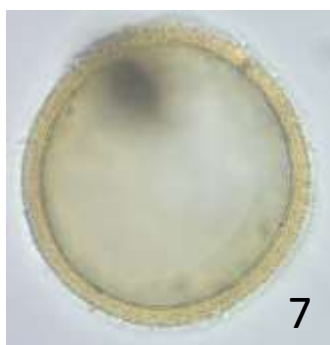
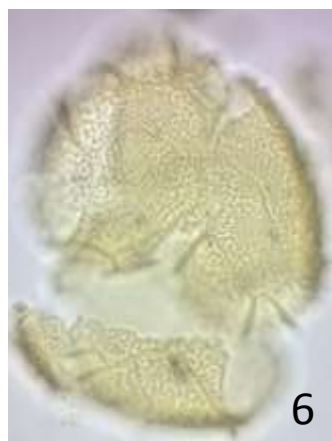
ODP 642B		ACRITARCHS		OTHERS								CONCENTRATIONS				
Depth (mbsf)	Calibrated ages (Ma)	Small spiny acritarchs	Acritarchs spp. indet.	Number of acritarch taxa counted	Bisaccate pollen	Non-bisaccate pollen	Spores	<i>Tsuga</i>	<i>Pterospermella</i>	<i>Gelasinicysta vangeelii</i>	Reworked dinocysts spp. Indet.	<i>lycopodium clavatum</i>	Dinoflagellate cysts/g sediment	Total error on dinoflagellate cyst consentartion	acritarchs/g sediment	Total error on acritarchs consentartion
65.69	3.08	17	6	7	92	14	71		3	1	30	454	1006	117	271	40
68.30	3.35	68	6	6	24	(+)	10			1	1	169	3431	455	1502	221
70.00	3.60	87	13	8	59	6	11			(+)	1	88	6864	1041	19845	2870
72.35	3.83	492	8	9	123	13	40				3	151	2926	385	10470	1312
74.90	4.08	995		7	71	11	22			1	2	76	4180	663	36437	5407
76.30	4.23	494		6	54	5	21			1	1	159	3230	434	12707	1586
77.36	4.50	19		1	12	2	(+)				1	107	12497	1761	490	130
77.80	4.64	180		5	51	34	10			(+)	2	19	66508	16668	74907	18744
78.40	4.69	255		5	30	5	9				6	16	45990	12431	76780	20633
79.92	4.81	373		5	38	1	3	(+)		(+)	3	20	52971	12968	61839	15112
80.55	4.84	305		6	41	2	23	(+)		1	(+)	111	9270	1286	11859	1628
82.01	4.91	481		5	175	23	82			5	3	310	4624	534	32790	3578
86.20	5.35	95		3	98	14	28	(+)		1	15	102	8025	1140	3459	521
87.55	5.44	132	3	4	116	13	22	(+)	1		3	129	8559	1151	2534	381
89.05	5.53	196		5	73	7	23	(+)			4	174	7232	918	4914	641
92.00	5.71	121		3	122	19	59			1	3	350	3521	407	1524	193
94.00	5.83	169		5	55	3	21	1		(+)	2	78	11334	1745	8253	1295
65.69	3.08	18,09 %	6,38 %													
68.30	3.35	49,64 %	4,38 %													
70.00	3.60	9,61 %	1,44 %													
72.35	3.83	30,83 %	0,50 %													
74.90	4.08	40,91 %														
76.30	4.23	41,72 %														
77.36	4.50	100 %														
77.80	4.64	27,65 %														
78.40	4.69	32,36 %														
79.92	4.81	47,34 %														
80.55	4.84	42,42 %														
82.01	4.91	11,23 %														
86.20	5.35	42,22 %														
87.55	5.44	84,62 %	1,92 %													
89.05	5.53	55,68 %														
92.00	5.71	56,81 %														
94.00	5.83	56,33 %														



