

**Magnetostratigraphically-calibrated dinoflagellate cyst bioevents for the
uppermost Eocene to lowermost Miocene of the western North Atlantic (IODP
Expedition 342, Paleogene Newfoundland sediment drifts)**

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Abstract

The Oligocene epoch represents a somewhat neglected chapter in paleoclimate and paleoceanographic history, which is at least partially due to the scarcity of complete Oligocene sedimentary archives and poor biostratigraphic age control. Many of the biotic events registered in Oligocene microfossils are strongly diachronous across latitudes as a response to increased global cooling and enhanced meridional temperature gradients. To improve biostratigraphic age control for the Oligocene of the North Atlantic Ocean, we carried out a high-resolution study of dinoflagellate cysts from Integrated Ocean Drilling Program (IODP) Sites U1405, U1406 and U1411 off Newfoundland. Together the sites comprise an apparently complete uppermost Eocene (34.9 Ma) to lowermost Miocene (21.7 Ma) sequence with good magnetostratigraphic age control. This allows us to firmly tie identified dinoflagellate cyst bioevents to the geomagnetic polarity timescale. In the dinoflagellate cyst assemblages studied we have identified and magnetostratigraphically-calibrated ten first and 19 last appearance datums. Our magnetostratigraphically-calibrated dinocyst-based biostratigraphy, which is based on an average sample resolution of a sample every ~150 kyrs, will contribute to an improved age framework for future paleoceanographical studies in the higher-latitude North Atlantic.

Keywords: Paleogene; Oligocene; biostratigraphy; dinoflagellates; North Atlantic; Integrated Ocean Drilling Program

1 Introduction

Positioned between the early Paleogene greenhouse and the well-developed Neogene icehouse worlds, the Oligocene epoch (33.9–23.03 Ma; Gradstein et al., 2012) represents in many ways the neglected ‘middle child’ of Cenozoic paleoceanography and paleoclimatology (Shipboard Scientific Party, 2002). This status has at least partially resulted from the sparseness of complete Oligocene

sedimentary archives. Shelfal sequences of Oligocene age often exhibit hiatuses caused by sea-level fluctuations that reflect the waxing and waning of Antarctic ice sheets (Miller et al., 1991; Wade and Pälike, 2004; Pälike et al., 2006). Likewise, deep-marine Oligocene sequences, which would have remained largely unaffected by sea-level dynamics directly, are often fragmentary due to the onset of strong bottom-water circulation near the Eocene/Oligocene boundary (Miller and Tucholke, 1983; Davies et al., 2001). Notwithstanding these limitations, the Oligocene deserves further attention from the paleoclimatic community because it represents one of the most interesting episodes in the evolution of Cenozoic climates. Studying the Oligocene allows one to decipher the processes underlying the transition from a climate state characterized by the lack of large-scale ice sheets and associated sea-level dynamics to a climate state characterized by a unipolar glaciation, pronounced, glacially induced sea-level oscillations and the establishment of a quasi-modern oceanic circulation regime (e.g., Coxall et al., 2005; Pälike et al., 2006; Zachos et al., 2008).

Disentangling the causal mechanisms behind the long-term climate evolution and short-term dynamics in Earth's history critically hinges on the availability of highly resolved, integrated stratigraphies (e.g., Kuiper et al., 2008). Despite the enormous progress in the development of geochemical and cyclostratigraphical approaches over the past decades, microfossil-based biostratigraphy has remained an indispensable stratigraphic tool both in academic research and industry applications (e.g., Beaudoin and Head, 2004; Coccioni et al., 2008; Tauxe et al., 2012; Jenkins, 2013). However, although individual marine plankton taxa occur across vast regions, their distribution is strongly influenced by water-mass or other oceanographic boundaries (Lazarus, 1983). Hence, as a response to increased global cooling and enhanced meridional temperature gradients from the late Eocene onwards, many biotic events registered in microfossil assemblages during the Oligocene are strongly diachronous across latitudes. These diachroneities can yield substantial uncertainties

in biostratigraphic age control, thereby compromising long-distance correlations. For instance, the ranges of many Oligocene calcareous nannoplankton taxa differ strongly from low to high latitudes, which has resulted in the development of two widely used zonal schemes – the zonation of Martini (1971) is largely based on temperate regions, whereas that of Bukry (1973) relies on low-latitude sections. Similarly, many planktic foraminifers show constrictions in ranges through the Eocene and Oligocene (Boersma and Silva, 1991), as do radiolaria (Maurrasse, 1979), diatoms (Baldauf and Barron, 1990), and organic-walled dinoflagellate cysts (dinocysts) (Williams and Bujak 1977; Williams et al., 2004). Clearly, further improvement of biostratigraphic age control for the Oligocene is required, in particular with regard to the generation of chronostratigraphically (i.e., paleomagnetically and/or cyclostratigraphically) well calibrated, temporally highly resolved datums (Luterbacher et al., 2004).

With regard to the notorious incompleteness of Oligocene strata, the drift sediments recovered during Integrated Ocean Drilling Program (IODP) Expedition 342 off Newfoundland represent a remarkable exception to the rule. Besides spanning the entire Oligocene and being apparently complete, they exhibit sedimentation rates that are exceptionally high for deep-marine settings (up to 10.4 cm/kyr) and have allowed exquisite preservation of calcareous, silicious and organic-walled microfossils (Norris et al., 2014a). The high-quality paleomagnetic age control of the IODP Exp. 342 sites discussed here (see Section 4.2) provide an opportunity to develop an integrated biomagnetostratigraphy for a number of microfossil groups that can be exported to the greater NW Atlantic region. This will ultimately allow for correlation of paleoceanographic events between the lower and higher latitudes.

2 Previous work on Oligocene dinocyst biostratigraphy

The backbone of microfossil-based biostratigraphy in the Oligocene is traditionally formed by calcareous plankton groups. However, the biostratigraphic utility of these

groups for the higher-latitude North Atlantic, and thereby also for correlation between higher and lower latitudes, is compromised by their diminished diversity and/or reduced preservation potential in polar to sub-polar settings (Baldauf and Barron, 1990; Lipps, 1993 and references therein). In contrast, organic-walled dinocysts are inert to chemical dissolution (albeit sensitive to oxidation), and they exhibit high species diversity in the Eocene to Oligocene of the high-latitude North Atlantic Ocean and adjacent seas (Damassa et al., 1990; Eldrett et al., 2004).

Over approximately the past 40 years, dinocyst biostratigraphy has emerged as a highly valuable tool in the age control of Oligocene successions from both shallow-marine, shelfal (e.g., Stover and Hardenbol, 1994; Van Simaeys et al., 2004; Schiøler, 2005; Śliwińska et al., 2010) and pelagic settings (e.g., Biffi and Manum, 1988; Brinkhuis and Biffi, 1993; Wilpshaar et al., 1996; Pross et al., 2010). In many cases, Oligocene dinocyst bioevents have been chronostratigraphically calibrated using information from calcareous microfossil groups, notably calcareous nannoplankton (e.g., Biffi and Manum, 1988; Head and Norris, 1989; Damassa et al., 1990; Pross, 2001; Van Simaeys et al., 2004). However, under a climate regime with strong meridional temperature gradients as was the case during the Oligocene, calcareous nannoplankton bioevents tend to be diachronous (Backman, 1987), and the preservation of calcareous nannoplankton assemblages in high-latitude settings is strongly compromised by enhanced carbonate dissolution (Berger et al., 1989; Eldrett et al., 2004).

To date, remarkably few dinocyst biostratigraphies with robust magnetostratigraphic calibration have become available for the Oligocene (Fig. 1). With the exception of the biostratigraphic data provided by Tauxe et al. (2012), Houben et al. (2013) and Peter Bijl (pers. comm.) for the high-latitude Southern Ocean, they are exclusively based on successions from the Northern Hemisphere (Fig. 2). Lower-latitude information from the Northern Hemisphere is primarily available from the Tethyan realm. Based on material from the Umbria–Marche region

of Central Italy, which is home to some of the most complete Oligocene successions known from the western Tethys, Brinkhuis and Biffi (1993) established a dinocyst zonation for the Eocene/Oligocene transition interval. Subsequently, Wilpshaar et al. (1996) extended this work into younger strata, generating a dinocyst zonation for the entire Oligocene. Their conclusion that this zonation could be used throughout the Mediterranean region was later confirmed by Peeters et al. (1998) and Torricelli and Biffi (2001). Integrating higher-resolution datasets from different sections in the Umbria-Marche Basin, Coccioni et al. (2008) and Pross et al. (2010) further refined the chronostratigraphic calibration of Oligocene dinocyst bioevents for the Tethyan realm.

Mid-latitudinal, magnetostratigraphically-calibrated dinocyst bioevents for the Oligocene are primarily known from the North Sea Basin (Fig. 1). Śliwińska et al. (2012) established an integrated bio- and magnetostratigraphy for the Rupelian and Chattian based on onshore deposits from Denmark. Dybkjær et al. (2012) studied the Oligocene-Miocene boundary interval, and Thomsen et al. (2012) presented a magnetostratigraphic calibration for some of the Eocene to earliest Oligocene bioevents previously identified by Heilmann-Clausen and Van Simaey (2005). A cross-calibration of magnetostratigraphic and dinocyst biostratigraphic data for part of the lower Rupelian of the northern Alpine Foreland basin in Southern Germany has been carried out by Kempf and Pross (2005).