## Plate I. Dinoflagellate cysts

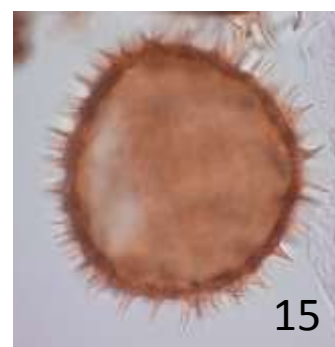
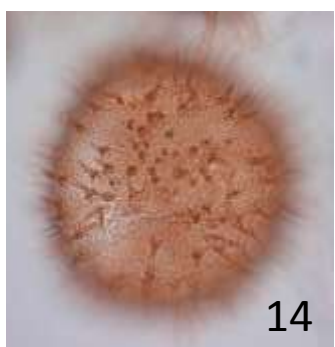
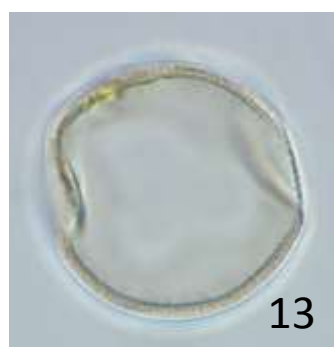
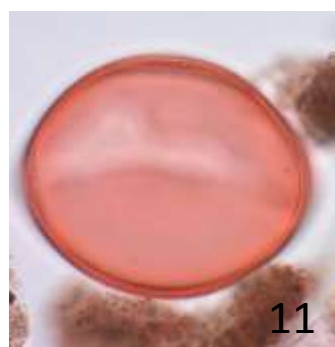
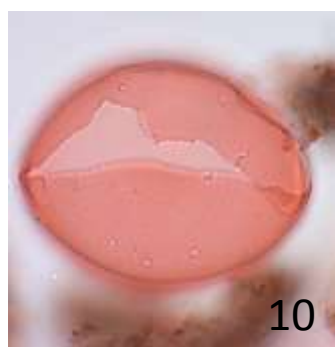
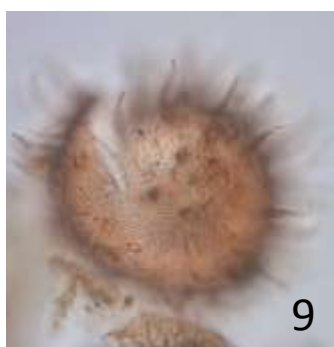
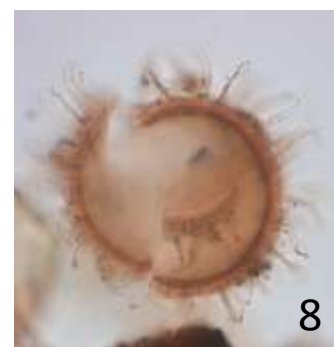
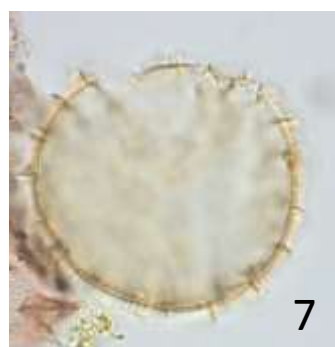
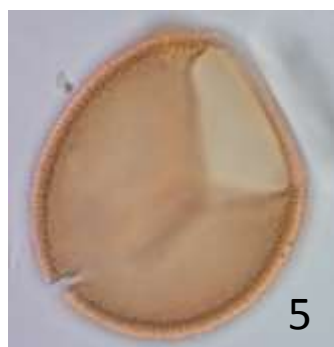
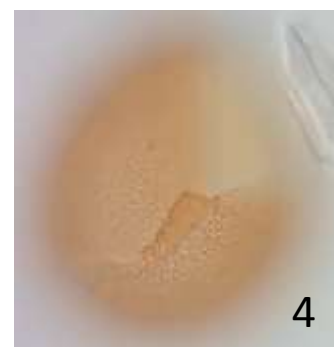
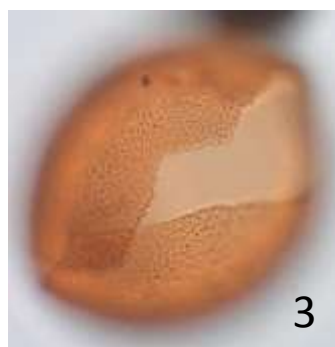
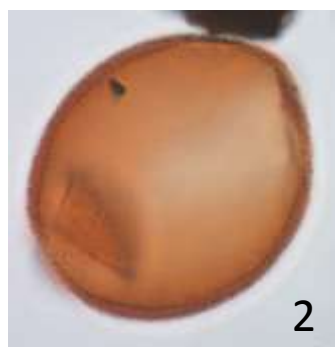
- 1**     *Selenopemphix brevispinosa* Head et al. 1989. Mid focus. Maximum width 40 µm; process length 3 µm. ODP 642B-11H-6A, 110–111 cm, slide 11J511, E.F. R51/0.
  
- 2 - 4**   *Ataxiodinium?* sp. A (this study). High focus (2), mid focus (3), and low focus (4). Maximum length (endocyst and pericyst) 29 µm. ODP 462B-11H-3A, 65–66 cm, slide 11J501, E.F. W49/3.
  
- 5, 6**   *Impagidinium vermiculatum* Simon Petroleum Technology Limited 1994. High focus (5) and low focus (6). Width of cingulum 72 µm. ODP 642B-11H-1A, 80–81 cm, slide 11J495, E.F. S62/0.
  
- 7, 8**   *Tectatodinium pellitum* Wall 1967. Mid focus (7) and low focus on dorsal surface (8). Maximum length 50 µm; central body 43 µm; wall thickness 4 µm. ODP 642B-11H-6A, 110–111 cm, slide 11J511, E.F. H46/2.
  
- 9**     *Trinovantedinium glorianum* (Head et al. 1989) deVerteuil and Norris 1992. Mid focus. Maximum length without antapical horns 55 µm; antapical horn 4 µm. ODP 642B-11H-1A, 80–81 cm, slide 11J495, E.F. R56/1.
  
- 10, 11** *Ataxiodinium zevenboomii* Head 1997. High focus (10) and mid focus (11). Maximum length 30 µm; central body 24 µm. ODP 642B-11H-1A, 80–81 cm, slide 11J495, E.F. W60/4.
  
- 12, 13** *Reticulatosphaera actinocoronata* (Benedek 1972) Bujak and Matsuoka 1986. High focus (12) and low focus (13). Maximum diameter including processes 45 µm; longest process 16 µm. ODP 462B-11H-3A, 65–66 cm, slide 11J501, E.F. P44/3.
  
- 14, 15** *Operculodinium tegillatum* Head 1997. High focus on dorsal surface (14) and mid focus (15). Maximum diameter 35 µm; process length 4, 5 µm. ODP 462B-10H-3, 102–103 cm, slide 12G135, E.F. W19/1.
  
- 16- 18** Cyst type 1 of Head and Mudie 1989. High focus (16), mid focus (17) and low focus (18). Maximum diameter 30 µm; central body 18 µm. ODP 462B-10H-2, 40–41 cm, slide 12G105, E.F. B59/2.