For the higher-latitude North Atlantic, a wealth of magnetostratigraphically-calibrated dinocyst data has become available from Deep-Sea Drilling Project (DSDP) Site 338 and Ocean Drilling Program (ODP) Sites 643 and 913 in the Norwegian–Greenland Sea (Fig. 2; Eldrett et al., 2004; Eldrett and Harding, 2009). Following up on the previous, low-resolution work of Manum (1976), Eldrett et al. (2004) developed magnetostratigraphies for the middle Eocene to lower Oligocene (Chronos C21r to C12n) of DSDP Site 338 as well as ODP Sites 319B and 643A; they identified numerous dinocyst bioevents for this time interval. An account of Eocene

dinocyst events at DSDP Site 338 was later presented by Eldrett and Harding (2009); this study also straddles the Eocene/Oligocene boundary. For ODP Site 647 in the Labrador Sea, Firth et al. (2012) established an integrated, early to late Eocene magneto- and multi-microfossil-group biostratigraphy that also yielded a number of dinocyst bioevents. They utilized some of the dinocyst datums previously magnetostratigraphically calibrated by Eldrett et al. (2004) in their identification of magnetic reversals. Depending on the interpretation of the paleomagnetic signals obtained, the ODP Site 647 record extends into the early or 'middle' Oligocene (Chronos C13r or C9n). Firth et al. (2012) also re-examined the original work on ODP Site 647 dinocysts of Head and Norris (1989).

Here we present magnetostratigraphically-calibrated dinocyst bioevents from the latest Eocene to earliest Miocene successions off Newfoundland that were drilled in 2012 during IODP Expedition 342 ('Paleogene Newfoundland Sediment Drifts'). The cores recovered during IODP Expedition 342 have yielded the first stratigraphically apparently complete record of the entire Oligocene in the higher-latitude Northwest Atlantic (Norris et al., 2014a). As such, and considering the high-quality magnetostratigraphical age control for the material (Norris et al., 2014a, Van Peer et al., in press), they can provide a future reference record for the greater Northwest Atlantic region, with the potential of exporting the magnetostratigraphically-calibrated biostratigraphical datums identified from their dinocyst assemblages to the higher-latitude North Atlantic. Ultimately, our study aims to establish a chronostratigraphic framework for future paleoenvironmentally- and paleoceanographically-oriented research on the Oligocene of the higher latitudes of the Northern Hemisphere.

3 Studied sites

The successions analyzed in this study have been recovered during IODP Expedition 342 from drift-sediment deposits ca. 700 km east-southeast of Newfoundland (Fig.

2). IODP Expedition 342 was designed to recover Paleogene sedimentary sequences with exceptionally high sedimentation rates, with the overarching goal of reconstructing the evolution of the carbonate compensation depth in the North Atlantic during the Paleogene. The Oligocene sequences have sedimentation rates of 1.5 to 10 cm/kyr (Norris et al., 2014a). Owing to these high sedimentation rates and the relatively high clay content of the sediments, calcareous, siliceous and notably organic-walled microfossils are unusually well preserved in much of the IODP Expedition 342 core material (Expedition 342 Scientists, 2012).

Because of their position in the Northwest Atlantic Ocean offshore Newfoundland, the IODP Expedition 342 drillsites provide archives of information on two different surface-water regimes, i.e., the (proto-) Gulf Stream and the (proto-) Labrador Current. For the studied time interval, there is no conclusive evidence about North Atlantic surface-water patterns. While the existence of the Gulf Stream is relatively well established from at least the early Miocene onwards (Pinet et al., 1981; Wade et al., 2001), the timing of the onset of the Labrador Current is a matter of ongoing debate, ranging from the Maastrichtian to the middle Miocene (Nederbragt, 1992; Via and Thomas, 2006; Kender and Kaminski, 2013). The presence of ice-rafted debris in the Arctic Sea since 46 Myr (St. John, 2008; Stickley et al., 2009) indicates seasonal sea-ice formation that might have exported fresh water to the lower latitudes via the (proto-) Labrador Current, suggesting that this current had likely been established by that time. Given this paleoceanographic setting, the successions from the studied sites allow reconstruction of the interplay between cold water-masses derived from the Labrador Sea and warm-water masses derived from the (sub-) tropical Atlantic.

During the Oligocene, the region off Newfoundland was situated at a paleo-latitude of $\sim 40^{\circ}\text{N}$ (Norris et al., 2014a). The Oligocene succession was deposited in a deep-water sediment drift setting, with paleo-waterdepths ranging from

approximately 2800 to 4000 m (Expedition 342 Scientists, 2012). The drift sediments likely originate from the Labrador margin and the Labrador Sea (Norris et al., 2014a). Successions from three IODP Expedition 342 sites were analyzed (Sites U1405, U1406, and U1411; Fig. 2). Together, these sequences span the entire Oligocene, including the Eocene-Oligocene and Oligocene-Miocene boundary intervals. The correlation between the records from different sites was achieved using magnetostratigraphic data (Norris et al., 2014b, c, d; Van Peer et al., in press). The stratigraphical, lithological and paleoceanographical characteristics of the investigated sites with particular reference to the sampled intervals are briefly discussed in the following.

From Site U1405 (coordinates: 40°08.30'N, 51°49.20'W; Fig. 2), we report dinocyst data from the latest Oligocene (Chron C6Cr) to earliest Miocene (Subchron C5Cn.1n). The site is situated on the J-Anomaly Ridge at a present-day water depth of 4285 m. During the Oligo-Miocene, greenish-grey clays to oozes were deposited that are characterized by varying abundances of radiolarians, diatoms and calcareous nannofossils. The carbonate content of these sediments ranges from 0 to 30 %. Across the Oligocene-Miocene transition there are several pale, carbonate-rich layers exhibiting high abundances of the nannofossil *Braarudosphaera*. Sedimentation rates based on the age model for Site U1405 (Norris et al., 2014b) are on the order of 10 cm/kyr across the studied interval. These exceptionally high sedimentation rates suggest an intensification of boundary-current flow strength and sediment transport, indicating a significant increase in drift development (Norris et al., 2014b).

Site U1406 (coordinates: 40°21.0'N, 51°39.0'W; Fig. 2) is also located on J-Anomaly Ridge at a present-day water depth of 3813 m. The sedimentary sequence recovered spans the Paleocene to early Miocene. Lithologically, the Oligocene succession at Site U1406 consists of carbonate-rich nannofossil ooze in the lowermost Oligocene that is overlain by ~180 m thick brown to green nannofossil

ooze representing the early Oligocene to early Miocene. Sedimentation rates at Site U1406 during the Oligocene are between 1.0 and 3.2 cm/kyr and thus generally lower than at the deeper sites (e.g., Site U1405). This suggests that Site U1406 represents a shallower part of the J-Anomaly drift sequence that was less strongly affected by sedimentation induced by the deep western boundary-current-induced sedimentation (Norris et al., 2014c).

Located on the Southeastern Newfoundland Ridge at a present-day water depth of 3300 m, Site U1411 (coordinates: 41°37.1'N, 49°00'W; Fig. 2) recovered a late Eocene (Chron C15n) to early Oligocene (Chron C8r) succession comprised primarily of silty clay, clay with nannofossils, and silty nannofossil clay (Norris et al., 2014d). More carbonate-rich nannofossil ooze is only present immediately above the Eocene/Oligocene boundary, probably representing the widespread carbonate overshoot observed at other Expedition 342 sites (Norris et al., 2014d). Eocene and Oligocene sedimentation rates at Site U1411 are ~1.5 cm/kyr on average. Even higher values occur at the Eocene-Oligocene boundary interval (up to 3.2 cm/kyr). These generally increased sedimentation rates from the middle Eocene onwards reflect the onset of drift sedimentation at the Southeastern Newfoundland Ridge (Norris et al., 2014d).

4 Material and methods

4.1 Sampling strategy

The investigated samples from the Oligocene Expedition 342 splice comprise cores from Sites U1411 (Eocene/Oligocene transition interval; reversal C13r/C15n to C12r/C13n), U1406 (early to late Oligocene; C12r/C13n to C6Cn.3n/C6Cr), and U1405 (Oligocene/Miocene transition interval; C6Cn.3n/C6Cr to C6AAr.3r). The splice has been developed based on shipboard magnetostratigraphic and biostratigraphic (planktic foraminiferal, calcareous nannoplankton and radiolarian) data (Norris et al., 2014b, c, d). Site U1405 was sampled from Sections U1405A-

10H-6W to U1405B-21H-3W (127.70–247.39 m CCSF-A [Core Composite Depth below Sea Floor]), Site U1406 from Sections U1406A-10H-1W to U1406A-22H-4A (96.91–239.33 m revised CCSF-A, Van Peer et al., in press), and Site U1411 from Sections U1411B-15H-4A to U1411C-12X-4A (135.31–188.43 m CCSF-A). A list of all studied samples is available as Online Supplementary Material accompanying this paper.

To achieve a targeted average temporal resolution between 100 and 150 kyrs, sampling distances were calculated following the sedimentation rates as indicated by shipboard stratigraphic work. This procedure resulted in twelve samples for the Eocene/Oligocene transition interval of Site U1411, 69 samples for the early to late Oligocene interval of Site U1406, and 13 samples for the Oligocene/Miocene transition interval of Site U1405. An additional 18 samples were examined to cover a hiatus and slumping structures at Site U1406 (Van Peer et al., in press). These samples were taken from the splice for Site U1411 (from Cores U1411B-4H-6W to U1411B-10H-6W, 27.55–87.6 m CCSF-A respectively). The revised depth for samples from Site U1406 is given as revised CCSF-A (Van Peer et al., in press).

4.2 Magnetostratigraphical age control

For the magnetostratigraphic calibration of dinocyst bioevents, the shipboard-measured magnetic polarity zones were used for all samples from Sites U1411 and U1405 (compare Norris et al., 2014b, d). For Site U1406, the positions of some reversals have been modified during post-cruise research by Van Peer et al. (pers. comm.), and we have applied this updated stratigraphy wherever available. The magnetostratigraphical reversal ages are based on the time scale of Gradstein et al. (2012). For the Oligocene the GTS2012 ages are primarily based on the astronomical tuning of ODP Site 1218 (Pälike et al., 2006). Correlation of individual polarity chrons to the geomagnetic polarity time scale was through shipboard biostratigraphical data and the identification of the magnetochron reversal pattern

(Norris et al., 2014a; Van Peer et al., in press). Biostratigraphic ages are determined from the relative position of dinocyst datums within the respective magnetochrons and given in percentages above the base of magnetochrons.

4.3 Palynological sample preparation and evaluation

In total, 113 samples were investigated for their dinocyst assemblages. The sampling strategy yielded an average temporal resolution on the order of 150 kyrs. Sample processing followed standard palynological techniques (e.g., Pross, 2001). Between 9 and 31 g of dry sediment were processed per sample. All samples from Sites U1405 and U1411, and 52 samples from Site U1406 were digested using 33 % hydrochloric acid (HCl) and 40 % hydrofluoric acid (HF); sieving was through a 15 μm nylon mesh. The residues were stained with 1% safranin ($\text{C}_{20}\text{H}_{19}\text{ClN}_4$), and one to five strew mounts were prepared per sample using glycerine jelly as a mounting medium. A slightly modified protocol was followed for a sample subset comprising 17 samples from Site U1406. After HCl and HF treatment, these samples were swirled in order to increase the concentration of palynomorphs, and the residues were sieved through an 11 μm mesh. Finally, all samples were briefly oxidized with potassium hydroxide (KOH, 5%). At least one strew-mount slide was prepared per sample by mounting the residue in glycerol jelly. A visual inspection of strew-mount slides obtained through the different processing protocols revealed no systematic differences in palynomorph preservation, with the exception of the stained material being easier to count and photograph.

Whenever possible, a minimum of 300 (mean: 339) dinocysts were counted per sample and identified to the species level; only in one sample less than 250 dinocysts were counted. To detect rare taxa that had not been registered during regular counts, at least one additional slide was scanned for each sample. Selected taxa were documented through photomicrographs using a Zeiss Axiocam105 color camera mounted to a Zeiss Scope.A1 light microscope. With the exception of the

sample subset from Site U1406, which is stored at the Geological Survey of Denmark and Greenland in Copenhagen, Denmark, all material is housed in the collection of the Institute of Earth Sciences, University of Heidelberg, Germany. If not stated otherwise, the dinocyst taxonomy follows Fensome and Williams (2004).

5 Results and discussion

All examined samples from the uppermost Eocene to lowermost Miocene of IODP Sites U1405, U1406 and U1411 yielded rich, exceptionally well and mostly three-dimensionally preserved palynomorph assemblages. The assemblages are dominated by dinocysts, but also contain lower numbers of (predominantly bisaccate) pollen grains and spores. Acritarchs are generally common, but reach exceptionally high abundances in a number of late Rupelian samples from Site U1406. The dinocyst assemblages are highly diverse; 110 taxa were identified (see Appendix for a full list of taxa).

5.1 Magnetostratigraphic calibration of dinocyst datums

The dinocyst assemblages contain numerous age-diagnostic marker taxa for the latest Eocene to earliest Miocene that have been described previously from the North Atlantic (e.g., Head and Norris, 1989; Williams and Manum, 1999; Eldrett et al., 2004; Fensome et al., 2009; Firth et al., 2012), the North Sea (e.g., Bujak and Mudge, 1994; Heilmann-Clausen and Van Simaey, 2005a), and the Tethys (e.g., Wilpshaar et al., 1996; Van Mourik and Brinkhuis, 2000; Pross et al., 2010). Semiquantitative range charts are presented in Figs. 3–6. An integrated scheme of the magnetostratigraphically-calibrated dinocyst bioevents is given in Fig. 7. All ages given refer to the 2012 time scale (Gradstein et al., 2012).

The Eocene-Oligocene transition as defined by the extent of Chron C13 (Gradstein et al., 2012) is characterized by the Last Appearance Datums (LADs) of *Areosphaeridium diktyoplokum*, *Charlesdowniea clathrata*, *Cordosphaeridium* cf.

funiculatum, *Hemiplacophora semilunifera*, *Lophocysta sulcolimbata*,
Schematophora speciosa, and *Stoveracysta* sp. 1. First Appearance Datums (FADs)
within that interval include those of *Chiropteridium galea*, *Chiropteridium*
lobospinosum, *Filisphaera filifera*, *Melitasphaeridium asterium*, *Spiniferites manumii*,
and *Svalbardella* spp. (Figs. 3–6). The middle part of the Rupelian from Chron C12
onwards is marked by the LADs of *Enneadocysta pectiniformis*, *S. manumii*, and
Phthanoperidinium comatum, as well as the FADs of *Hystrichokolpoma pusillum* and
Oligokolpoma galeottii Pross et al., 2010. The Chattian exhibits only a few dinocyst
bioevents; these are the LADs of *Areoligera semicirculata*, *Saturnodinium pansum*,
and *Wetzeliiella* spp.. The Oligocene-Miocene boundary interval as defined by the
extent of Chrons C6C and C6B is marked by the LADs of *Deflandrea* spp., *F. filifera*,
H. pusillum, and *Svalbardella* spp, and the FAD of *Artemisiocysta cladichotoma*
(Figs. 3-7). Detailed characterizations of all registered dinocyst bioevents (FADs and
LADs) are provided below in ascending stratigraphic order. A stratigraphically
arranged compilation of magnetostratigraphically-calibrated FADs and LADs as they
are known from different ocean basins is provided in Tables 1 and 2, respectively.
We reiterate that all ages given refer to the time scale of Gradstein et al. (2012); this
also applies to the dates derived from previously published papers, which have been
recalculated accordingly to the Gradstein et al. (2012) timescale. The positions of the
individual dinocyst events with regard to the Calcareous Nannoplankton Zones as
identified in the Expedition 342 cores (Norris et al., 2014c) are also indicated.

5.1.1 LAD of *Schematophora speciosa*

Core position: U1411B-18H-2A, 164.43 m CCSF-A.

Magnetostratigraphic calibration: 69 % from the bottom of Chron C13r.

Position with regard to calcareous nannoplankton zonation: NP21.

Age assignment: 34.1 Ma.

Discussion: On the Scotian Margin off southeastern Canada, *Schematophora speciosa* has previously been described to have a late Eocene (middle Priabonian) LAD (Fensome et al., 2009), which is in agreement with our findings. Other than on the Scotian Margin, the taxon has not been registered previously in the North Atlantic. In the Mediterranean region, the LAD of *S. speciosa* occurs at the top of the *Schematophora speciosa* Interval Zone, which is calibrated to Chron C13r and the basal part of NP21 (Brinkhuis and Biffi, 1993). Hence, the region-specific LADs of *S. speciosa* appear to be quasi-synchronous in the western North Atlantic and the western Tethys.

5.1.2 LAD of *Cordosphaeridium* cf. *funiculatum*

core position: U1411C-9H-4A, 159.68 m CCSF-A.

Magnetostratigraphic calibration: 77 % of Chron C13r.

Position with regard to calcareous nannoplankton zonation: NP21.

Age assignment: 34.0 Ma.

Discussion: *Cordosphaeridium* cf. *funiculatum* of Biffi and Manum (1988) differs from the type material of *C. funiculatum* as described by Morgenroth (1966a) in having shorter and thicker processes. The taxon has been previously reported from the upper Eocene of the Labrador Sea (ODP Site 647) as *Cordosphaeridium* sp. cf. *funiculatum*. In the Labrador Sea, it occurs until the end of NP20 (Head and Norris, 1989). In the western Tethys, the taxon occurs during the lower part of NP21, which is correlative to the latest Eocene (Biffi and Manum, 1988). Our results are well in agreement with the records from the Labrador Sea and the Tethyan region. As all previous findings of *C. cf. funiculatum* are limited to the late Eocene, this taxon may represent an important supraregional marker with remarkably similar LADs in lower-latitude settings of the western Tethys and the higher-latitude western North Atlantic.

5.1.3 LAD of *Hemiplacophora semilunifera*

418 *Core position:* U1411B-17H-3A, 154.91 m CCSF-A.
419 *Magnetostratigraphic calibration:* 93 % of Chron C13r.
420 *Position with regard to calcareous nannoplankton zonation:* NP21.
421 *Age assignment:* 33.8 Ma.
422 *Discussion:* To date, *Hemiplacophora semilunifera* has been rarely detected
423 previously in the North Atlantic region. Head and Norris (1989) reported the species
424 from ODP Site 647 in the Labrador Sea, where it disappears by the end of NP21. For
425 central Italy, Brinkhuis and Biffi (1993) determined the LAD of *H. semilunifera* to
426 terminate their *Glaphyrocysta semitecta* Interval Zone of the earliest early Oligocene.
427 This zone corresponds to the middle part of NP21, and its top is assigned to the
428 lowermost part of Chron C13r. The apparently synchronous disappearance of *H.*
429 *semilunifera* in both the western North Atlantic and the Tethys indicates the high
430 stratigraphic relevance of the species.

431

432 **5.1.4 FAD and LAD of *Lophocysta sulcolimbata***

433 *Core positions:* FAD: U1411C-11X-5A, 178.83 m CCSF-A; LAD: U1411B-17H-3A,
434 154.91 m CCSF-A.
435 *Magnetostratigraphic calibration:* 31 % of Chron C13r and 93 % of Chron C13r,
436 respectively.
437 *Position with regard to calcareous nannoplankton zonation:* NP 21.
438 *Age assignment:* 34.6 and 33.8 Ma, respectively.
439 *Discussion:* In our sample material, *Lophocysta sulcolimbata* occurs in relatively low
440 numbers, albeit repeatedly within a very short time interval of 0.8 Myr, which
441 suggests that it may represent a useful biostratigraphic marker with a remarkably
442 short range. However, previously published information on *L. sulcolimbata* from the
443 greater North Atlantic region does not yield a consistent picture of the taxon's range.
444 Head and Norris (1989) provided a photomicrograph of the taxon (as *Lophocysta* sp.
445 1) from ODP Site 647 in the Labrador Sea. For ODP Site 985 in the Norwegian Sea,

Williams and Manum (1999) give a FAD at 21.1 Ma, which is much later than our findings. In the Central Danish Basin, the species was observed in the upper Eocene (Heilmann-Clausen and Van Simaey, 2005). Based on these widely divergent ranges, the FAD and LAD of *L. sulcolimbata* as identified in our samples may only be employed regionally for the Newfoundland Margin as latest Eocene events.

5.1.5 LAD of *Areosphaeridium diktyoplokum*

Core position: U1411C-8H-4A, 150.11 m CCSF-A.

Magnetostratigraphic calibration: 9 % of Chron C13n.