## Plate II. Dinoflagellate cysts

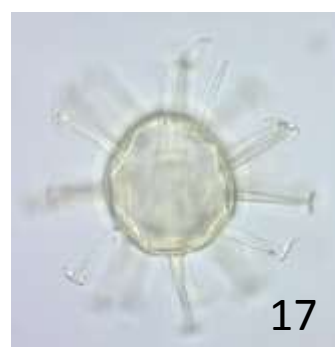
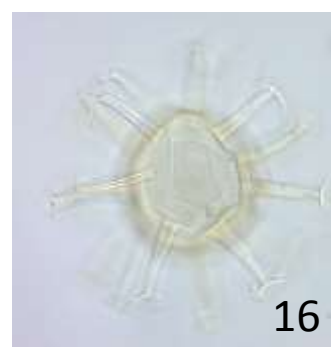
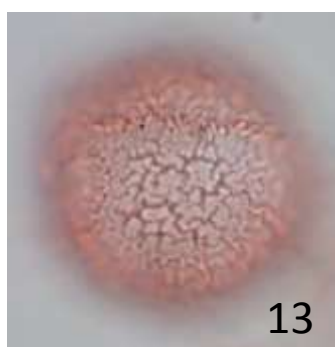
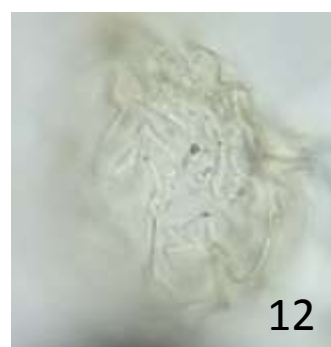
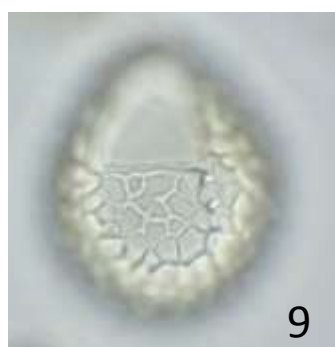
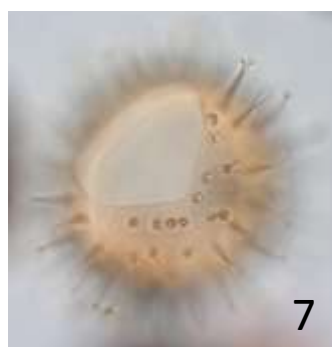
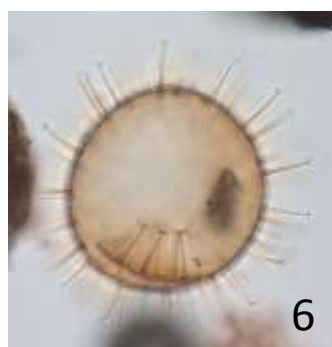
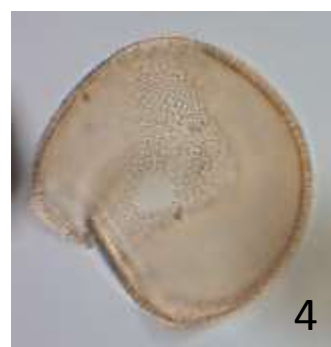
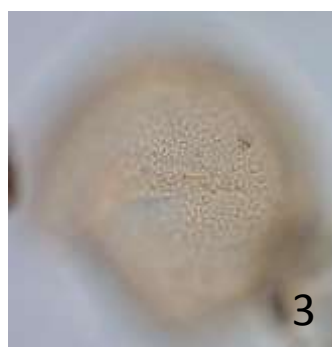
- 1- 3** *Bitectatodinium raedwaldii* Head 1997. High focus on ventral surface (1), mid focus (2) and low focus on dorsal surface (3). Max diameter 47  $\mu\text{m}$ ; central body 43  $\mu\text{m}$ . ODP 642B-8H-6A, 129–130 cm, slide 12F401, E.F. K41/0.
- 4, 5** *Filisphaera filifera* subsp. *filifera* (Bujak, 1984) Head 1994. High focus (4) and mid focus (5). Maximum diameter 58  $\mu\text{m}$ ; central body 52  $\mu\text{m}$ . ODP 642B-9H-2A, 40–41 cm, slide 12F471, E.F. A37/3.
- 6, 7** *Corrudinium harlandii* Matsuoka 1983. High focus (6) and mid focus (7). Maximum diameter 35  $\mu\text{m}$ . ODP 642B-9H-3A, 60–61 cm, slide 12G10, E.F. M59/1.
- 8, 9** *Operculodinium?* *eirikianum* Head et al. 1989 emend. Head 1997 var. *crebrum* De Schepper and Head 2008. Mid focus (8) and low focus (9) Maximum body diameter 39  $\mu\text{m}$ ; central body 33  $\mu\text{m}$ ; process length 13  $\mu\text{m}$ . ODP 642B-9H-3A, 60–61 cm, slide 12G10, E.F. M52/3.
- 10, 11** *Bitectatodinium?* *serratum* (Head et al. 1989) Lentin and Williams 1993. High focus on dorsal surface (10) and mid focus (11). Maximum diameter 54  $\mu\text{m}$ . ODP 642B-10H-3A, 102–103 cm, slide 12G135, E.F. R12/4.
- 12, 13** *Batiacasphaera micropapillata* Stover 1977. High focus on dorsal surface (12) and mid focus (13). Maximum diameter 26  $\mu\text{m}$ ; central body 24  $\mu\text{m}$ . ODP 642B-11H-3A, 65–66 cm, slide 11J501, E.F. M43/3.
- 14, 15** *Operculodinium centrocarpum* s.s. (Deflandre and Cookson 1955) Wall 1967. High focus on ventral surface (14) and mid focus (15). Maximum diameter 55  $\mu\text{m}$ ; central body 51  $\mu\text{m}$ ; process length 7  $\mu\text{m}$ . ODP 642B-10H-1A, 145–146 cm, slide 12G104, E.F. W44/0.
- 16, 17** Small *Spiniferites/Achomosphaera* (this study). High focus (16) and mid focus (17). Maximum diameter including processes 22  $\mu\text{m}$ ; process length 7  $\mu\text{m}$ . ODP 642B-11H-6A, 110–111 cm, slide 11J511, E.F. W56/4.