Position with regard to calcareous nannoplankton zonation: NP21.

Age assignment: 33.7 Ma.

Discussion: In our material from IODP Expedition 342, the LAD of *Areosphaeridium diktyoplokum* post-dates the Eocene/Oligocene boundary by 0.2 Ma. Highly similar LADs are suggested from other sites in the North Atlantic. In the Norwegian-Greenland Sea, *A. diktyoplokum* disappears within Chron C13 between 33.3 and 33.5 Ma (Eldrett et al., 2004). In the Labrador Sea, its LAD falls within NP21/NP22 (Head and Norris, 1989). In the North Sea Basin, the taxon disappears in the lowermost part of Chron C12r (Śliwińska et al., 2012), which is consistent with the indirect calibration of this bioevent against NP21/NP22 in that region (Bujak and Mudge, 1994; Van Simaey et al., 2005a). While the LADs of *A. diktyoplokum* as registered in the greater North Atlantic region are highly consistent, the available information suggests a slightly later disappearance in the Tethyan realm. In Italy, *A. diktyoplokum* has been reported to occur consistently in lowermost Oligocene strata, and its LAD has been calibrated against a level close to the top of Chron C13n at 33.4 Ma (Pross et al., 2010; compare also discussion in Brinkhuis and Visscher, 1995, and van Mourik and Brinkhuis, 2005, and references therein). On the basis of the temporal resolution of the available sample sets, the diachroneity between the North Atlantic and Tethyan LADs of *A. diktyoplokum* amounts to ~0.4 Myr.

474

475 **5.1.6 LAD of *Charlesdowniea clathrata***

476 *Core position:* U1411C-8H-4A, 150.11 m CCSF-A.

477 *Magnetostratigraphic calibration:* 9 % of Chron C13n.

478 *Position with regard to calcareous nannoplankton zonation:* NP21.

479 *Age assignment:* 33.7 Ma.

480 *Discussion:* *Charlesdowniea clathrata* is relatively rare in the studied material; it has
481 not been reported previously from the western North Atlantic. In the eastern North
482 Sea Basin, the species has a mid-Rupelian LAD (Schiøler, 2005). In the western
483 Tethys, the magnetostratigraphically-calibrated LAD of *C. clathrata* was determined
484 as 32.4 Ma (Pross et al., 2010). These findings suggest a pronounced diachroneity
485 between the LADs of *C. clathrata* in the Tethyan realm and the North Atlantic, which
486 amounts to ~1.3 Myr based on the temporal resolution of the available data.

487

488 **5.1.7 FAD of *Filisphaera filifera***

489 *Core position:* U1411C-8H-4A, 150.11 m CCSF-A.

490 *Magnetostratigraphic calibration:* 9 % of Chron C13n.

491 *Position with regard to calcareous nannoplankton zonation:* NP21.

492 *Age assignment:* 33.7 Ma.

493 *Discussion:* In the IODP Expedition 342 material, *Filisphaera filifera* occurs
494 repeatedly (albeit in low numbers) in the upper Eocene and lowermost Oligocene;
495 the taxon then reappears in the upper Rupelian (corresponding to an age of 29.3
496 Ma). As *F. filifera* has originally been described from the Neogene and Quaternary
497 (Head, 1994), our findings imply a greatly extended range of this taxon in comparison
498 to previous work. However, they are broadly consistent with previous observations
499 from the North Sea Basin, where *F. filifera* has been reported from late Oligocene
500 and early Miocene strata (D. Zevenboom, cited in Head, 1994; Van Simaey et al.,
501 2005a).

502

503 **5.1.8 FAD of *Spiniferites manumii***

504 *Core position:* U1411C-8H-4A, 150.11 m CCSF-A.

505 *Magnetostratigraphic calibration:* 9 % of Chron C13n.

506 *Position with regard to calcareous nannoplankton zonation:* NP21.

507 *Age assignment:* 33.7 Ma.

508 *Discussion:* *Spiniferites manumii* occurs persistently, albeit in low numbers from 33.7

509 Ma onwards in the lower Rupelian of the Newfoundland Drift sediments studied. In

510 the Norwegian Sea, the FAD of *S. manumii* is calibrated to 31.4 Ma for ODP Site 985

511 based on the export of magnetostratigraphical signals from ODP Site 643 (Williams

512 and Manum, 1999), and in the Norwegian-Greenland Sea, the taxon appears close

513 to the C13n/C13r reversal (33.0 Ma; Eldrett et al., 2004). Because *S. manumii* has an

514 extremely short range, the taxon is considered as one of the best intra-Rupelian

515 markers in Europe (Śliwińska et al., 2012; compare also Section 5.1.14). Our new

516 data from the Newfoundland Drift sediments allow us to export this intra-Rupelian

517 marker to the western North Atlantic, where its FAD is only slightly older than in the

518 Norwegian-Greenland Sea.

519

520 **5.1.9 LAD of *Stoveracysta* sp. 1**

521 *Core position:* U1411B-16H-4A, 145.31 m CCSF-A.

522 *Magnetostratigraphic calibration:* 35 % of Chron C13n.

523 *Position with regard to calcareous nannoplankton zonation:* NP21.

524 *Age assignment:* 33.5 Ma.

525 *Discussion:* *Stoveracysta* sp. 1 could not be attributed to previously established taxa

526 (compare taxonomic remarks), and the genus *Stoveracysta* has not been reported

527 previously from the western North Atlantic. *Stoveracysta* sp. 1 strongly resembles

528 (?)*Stoveracysta* sp. sensu Biffi and Manum (1988), which has been described from

529 early Miocene sediments of the Marche Region in central Italy (see taxonomic

appendix). For the same region, Brinkhuis and Biffi (1993) identified various species of *Stoveracysta* in the Eocene/Oligocene boundary interval, and Pross et al. (2010) reported a magnetostratigraphically-calibrated LAD for representatives of the genus *Stoveracysta* at 30.9 Ma. These findings postdate our findings from the western North Atlantic.

5.1.10 FAD of *Melitasphaeridium asterium*

Core position: U1411B-16H-4A, 145.31 m CCSF-A.

Magnetostratigraphic calibration: 35 % of Chron C13n.

Position with regard to calcareous nannoplankton zonation: NP21.

Age assignment: 33.5 Ma.

Discussion: To date, the FAD of *Melitasphaeridium asterium* has not been used as a biostratigraphic datum in the North Atlantic. In the Danish sector of the North Sea Basin, the FAD of *M. asterium* occurs in the lower part of Subchron C16n.1n (Thomsen et al., 2012), which is much earlier than in the western North Atlantic.

5.1.11 LAD of *Lentinia serrata* complex

Core position: U1411B-16H-4A, 145.31 m CCSF-A.

Magnetostratigraphic calibration: 69 % of Chron C13n.

Position with regard to calcareous nannoplankton zonation: NP21.

Age assignment: 33.3 Ma.

Discussion: The ornamentation in most of the observed specimens here attributed to the *L. serrata* complex is reflected in penitabular denticles and parasutural crests as they are characteristic for the genus *Lentinia* Bujak in Bujak et al. (1980). Our material, however, also contains specimens with a greatly reduced number of denticles, which would allow attribution to the genus *Vozzhennikovia* Lentin and Williams (1976), and the full range of transitions between both endmembers. As the overall morphological characteristics of the encountered specimens are strongly

reminiscent of *L. serrata*, and even in our excellently preserved material the size and exact shape of the archeopyle (compare discussions in Bujak in Bujak et al., 1980, and Sluijs et al., 2009) is only visible in relatively few specimens, we refer to them as *Lentinia serrata* complex in our study.

In the western North Atlantic, *L. serrata* has been previously observed in the Labrador Sea (Head and Norris, 1989) and off eastern Canada (Fensome et al., 2009). Based on a combination of nannoplankton and well-log data, Fensome et al. (2009) have suggested an earliest Rupelian LAD of this species, which is consistent with our results. In the southern North Sea Basin, *L. serrata* was only observed in the late Eocene (Stover and Hardenbol, 1993), while in the eastern North Sea Basin the species extends into the late Eocene to Rupelian (Heilmann-Clausen and Van Simaey, 2005a; Śliwińska et al., 2012). In the Tethyan realm, *L. serrata* is known from the uppermost Eocene to lowermost Oligocene of Central Italy (Brinkhuis and Biffi, 1993); it disappears within Chron C12r at 32.4 Ma (Pross et al., 2010). Based on the available sample resolution, the LAD of *L. serrata* in the western Tethys thus postdates the here identified LAD for the *L. serrata* complex in the western North Atlantic by ~0.9 Myr.

5.1.12 FAD of *Chiropteridium lobospinosum*

Core position: U1406B-21H-3W, 225.9 m CCSF-A.

Magnetostratigraphic calibration: 54 % of Chron C12r.

Position with regard to calcareous nannoplankton zonation: NP22.

Age assignment: 32.0 Ma.

Discussion: The FAD of *Chiropteridium lobospinosum* in the Newfoundland Drift sediments postdates its appearance in the Norwegian-Greenland Sea; there, the taxon first occurs at 33.5 Ma (Eldrett et al., 2004). In the Labrador Sea, *C. lobospinosum* appears at the beginning of NP23 (Head and Norris, 1989), and for the North Sea Basin, the FAD of *C. lobospinosum* has been indirectly calibrated against

NP22 (Köthe, 1990; Van Simaëys et al., 2005a; Śliwińska et al., 2012). In the Tethyan region, *Chiropteridium* spp. (mainly *C. lobospinosum*) has already been recorded within the lower part of Chron C12r, and the first consistent occurrence has been calibrated against Subchron C11n.1n at 29.75 Ma (Pross et al., 2010). Hence, *C. lobospinosum* has a regionally diachronous FAD; in the Norwegian-Greenland Sea, the species appears earlier than in the Newfoundland Drift succession, whereas its FAD in the Tethyan realm it occurs even later than in both these regions. Although not magnetostratigraphically constrained, the FAD in the North Sea sites appears similar to our record.

4.1.13 FAD of *Hystriochokolpoma pusillum*

Core position: U1406B-21H-3W, 225.9 m CCSF-A.

Magnetostratigraphic calibration: 54 % of Chron C12r.

Position with regard to calcareous nannoplankton zonation: NP22.

Age assignment: 32.0 Ma.

Discussion: In the Tethys region, the FAD of *Hystriochokolpoma pusillum* is dated at 32.3 Ma (Pross et al., 2010) and thus (considering our sampling resolution of ~150 kys) is virtually synchronous with the appearance of the species in the western North Atlantic.

5.1.14 LAD of *Spiniferites manumii*

Core position: U1406C-21X-4W, 222.24 m CCSF-A.

Magnetostratigraphic calibration: 73 % of Chron C12r.

Position with regard to calcareous nannoplankton zonation: NP22.

Age assignment: 31.6 Ma.

Discussion: In the Norwegian-Greenland Sea, the LAD of *Spiniferites manumii* is observed in the upper part of Chron C12r at ~30.8 Ma (Eldrett et al. 2004; recorded as *Spiniferites* sp. 1 sensu Manum et al. 1989). In the North Sea Basin, the LAD of

the species is indirectly calibrated against the upper part of Chron C12r (Lagrou et al., 2004; Van Simaey et al., 2005a), and biostratigraphically calibrated against the upper part of NP23 (Van Simaey et al., 2005a). We conclude that the FAD (compare Section 5.1.9) and LAD of *S. manumii* are thus remarkably synchronous across the greater North Atlantic region. The highly restricted stratigraphic range of ~2 Ma makes *S. manumii* an exceptionally good intra-Rupelian marker for this region.

5.1.15 LAD of *Phthanoperidinium comatum*

Core position: U1406B-20H-1W, 209.15 m CCSF-A.

Magnetostratigraphic calibration: 75 % of Chron C12n.

Position with regard to calcareous nannoplankton zonation: NP23.

Age assignment: 30.7 Ma.

Discussion: The LAD of *Phthanoperidinium comatum* as derived from our dataset agrees with the record of Head and Norris (1989) from the Labrador Sea, where the LAD is calibrated against NP23. This is consistent with the early Rupelian LAD of *P. comatum* in the Danish North Sea (Schiøler, 2005). For the western Tethys, Pross et al. (2010) reported rare findings of *P. comatum* until the end of Chron C9r. Hence, our results show an apparently synchronous LAD of the species in our dataset and other North Atlantic sites, but a diachroneity between these North Atlantic sites and the Tethyan region, where the species disappears later.

5.1.16 FAD of *Chiropteridium galea*

Core position: U1406A-19H-5W, 204.73 m CCSF-A.

Magnetostratigraphic calibration: 31 % of Chron C11r.

Position with regard to calcareous nannoplankton zonation: NP23.

Age assignment: 30.5 Ma.

Discussion: The FAD of *Chiropteridium galea* is a well-known biostratigraphic datum for the latest Eocene to earliest Oligocene (Williams and Bujak, 1985; Damassa et al., 1990). Its FAD in the Norwegian-Greenland Sea is between 33.5 and 33.1 Ma (Eldrett et al., 2004). For the Labrador Sea, where it occurs much earlier, a biostratigraphically calibrated FAD of the species has been determined at the beginning of NP18 (as *Chiropteridium mespilanum*; Head and Norris, 1989). Data from the southern North Sea Basin indicate an indirectly calibrated FAD of *Chiropteridium* spp. in the uppermost part of NP22 (Van Simaey et al., 2005a); the FAD of *C. galea* (i.e., a member of the *Chiropteridium* plexus) in northwestern Germany occurs at the same time (Köthe, 1990). A comparison of available FADs within the North Atlantic region suggests a strong diachroneity, with the earliest FAD in the Labrador Sea (NP18, i.e., older than 38.1 Ma; Head and Norris, 1989) and a much later FAD (30.5 Ma – this study) off Newfoundland. The FAD of *C. galea* within the Norwegian-Greenland Sea (Eldrett et al., 2004) also predates the FAD as identified in the Newfoundland Drift succession, whereas data from the North Sea Basin (Van Simaey et al., 2005a; Köthe, 1990; at least 32.9 Ma) suggest a later first appearance in that region.

5.1.17 FAD of *Oligokolpoma galeottii*

Core position: U1406A-19H-5W, 204.73 m CCSF-A.

Magnetostratigraphic calibration: 31 % of Chron C11r.

Position with regard to calcareous nannoplankton zonation: NP23.

Age assignment: 30.4 Ma.

Discussion: *Oligokolpoma galeottii* Pross et al., 2010 has previously been described from the western Tethys (Pross et al., 2010) with an FAD in the uppermost part of Chron C12r, at 31.3 Ma. In our records from the Newfoundland Drift sediments, the taxon appears slightly later, at 30.4 Ma.

5.1.18 FAD of *Artemisiocysta cladodichotoma*

Core position: U1411B-10H-2W, 81.6 m CCSF-A.

Magnetostratigraphic calibration: not identified, between Subchrons C11n.2n and C10n.2n.

Position with regard to calcareous nannoplankton zonation: NP23/NP24.

Age assignment: 29.6 Ma–28.3 Ma (based on a linear interpolation).

Discussion: In our Newfoundland Drift material, specimens of *Artemisiocysta cladodichotoma* were identified in three samples from a short interval in Hole U1411B without reliable magnetostratigraphic information. Based on linear interpolation, the age can be constrained to fall between 29.6 Ma and 28.3 Ma. In younger strata, *A. cladodichotoma* is continuously present from 22.7 Ma onwards. In the North Sea Basin, the FAD of *A. cladodichotoma* is considered an important biostratigraphic marker for the basal Chattian (Van Simaeys et al. 2005a). In successions from the Danish sector of the North Sea Basin, the taxon is extremely rare and only occurs across a short interval straddling the magnetochron C9r/C9n reversal (Śliwińska et al., 2012). In the Umbria-Marche Basin of Central Italy, *A. cladodichotoma* is already observed in Chrons C8 and C9n (Pross et al., 2010). Despite the remaining uncertainties in our age assignment from Site U1411, a considerably earlier FAD of *A. cladodichotoma* emerges for the western North Atlantic. This offset may well be due to paleoceanographic factors, its inconspicuous appearance (easily overlooked) and/or the rarity of the taxon in Chattian dinocyst assemblages.

5.1.19 LAD of *Enneadocysta pectiniformis*

Core position: U1406B-17H-2W, 165.59 m CCSF-A.

Magnetostratigraphic calibration: Chron C9n.

Position with regard to calcareous nannoplankton zonation: NP25.

Age assignment: 26.7 Ma.

Discussion: Enneadocysta pectiniformis (Gerlach, 1961) Stover and Williams, 1995 differs from *Enneadocysta arcuata* (Eaton, 1971) Stover and Williams, 1995 through the absence of plate 6'' and thus also the process on plate 6''; however, the plate is not a necessarily present feature for *E. arcuata* (Stover and Williams, 1995, Table 2). As this difference is not always observable, and their overall morphologies and sizes are highly similar, the two species were not separated in the present study and counted as *E. pectiniformis* following Schiøler (2005).

In the Labrador Sea, the LADs of *E. arcuatum* and *E. pectiniformis* are calibrated against NP23 and NP 24, respectively (Head and Norris, 1989). For the North Sea Basin, Van Simaeys et al. (2005a) report *E. pectiniformis* to disappear in the middle part of NP23, while Schiøler (2005) describes an LAD of *Enneadocysta* spp. within the upper half of the Rupelian. For the western Tethys, Pross et al. (2010) reported a LAD of *E. pectiniformis* at 27.9 Ma. We conclude that the LAD of *E. pectiniformis* in the Newfoundland Drift sediments postdates the LADs available for the Labrador Sea, North Sea Basin and Tethyan region. The apparent discrepancy in LADs between the Tethys and the North Sea Basin has been previously observed by Pross et al. (2010), who connected it to a gradual abundance decline of *E. pectiniformis* towards its range top.

5.1.20 LAD of *Areoligera semicirculata*

Core position: U1406C-16H-5W, 155.89 m CCSF-A.

Magnetostratigraphic calibration: 27 % of Chron C8r.

Position with regard to calcareous nannoplankton zonation: NP25.

Age assignment: 26.3 Ma.

Discussion: *Areoligera semicirculata* is rather rare in the material from the Newfoundland Drift and never reaches more than 1% of the dinocyst assemblages. In the Norwegian Sea, the LAD of *A. semicirculata* has been magnetostratigraphically calibrated at 30.4 Ma (Williams and Manum, 1999). Its LAD

is an important marker for the early Chattian in NW Europe (Köthe, 1990; Van Simaeys et al., 2005a). In Denmark, *A. semicirculata* is common within Chron C8r (Śliwińska et al. 2012). In the western Tethys, the LAD occurs within Chron C9n at 27.4 Ma (Pross et al. 2010). Hence, the LAD for the Newfoundland Drift succession is in close agreement with the data from the North Sea. Diachroneities exist for the Labrador Sea and the Tethys, where *A. semicirculata* disappears earlier.

5.1.21 LAD of *Saturnodinium pansum*

Core position: U1406C-16H-5W, 155.89 m CCSF-A.

Magnetostratigraphic calibration: 27 % of Chron C8r.

Position with regard to calcareous nannoplankton zonation: NP25.

Age assignment: 26.3 Ma.

Discussion: *Saturnodinium pansum* was first described from middle to upper Oligocene strata of the Blake Plateau, North Atlantic (Stover, 1977). To date, there is no record of *S. pansum* in the Norwegian Sea, although other Chattian taxa such as *Areoligera semicirculata* or *Distatodinium biffii* are present there (KKS, unpublished data). In contrast, *S. pansum* is well known from the North Sea Basin. There, its LAD is biostratigraphically calibrated against the basal part of the alternative NP25* (for details see Van Simaeys et al. 2005a). In the German sector of the North Sea Basin, the taxon was observed within the Aquitanian (Köthe and Piesker, 2007), while in the eastern North Sea Basin the taxon was never observed above the mid-Chattian (i.e., Chron C8r; Śliwińska et al., 2012; K. Dybkjær, personal communication). In the Mediterranean region, the taxon was reported from the lower Rupelian (Chron C12r) and upper Chattian (Chron C7n- C6?; Pross et al., 2010). Summarizing the available evidence, we observe a synchronous disappearance of *S. pansum* in the Newfoundland Drift region and the eastern North Sea Basin. Notably, these regions have also yielded the northernmost records of *S. pansum* as yet known. The

observed distribution pattern of *S. pansum* may furthermore suggest that the taxon is adapted to relatively warm surface waters.