### Plate III. Dinoflagellate cysts

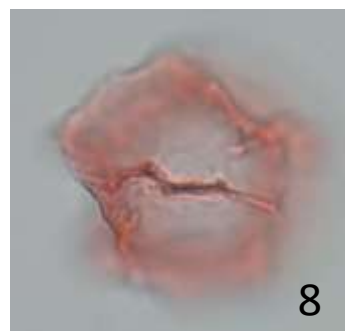
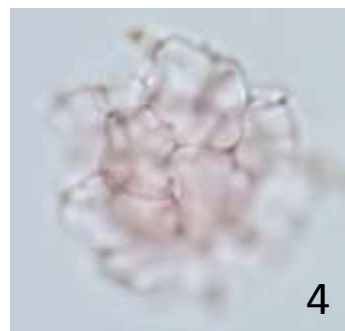
- 1, 2** *Spiniferites elongatus* Reid 1974. High focus (1) and mid focus (2). Maximum length 36  $\mu\text{m}$ ; process 14  $\mu\text{m}$ . ODP 642B-9H-2A, 40–41 cm, slide 12F471, E.F. B26/2.
- 3, 4** *Filisphaera microornata* (Head et al. 1989) Head, 1994. High focus (3) and mid focus (4). Maximum diameter 50  $\mu\text{m}$ ; central body 45  $\mu\text{m}$ . ODP 642B-9H-2A, 40–41 cm, slide 12F471, E.F. A27/3.
- 5- 7** *Operculodinium centrocarpum* sensu Wall and Dale 1966. High focus on ventral surface (5), mid focus (6) and low focus on dorsal surface (7). Maximum diameter central body 35  $\mu\text{m}$ ; process length 9  $\mu\text{m}$ . ODP 642B-9H-3A, 60–61 cm, slide 12G10, E.F. L52/3.
- 8, 9** *Corrudinium devernaliae* Head and Norris 2003. Mid focus (8) and low focus on dorsal side (9). Length 33  $\mu\text{m}$ . ODP 642B-10H-4, 15–16 cm, slide 11J378, E.F. Q48/0.
- 10- 12** *Ataxiodinium choane* Reid 1974. High focus on dorsal surface (10), mid focus (11) and low focus on ventral surface. Maximum diameter (including periblast) 34  $\mu\text{m}$ . ODP 642B-11H-6A, 60–61 cm, slide 11J378, E.F. Q48/0.
- 13- 15** *Corrudinium? labradori* Head et al. 1989. High focus on ventral surface (13), mid focus (14) and low focus on dorsal surface (15). Maximum diameter 26  $\mu\text{m}$ ; central body 23. ODP 642B-10H-2A, 100–101 cm, slide 12G132, E.F. X52/0.
- 16, 17** *Melitasphaeridium choanophorum* (Deflandre and Cookson 1955) Harland and Hill 1979. High focus on dorsal surface (16) and mid focus (17). Maximum diameter 20  $\mu\text{m}$ ; process length 21  $\mu\text{m}$ . ODP 642B-11H-3A, 65–66 cm, slide 11J501, E.F. W60/1.
- 18, 19** *Invertocysta lacrymosa* Edwards 1984. Mid focus (18) and low focus (19). Maximum length 38  $\mu\text{m}$ ; central body 29  $\mu\text{m}$ . ODP 642B-9H-2A, 40–41 cm, slide 12F471, E.F. W51/1.