5.1.22 LAD of *Wetzeliiella gochtiil/symmetrica* group

Core position: U1406B-14H-5W, 144.73 m CCSF-A.

Magnetostratigraphic calibration: 13 % of Subchron C8n.2n.

Position with regard to calcareous nannoplankton zonation: NP25.

Age assignment: 25.9 Ma.

Discussion: In the Newfoundland Drift sediments, *Wetzeliiella* spp. mainly comprise *W. gochti* and *W. symmetrica* as well as transitional forms between these two taxa. At the Scotian Margin off Canada, *W. gochti* exhibits a middle Chattian LAD, and the LAD of *W. symmetrica* is at the top of the Chattian (Fensome et al., 2009). In the Labrador Sea, *W. symmetrica* occurs until NP24 (Head and Norris, 1989). In the North Sea, the LAD of *W. symmetrica* has been determined at the NP24/NP25 boundary, and the LAD of *W. gochti* has been recorded within the lowermost NP25 (Van Simaey et al., 2005a). This North Sea datum also applies to Schiøler (2005), who provides a LAD for the *W. gochti*/*W. symmetrica* group in the basal Chattian. In the western Tethys, only *W. gochti* was found, which has a LAD at 26.9 Ma (Pross et al., 2010). In the Labrador Sea and the North Sea Basin, species of the genus *Wetzeliiella* disappear earlier than in the Newfoundland Drift succession.

5.1.23 LAD of *Filisphaera filifera*

Core position: U1405A-15H-3W, 173.86 m CCSF-A.

Magnetostratigraphic calibration: 25 % of Subchron C6Cn.2n.

Position with regard to calcareous nannoplankton zonation: NN1.

Age assignment: 22.7 Ma.

Discussion: *Filisphaera filifera* has not been reported from the North Atlantic before. In the North Sea Basin, the taxon disappears at the Oligocene-Miocene boundary

(Schiøler, 2005), which is very close to the LAD identified for the Newfoundland Drift successions. However, *F. filifera* also occurs in the younger Neogene and Quaternary (Head, 1994; compare Section 5.1.8).

5.1.24 LAD of *Hystriochokolpoma pusillum*

Core position: U1405A-16H-4W, 185.92 m CCSF-A.

Magnetostratigraphic calibration: 69 % of Subchron C6Cn.1r.

Position with regard to calcareous nannoplankton zonation: NN2.

Age assignment: 22.8 Ma.

Discussion: Based on the available information, *Hystriochokolpoma pusillum* exhibits strongly diachronous range tops in the western North Atlantic (this study), the North Sea (Schiøler, 2005) and the western Tethys (Biffi and Manum, 1988). In the North Sea, *H. pusillum* disappears in the uppermost Rupelian (Schiøler, 2005). In the western Tethys, the taxon occurs regularly until at least 23.6 Ma (Pross et al., 2010); its LAD is during NN1 (Biffi and Manum, 1988). Thus, the even younger LAD registered for the Newfoundland Drift material may mark the youngest occurrence of *H. pusillum* as yet known.

5.1.25 LAD of *Deflandrea* spp.

Core position: U1405A-14H-5W, 167.71 m CCSF-A.

Magnetostratigraphic calibration: 25 % of Subchron C6Bn.2n.

Position with regard to calcareous nannoplankton zonation: NN2.

Age assignment: 22.2 Ma.

Discussion: The LAD of *Deflandrea* spp., mostly represented by the species *D. phosphoritica*, is a classical biostratigraphic marker for the Oligocene-Miocene boundary interval. For the Scotian Margin off Canada, Fensome et al. (2009) reported the LAD of *Deflandrea* spp. to coincide with the top of the Chattian, which is

consistent with our findings from the Newfoundland Drift succession. Data on the LAD of *Deflandrea* spp. in the North Sea Basin suggest a more complex disappearance pattern for that region. In the Danish sector of the North Sea Basin, Dybkjær et al. (2012) used *D. phosphoritica* in their characterization of the Oligocene-Miocene boundary. They observed *D. phosphoritica* in the late Chattian and early Aquitanian, with the taxon disappearing shortly before the Oligocene-Miocene boundary and then repeatedly re-occurring in the basal Aquitanian. Findings of *Deflandrea* spp. in the lower Miocene of the same region have previously been reported by Schiøler (2005).

5.1.26 FAD and LAD of *Svalbardella* spp.

Core position: for the FAD U1411C-8H-4A, 150.11 m CCSF-A; for the LAD U1405B-15H-5W, 160.95 m CCSF-A.

Magnetostratigraphic calibration: 8 % of Chron C13n to 61 % of Subchron C6Bn.2n.

Position with regard to calcareous nannoplankton zonation: NP21-NN2.

Age assignment: 33.7-22.1 Ma.

Discussion: *Svalbardella* spp. reaches exceptionally high abundances and exhibits repeated recurrences in the Newfoundland Drift material. The genus *Svalbardella* is a typical representative of high-latitude North Atlantic dinocyst assemblages during the middle to late Eocene and the Oligocene (Manum 1960, 1976; Manum and Thordsen, 1986; Head and Norris, 1989; Eldrett et al., 2004). During surface-water cooling pulses associated with Oligocene glacial episodes, the genus also briefly occurred in the North Sea (Van Simaey, 2004; Śliwińska et al., 2010; Śliwińska and Heilmann-Clausen, 2011; Clausen et al., 2012), the Tethyan realm (Brinkhuis and Biffi, 1993; Van Simaey et al., 2005b; Coccioni et al., 2008; Pross et al., 2010), and the high latitudes of the southern hemisphere (Brinkhuis et al., 2003; Van Simaey et al., 2005b). As such, the genus represents arguably the best indicator of surface-

water cooling in Paleogene dinocyst assemblages (compare Sluijs et al., 2005) and thus has attracted considerable attention over the past 15 years or so.

The two most important features that distinguish the genus *Svalbardella* from the morphologically similar genus *Palaeocystodinium* are a visible paracingulum and bluntly rounded apical and antapical horns. To date, the genus comprises two formally established species, *S. cooksoniae* (Manum, 1960) and *S. partimtabulata* (Heilmann-Clausen and Van Simaey, 2005). However, in addition to these species, a number of similar dinocyst morphotypes has informally and peripherally been referred to *Svalbardella* (e.g., Schiøler, 2005; Śliwińska et al., 2012). Some of these morphotypes exhibit clearly rounded horns, but lack a visible paracingulum and are therefore sometimes referred to as *Palaeocystodinium* (e.g., Damassa et al., 1996). This morphological variety of the *Svalbardella*/*Palaeocystodinium* complex is also documented in our material from the Newfoundland Drift succession (Plate VII, 12-15). To avoid nomenclatoric confusion, we have attributed 'Svalbardella/*Palaeocystodinium*-like' dinocyst morphotypes to *Svalbardella* spp. if they exhibited rounded horns and/or paracingular tabulation. It has been speculated that the morphology may have been affected by sea-surface temperature (e.g., Van Simaey et al., 2005b).

In the Norwegian Sea, *S. cooksoniae* appears at 42.2 Ma (Eldrett et al., 2004). In the eastern North Sea Basin, *S. partimtabulata* appears first in Chron C18r and the upper part of NP16 (Heilmann-Clausen and Van Simaey, 2005; Thomsen et al., 2012). Hence, the oldest documentation of *Svalbardella* spp. in our Newfoundland Drift material may not necessarily represent the true FAD of *Svalbardella* spp. in the western North Atlantic. In the Labrador Sea, the LAD of *S. cooksoniae* is indirectly calibrated to NP23 (Head and Norris, 1989). Significantly earlier LADs have been reported from the Norwegian Sea (30.4 Ma, ODP Site 985; Williams and Manum, 1999) and the Norwegian-Greenland Sea (33.5 Ma, ODP Sites 338 and 643A; Eldrett et al., 2004). In the North Sea Basin, the youngest records of

Svalbardella spp. are from the lower Chattian (Schiøler, 2005) and Chron C9n (Śliwińska et al., 2012), respectively. In the western Tethys, Coccioni et al. (2008) and Pross et al. (2010) recorded a recurrence interval of *Svalbardella* spp. between 29.1 and 27.1 Ma; it coincides with the Oi-2b benthic $\delta^{18}\text{O}$ glacial episode of Miller et al. (1991), which represents the strongest glaciation of the Oligocene (Pälike et al., 2006). Summarizing the above, the occurrence pattern of *Svalbardella* spp. is strongly controlled by the regionally prevailing surface-water temperature regime. In light of the high variability of Oligocene climates, their FADs and LADs can hence only be employed for short-distance correlations on intra-basinal scales. On the other hand, *Svalbardella* spp. can serve as a highly sensitive paleoenvironmental indicator for changes in surface-water temperatures.

5.2 Additional observations

Although the Newfoundland Drift sediments have yielded highly diverse dinocyst assemblages, a number of well-known biostratigraphic markers for the Oligocene of the North Atlantic region are poorly represented or even conspicuously absent. For instance, only single specimens of *Distatodinium biffii* and *Rhombodinium draco* were encountered in the study material. *Distatodinium biffii* is an important marker for the Rupelian-Chattian boundary in the North Sea (Śliwińska et al., 2012) and in the Tethyan realm (Coccioni et al., 2008; Pross et al., 2010). The same holds for *R. draco*, the LAD of which biostratigraphically defines the Rupelian-Chattian boundary and the lowermost part of the Chattian in the North Sea (Köthe, 1990; Schiøler, 2005; Van Simaey et al., 2005a).

The Eocene-Oligocene transition interval of the Newfoundland Drift succession is characterized by a number of LADs of typical lower-latitude, Tethyan marker species such as *Schematophora speciosa*, *Hemiplacophora semilunifera*, and *Cordosphaeridium cf. funiculatum* (Fig. 5). Considering that cyst-forming dinoflagellates are highly sensitive to changes in the shallow surface waters,

891 especially with regard to changes in temperature (e.g., Sluijs et al., 2005), the
892 disappearance of these lower-latitude taxa during the latest Eocene and earliest
893 Oligocene points to surface-water cooling off Newfoundland, possibly due to an
894 enhanced influence of the proto-Labrador Current.

895 This hypothesis is supported by the first documentation of the cold-water
896 indicator *Svalbardella* spp. in the same interval, which also suggests a surface-water
897 cooling. This can be explained by the southward expansion of cool surface-water
898 masses from the high northern latitudes where surface-water temperatures declined
899 earlier. In the Labrador Sea, the genus *Svalbardella* already appears during the early
900 Eocene (Head and Norris, 1989).

902 **6 Concluding remarks**

903 Our detailed dinocyst study on the Newfoundland Drift sediments recovered during
904 IODP Expedition 342 has yielded the first magnetostratigraphically-calibrated
905 dinocyst bioevents for the uppermost Eocene to lowermost Miocene of the western
906 North Atlantic. Comparison with magnetostratigraphically-calibrated dinocyst datums
907 from elsewhere in the North Atlantic, the North Sea, and the western Tethys helps to
908 quantify spatial leads and lags for a number of dinocyst events, although such efforts
909 are hindered by the yet low availability of chronostratigraphically constrained
910 appearance data from many regions. For the Eocene-Oligocene boundary interval,
911 we observe a high degree of synchronicity between dinocysts bioevents offshore
912 Newfoundland and in the western Tethys (e.g., *Schematophora speciosa*,
913 *Cordosphaeridium* cf. *funiculatum* and *Hemiplacophora semilunifera*).

914 The demise of lower-latitude taxa across the Eocene-Oligocene transition
915 interval in concert with the appearance of the cold-water indicator *Svalbardella* spp.
916 points to a surface-water cooling off Newfoundland during that time. Due to the
917 applicability of dinocyst biostratigraphy to high-latitude settings, and considering that
918 calcareous and siliceous plankton groups exhibit reduced diversities, relatively low

preservation potential or both in polar to sub-polar environments, the dinocyst bioevents identified and independently dated in our study contribute to an improved age framework for future paleoceanographical studies in the higher-latitude North Atlantic. Ultimately, the chronostratigraphically constrained dinocyst bioevents identified in our study may contribute to an improved understanding of the paleoclimatic and paleoceanographic evolution of the Oligocene world.

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Appendix A. Taxonomic remarks

An alphabetical list of all identified dinocyst taxa is given in Table A.1, and selected taxa are depicted on Plates I–VIII. For taxonomic citations, we refer to Fensome and Williams (2004) and the updated online version (Fensome et al., 2008); only taxa and emendations that are not included into these reference catalogues are treated here.

Selected taxonomy

Division: DINOFLAGELLATA (Bütschli, 1885) Fensome et al., 1993

Subdivision: DINOKARYOTA Fensome et al., 1993

947 Class: DINOPHYCEAE Pascher, 1914
 948 Subclass: PERIDINIPHYCIDEAE Fensome et al., 1993
 949 Order: GONYAULACALES Taylor, 1980
 950 Suborder: GONYAULACINEAE Fensome et al., 1993
 951 Family: GONYAULACINEAE Lindemann, 1928
 952 Subfamily: GONYAULACINEAE Fensome et al., 1993
 953
 954 Genus: *STOVERACYSTA* Clowes, 1985
 955 *Stoveracysta* sp. 1
 956 Pl. VII, 10, 11
 957 *Dimensions:* mean width: 41.2 μm , mean archeopyle diameter: 30.5 μm , mean
 958 overall length: 54 μm (n=5).
 959 *Description:* *Stoveracysta* sp. 1 is a morphotype of *Stoveracysta* with one apical and
 960 two antapical protrusions that are not always expressed. The ornamentation of the
 961 ectophragm consists of low (c. 2 μm high), perforate penitabular septa, and plate 1''
 962 is very small.
 963 *Remarks:* The species resembles (?) *Stoveracysta* sp. of Biffi and Manum (1988, p.
 964 194-196, Pl. 7, Figs. 10-11 and 13-14) in having two antapical lobes and an
 965 ectophragm that forms penitabular ridges. However, *Stoveracysta* sp. 1 differs from
 966 (?) *Stoveracysta* sp. of Biffi and Manum (1988) in lacking a visible cingulum, but
 967 showing other clearly visible plates. Furthermore, (?) *Stoveracysta* sp. of Biffi and
 968 Manum (1988) has continuous rather than perforate septa/membranes.
 969
 970
 971 **Literature**
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Figure captions

Figure 1: Compilation of magnetostratigraphically-calibrated dinocyst biostratigraphies available for the North Atlantic, North Sea, and the western Tethys region.

Figure 2: Geographical map of the North Atlantic region, with locations of studied sites (star) and locations of other dinocyst studies discussed in the text. 1 – Fensome et al. (2009); 2 – Head and Norris (1989); 3 – Eldrett et al. (2004); 4 – Manum (1976); Williams and Manum (1999); 5 – Bujak and Mudge (1994); 6 – Śliwińska et al. (2012); 7 – Heilmann-Clausen and Van Simaeys (2005), Thomsen et al. (2012); 8 – Schiøler (2005), Dybkjær et al. (2012); 9 – Van Simaeys et al. (2004), Van Simaeys et al. (2005); 10 – Munsterman and Brinkhuis (2004); 11 – Kempf and Pross (2005); 12 – Biffi and Manum (1988), Brinkhuis and Biffi (1993), Wilpshaar et al. (1996), Pross et al. (2010).

Figure 3: Semiquantitative range chart of dinocyst taxa encountered at Site U1405 of IODP Expedition 342, including shipboard-generated magnetostratigraphy and Calcareous Nannoplankton Zonation (Norris et al., 2014d).

Figure 4: Semiquantitative range chart of dinocyst taxa encountered at Site U1406 of IODP Expedition 342, plotted on revised composite depth scale (revised CCSF-A) and including revised magnetostratigraphy (Van Peer et al., in press), and shipboard Calcareous Nannoplankton Zonation (Norris et al., 2014c).

Figure 5: Semiquantitative range chart of dinocyst taxa encountered at Site U1411 of IODP Expedition 342, including shipboard-generated magnetostratigraphy and Calcareous Nannoplankton Zonation (Norris et al., 2014b).

1298

1299 Figure 6: Semiquantitative range chart of dinocyst taxa encountered at Site U1411 of
1300 IODP Expedition 342, including shipboard-generated magnetostratigraphy and
1301 Calcareous Nannoplankton Zonation (Norris et al., 2014b).

1302

1303 Figure 7: Integrated scheme of magnetostratigraphically-calibrated dinocyst events
1304 for the uppermost Eocene to lowermost Miocene of the Newfoundland Margin based
1305 on the observations from IODP Sites U1405, U1406 and U1411. Time scale,
1306 magnetostratigraphy, and Calcareous Nannoplankton Zones after Gradstein et al.
1307 (2012).

1308

1309 **Table captions**

1310

1311 **Table 1:** Compilation of magnetostratigraphically-calibrated dinocyst FADs as known
1312 from different regions in the Northern Hemisphere for the latest Eocene to earliest
1313 Miocene. Data are from Eldrett et al. (2004) for the Norwegian-Greenland Sea,
1314 Williams and Manum (1999) for the Norwegian Sea, Śliwińska et al. (2012) for the
1315 Danish land area, and Pross et al. (2010) for the Umbria-Marche region of Central
1316 Italy. Given ages refer to Gradstein et al. (2012).

1317

1318 **Table 2:** Compilation of magnetostratigraphically-calibrated dinocyst LADs as known
1319 from different regions in the Northern Hemisphere for the latest Eocene to earliest
1320 Miocene. Data are from Eldrett et al. (2004) for the Norwegian-Greenland Sea,
1321 Williams and Manum (1999) for the Norwegian Sea, Śliwińska et al. (2012) for the
1322 Danish land area, and Pross et al. (2010) and Wilpshaar et al. (1996; marked by *)
1323 for the Umbria-Marche region of Central Italy. Given ages refer to Gradstein et al.
1324 (2012).

1325

Appendix A, Table A.1

Alphabetical list of all identified taxa, key to their occurrences in the range charts (Figs. 3–6), and key to positions of respective photomicrographs in Plates I to VIII.

Plate captions

Plate I: Scale bar = 20 µm applies to all figures; all photographs taken using differential interference contrast.

- | | |
|------|---|
| 1, 2 | <i>Apteodinium australiense</i> (Deflandre and Cookson, 1955) Williams, 1978; Sample U1406 A17 H4 84-86 cm; Slide 14G394 A; England Finder coordinates L36/2; specimen in high and low focus. |
| 3 | <i>Apteodinium spiridoides</i> Benedek, 1972; Sample U1406 B13 H3 84-86 cm; Slide 14G494 A; T17. |
| 4 | <i>Areoligera semicirculata</i> (Morgenroth, 1966b) Stover and Evitt, 1978; Sample U1406 C16 H6 76-78 cm; P46. |
| 5 | <i>Areosphaeridium diktyoplokum</i> (Klumpp, 1953) Eaton, 1971; Sample U1411 B17 H3 126-128 cm; Slide 15A82 A; P26/2. |
| 6 | <i>Artemisiocysta cladodichotoma</i> Benedek, 1972; Sample U1405 B19 H5 136-138 cm; Slide 14L220; S28. |
| 7 | <i>Batiacasphaera micropapillata</i> Stover, 1977; Sample U1406 B11 H3 84-86 cm; Slide 14G404 A; N25/3. |
| 8, 9 | <i>Cerebrocysta bartonensis</i> Bujak in Bujak et al., 1980; Sample U1411 C12 X3 113-115 cm; Slide 15A234 A; S35/1; specimen in high and low focus. |

Plate II: Scale bar = 20 µm applies to all figures; all photographs taken using differential interference contrast.