**Plate IV - Acritarchs**

- 1, 2** *Cymatiosphaera? invaginata* Head, Norris and Mudie 1989. High focus (1) and mid focus (2). Maximum diameter 21  $\mu\text{m}$ ; central body 14  $\mu\text{m}$ . ODP 642B-9H-3A, 60–61 cm, slide 12G10, E.F. B36/0.
- 3, 4** *Cymatiosphaera? aegirii* De Schepper and Head 2013. Mid focus (3) and low focus (4). Maximum diameter 25  $\mu\text{m}$ ; central body 15  $\mu\text{m}$ . ODP 642B-9H-3A, 60–61 cm, slide 12G10, E.F. C51/0.
- 5, 6** *Cymatiosphaera? icenorum* De Schepper and Head 2013. High focus (5) and mid focus (6). Maximum diameter 25  $\mu\text{m}$ ; process length 7  $\mu\text{m}$ . ODP 642B-9H-4A, 145–146 cm, slide 12G72, E.F. C38/3.
- 7** *Nannobarbophora walldalei* Head 1996. Mid focus. Maximum diameter 25  $\mu\text{m}$ ; process length 5  $\mu\text{m}$ . ODP 642B-8H-6A, 129–130 cm, slide 12F401, E.F. B51/3.
- 8, 9** *Lavradospaera crista* De Schepper and Head 2008. High focus (8) and low focus (9). Maximum diameter 25  $\mu\text{m}$ ; central body 16  $\mu\text{m}$ . ODP 642B-9H-3A, 60–61 cm, slide 12G10, E.F. O35/0.







## Recorded dinoflagellate cysts species

*Achomosphaera andalousiensis* subsp. *andalousiensis* Jan du Chêne 1977

*Achomosphaera andalousiensis* subsp. *suttonensis* Head 1997

*Amiculospaera umbraculum* Harland 1979

*Ataxiodinium choane* Reid 1974

*Ataxiodinium confusum* Versteegh and Zevenboom in Versteegh 1995

*Ataxiodinium zevenboomii* Head 1997

*Barssidinium graminosum* Lentin et al. 1994

*Barssidinium pliogenicum* (Head 1993) Head 1994

*Batiacasphaera micropapillata* Stover 1977

*Bitectatodinium raedwaldii* Head 1997

*Bitectatodinium?* *serratum* (Head et al. 1989) Lentin and Williams 1993

*Bitectatodinium tepikiense* Wilson 1973

*Cerebrocysta?* *namocensis* Head et al. 1989

*Corrudinium devernaliae* Head and Norris 2003

*Corrudinium harlandii* Matsuoka 1983

*Corrudinium?* *labradori* Head et al. 1989

Cyst of *Pentapharsodinium dalei* Indelicato and Loeblich III 1986

Cyst type 1 of Head and Mudie 1989

*Dapsilidinium pseudocolligerum* (Stover 1977) Bujak et al. 1980

*Filisphaera filifera* subsp. *filifera* (Bujak 1984) Head 1994

*Filisphaera filifera* subsp. *pilosa* (Matsuoka and Bujak 1988) Head 1994

*Filisphaera microornata* (Head et al. 1989) Head 1994

*Habibacysta tectata* Head Norris and Mudie 1989

*Heteraulacacysta* sp. A Costa and Dowie 1979

*Hystriochokolpoma rigaudiae* Deflandre and Cookson 1955

*Impagidinium aculeatum* (Wall 1967) Lentin and Williams 1981

- Impagidinium pallidum* Bujak 1984
- Impagidinium paradoxum* (Wall 1967) Stover and Evitt 1978
- Impagidinium patulum* (Wall 1967) Stover and Evitt 1978
- Impagidinium solidum* Versteegh and Zevenboom in Versteegh 1995
- Impagidinium* sp. 1 of De Schepper and Head 2009
- Impagidinium* sp. 2 of De Schepper and Head 2009
- Impagidinium vermiculatum* Simon Petroleum Technology Limited 1994
- Invertocysta lacrymosa* Edwards 1984
- Invertocysta tabulata* Edwards 1984
- Lejeunecysta catomus* (Harland in Harland et al. 1991) Lentin and Williams 1993
- Lejeunecysta hatterasensis* Head and Norris 2003
- Lingulodinium machaerophorum* (Deflandre and Cookson 1955) Wall 1967
- Melitasphaeridium choanophorum* (Deflandre and Cookson 1955) Harland and Hill 1979
- Nematosphaeropsis labyrinthus* (Ostenfeld 1903) Reid 1974
- Nematosphaeropsis lativittata* Wrenn 1988
- Operculodinium centrocarpum* s.s. (Deflandre and Cookson 1955) Wall 1967
- Operculodinium centrocarpum* sensu Wall and Dale 1966
- Operculodinium centrocarpum/israelianum*; *Operculodinium centrocarpum* (Deflandre and Cookson 1955) Wall 1967 *Operculodinium israelianum* Rossignol 1962
- Operculodinium?* *eirikianum* Head et al. 1989 emend. Head 1997 var. *crebrum* De Schepper and Head 2008
- Operculodinium?* *eirikianum* Head et al. 1989 emend. Head 1997 var. *eirikianum* (autonym)
- Operculodinium janduchenei* Head Morris and Mudie 1989
- Operculodinium* sp. 1 of Louwye et al. 2004
- Operculodinium tegillatum* Head 1997
- Pyxidinopsis braboi* De Schepper et al. 2004
- Pyxidinopsis pastilliformis* (Head et al. 1989) Head in Matsuoka and Head 1992
- Pyxidinopsis tuberculata* Versteegh and Zevenboom in Versteegh 1995

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

*Selenopemphix brevispinosa* Head et al. 1989

*Selenopemphix dionaeacysta* Head et al. 1989

*Selenopemphix nephroides* Benedek 1972

*Selenopemphix quanta* (Bradford 1975) Matsouka 1985

*Spiniferitus elongatus* Reid 1974

*Spiniferites membranaceus* (Archangelsky 1969) Lentin and Williams 1973

*Spiniferites mirabilis/hyperacanthus*; *Spiniferites mirabilis* (Rossignol 1964), *Spiniferites hyperacanthus* (Deflandre and Cookson 1955) Cookson and Eisenack 1974

*Spiniferites* sp. A of Louwye and De Schepper 2010

*Tectatodinium pellitum* Wall 1967

*Trinovantedinium glorianum* (Head et al. 1989) deVerteuil and Norris 1992

*Tuberculodinium vancampoe* (Rossignol 1962) Wall 1967

### **Dinoflagellate cysts only differentiated to genus**

*Brigantedinium* (Reid 1977) Lentin and Williams 1993

*Echinidinium* (Zonneveld 1997) Head et al. 2001

### **Recorded Achritarchs**

*Cymatiosphaera? aegirii* De Schepper and Head 2013

*Cymatiosphaera? icenorum* De Schepper and Head 2013

*Cymatiosphaera? invaginata* Head, Norris and Mudie 1989

*Lavradosphaera* cf. *canalis* De Schepper and Head 2013

*Lavradosphaera crista* De Schepper and Head 2008

*Nannobarbophora walldalei* Head 1996

**Recorded Other Palynomorphs**

*Gelasinicysta vangeelii* Head 1992

*Pterospermella* Eisenack 1972

**Dinoflagellate cysts mentioned in the text but not recorded in the present study**

Algal cyst type 1 of Head (1996)

*Barssidinium evangelinae* Lentin et al. 1994

*Cristadinium cristatoserratum* Head et al. 1989

*Edwardsiella sexispinosa* Versteegh and Zevenboom in Versteegh 1995

*Nematosphaeropsis lemniscata* Bujak 1984

*Hystriosphraeropsis obscura* (Habib 1972) Wrenn 1988

*Impagidinium multiplexum* Wall and Dale (1968)

*Pyxidinopsis vesiculata* Head and Norris 2003

*Selenopemphix armageddonensis* de Verteuil and Norris 1992

**Acritarchs mentioned in the text but not recorded in the present study**

*Lavradospaera Lucifer* De Schepper and Head 2008

*Leiosphaera rockhallensis* De Schepper and Head 2008

*Decahedrella martinheadii* Manum 1997