- 1354 1 *Cordosphaeridium minimum* (Morgenroth, 1966a) Benedek, 1972;
1355 Sample U1406 A19 H3 84-86 cm; Slide 14G398 A; England Finder
1356 coordinates P25/3.
- 1357 2, 3 *Corrudinium incompositum* (Drugg, 1970b) Stover and Evitt, 1978;
1358 Sample U1411 B17 H3 126-128 cm; Slide 15A82 A; G40/3; specimen
1359 in high and low focus.
- 1360 4 *Cyclodictyon* spp.; Sample U1406 C18 H5 76-79 cm; Slide A; C41.
- 1361 5, 6 *Chiropteridium galea* (Maier, 1959) Sarjeant, 1983; Sample U1406
1362 B17 H3 84-86 cm; Slide 14H44 A; U19; specimen in high and low
1363 focus.
- 1364 7, 8 *Chiropteridium lobospinosum* Gocht, 1960; Sample U1406 B14 H3 84-
1365 86 cm; Slide 14G498 A; W17; specimen in high and low focus.
1366
- 1367 **Plate III:** Scale bar = 20 μ m applies to all figures; photographs taken using
1368 differential interference contrast.
- 1369 1 *Cordosphaeridium* cf. *funiculatum* sensu Biffi and Manum, 1988;
1370 Sample U1411 C9 H4 59-61 cm; Slide 15A181; R17/3.
- 1371 2, 3 *Cordosphaeridium cantharellus* (Brosius, 1963) Gocht, 1969; Sample
1372 U1406 B17 H3 84-86 cm; Slide 14H44 A; U31/2; specimen in high
1373 and low focus.
- 1374 4 *Dapsilidinium pseudocolligerum* (Stover, 1977) Bujak et al., 1980;
1375 Sample U1406 A18 H2 84-86 cm; Slide 14G396 C; S17.
- 1376 5 *Dinopterygium cladoides* Deflandre, 1935; Sample U1411 A17 H4 84-
1377 86 cm; Slide 14G394 A; T25/1.
- 1378 6, 7 *Cribrroperidinium* sp.1; Sample U1411 B17 H3 126-128 cm; Slide
1379 15A82 A; F33/1, specimen in high and low focus.
- 1380 8, 9 *Distatodinium biffii* Brinkhuis et al., 1992; Sample U1406 C16 H5 76-
1381 78cm; Slide A; S35/2; specimen in high and low focus.

- 1382 10 *Enneadocysta magna* Fensome et al., 2006; Sample U1406 A19 H3
 1383 84-86 cm; Slide 14G398 A; G30.
 1384
- 1385 **Plate IV:** Scale bar = 20 μ m applies to all figures; all photographs taken using
 1386 differential interference contrast.
- 1387 1 *Deflandrea phosphoritica* Eisenack, 1938b; Sample U1411 C7 H6 6-8
 1388 cm; Slide 15A178 B; England Finder coordinates S44/3.
- 1389 2 *Charlesdowniea clathrata* (Eisenack, 1938b) Lentin and
 1390 Vozzhennikova, 1989; Sample U1411 B18 H2 123-125 cm; Slide
 1391 15A172 A; T27.
- 1392 3 *Enneadocysta pectiniformis* (Gerlach, 1961) Stover and Williams;
 1393 Sample U1411 C11 X5 133-135 cm; Slide 15A232 A; S18.
- 1394 4 *Gelatia inflata* Bujak, 1984; Sample U1406 A18 H3 84-86 cm; Slide
 1395 14G397 B; R39/2.
- 1396 5 *Hemiplacophora semilunifera* Cookson and Eisenack, 1965a; Sample
 1397 U1411 C9 H4 59-61 cm; Slide 15A181 A; R40.
- 1398 6, 7 *Filisphaera filifera* Bujak, 1984; Sample U1406 B14 H3 84-86 cm;
 1399 Slide 14G498 A; T28/2; specimen in high and low focus.
- 1400 8, 9 *Impagidinium* sp.; Sample U1411 C9 H4 59-61 cm; Slide 15A181 A;
 1401 S43; specimen in high and low focus.
 1402
- 1403 **Plate V:** Scale bar = 20 μ m applies to all figures; all photographs taken using
 1404 differential interference contrast.
- 1405 1 *Glaphyrocysta semitecta* (Bujak in Bujak et al., 1980) Lentin and
 1406 Williams, 1981; Sample U1411 B16 H4 41-43 cm; Slide 15A80 A;
 1407 England Finder coordinates U24/1.
- 1408 2 *Glaphyrocysta* sp.; Sample U1406 B17 H3 76-79 cm; Slide 14H44 A;
 1409 U31/2.

1410	3	<i>Homotryblium plectilum</i> Drugg and Löblich Jr., 1976; Sample U1406
1411		A17 H4 84-86 cm; Slide 14G394 A; S30/3.
1412	4	<i>Hystrihokolpoma pusillum</i> Biffi and Manum, 1988; Sample U1406
1413		B13 H3 84-86 cm; Slide 14G494 C; J24/1.
1414	5	<i>Oligokolpoma</i> sp.; Sample U1406 A19 H5 84-86 cm; Slide 14G400
1415		B; H34/2.
1416	6, 7	<i>Hystrihokolpoma rigaudiae</i> Deflandre and Cookson, 1955; Sample
1417		U1411 C9 H4 59-61 cm; Slide 15A181 A; G32; specimen in high and
1418		low focus.
1419	8	<i>Hystrihokolpoma cinctum</i> Klumpp, 1953; Sample U1406 C16 H6 84-
1420		86 cm; Slide 14H113 A; T13.
1421		
1422	Plate VI: Scale bar = 20 μ m applies to all figures; all photographs taken using	
1423	differential interference contrast.	
1424	1	<i>Impletosphaeridium insolitum</i> Eaton, 1976; Sample U1405 C17 H2
1425		94-96 cm; Slide 14L228 A; England Finder coordinates P13/4.
1426	2	<i>Lejeunecysta fallax</i> (Morgenroth, 1966b) Artzner and Dörhöfer, 1978;
1427		Sample U1405 B21 H3 12-14 cm; Slide 14L222A; G18/3.
1428	3, 4	<i>Lentinia serrata</i> Bujak in Bujak et al., 1980; Sample U1411 B16 H4
1429		41-43 cm; Slide 15A80 A; T41; specimen in high and low focus.
1430	5	<i>Lingulodinium machaerophorum</i> (Deflandre and Cookson, 1955) Wall,
1431		1967; Sample U1406 B14 H3 84-86 cm; Slide 14G498 A; O20/4.
1432	6, 7	<i>Lophocysta sulcolimbata</i> Manum, 1979; Sample U1411 B15 H4 0-2
1433		cm; Slide 15A78 A; N38; specimen in high and low focus.
1434	8	<i>Melitasphaeridium asterium</i> (Eaton, 1976) Bujak et al., 1980; Sample
1435		U1406 B11 H2 84-86 cm; Slide 14G403 A; R29/4.
1436	9	<i>Microdinium reticulatum</i> Vozzhennikova, 1967; Sample U1406 A22
1437		H4 38-40 cm; Sample 14A4 A; S20/2.

- 1438 10, 11 *Oligokolpoma galeottii* Pross et al., 2010; Sample U1406 A19 H3 84-
1439 86 cm; Slide 14G398 A; S21/3; specimen in high and low focus.
- 1440 12, 13, 14 *Nematosphaeropsis labyrinthus* (Ostenfeld, 1903) Reid, 1974; Sample
1441 U1406 A22 H4 38-40 cm; Slide 15A4A; S34/4; specimen in high and
1442 low focus.
- 1443
- 1444 **Plate VII:** Scale bar = 20 µm applies to all figures; all photographs taken using
1445 differential interference contrast.
- 1446 1 *Operculodinium centrocarpum* Deflandre and Cookson, 1955) Wall,
1447 1976; Sample U1406 A17 H4 84-86 cm; Slide 14G394 B; England
1448 Finder coordinates M27/1.
- 1449 2 *Phthanoperidinium comatum* (Morgenroth, 1966b) Eisenack and
1450 Kjellström, 1972; Sample U1411 B15 H4 0-2 cm; Slide 15A78 A; P24.
- 1451 3 *Reticulosphaera actinocoronata* (Benedek, 1972) Bujak and
1452 Matsuoka, 1986; Sample U1406 B14 H3 84-86 cm; Slide 14G498 A;
1453 S19.
- 1454 4 *Saturnodinium pansum* (Stover, 1977) Brinkhuis et al., 1992; Sample
1455 U1406 C16 H5 76-78 cm; Slide A; J42/2.
- 1456 5 *Rhombodinium draco* Gocht, 1955; Sample U1411 C8 H4 146-148
1457 cm; Slide 15A180A; V28/2.
- 1458 6 *Spiniferites manumii* (Lund, 2002) Schiøler, 2005; Sample U1406 A22
1459 H4 38-40 cm; Slide 15A4 A; H38/2.
- 1460 7 *Spiniferites pseudofurcatus* (Klumpp, 1953) Sarjeant, 1970; Sample
1461 U1406 B11 H5 84-86 cm; Slide 14G487A; T34.
- 1462 8 *Pentadinium laticinctum* Gerlach, 1961; Sample U1406 A17 H5 84-86
1463 cm; Slide 14G395 C; P22.
- 1464 9 *Schematophora speciosa* Deflandre and Cookson, 1955; Sample
1465 U1411 B18 H2 123-125 cm; Slide 15A172 A; F28/1.

1466	10, 11	<i>Stoveracysta</i> sp. 1; Sample U1411 C8 H4 146-148 cm; Slide 15A180
1467		A; P28; specimen in high and low focus.
1468	12	<i>Svalbardella</i> sp. 1; Sample U1411 C8 H4 146-148 cm; Slide 15A180
1469		A; H44/3.
1470	13	<i>Svalbardella</i> sp. 2; Sample U1406 A19 H5 84-86 cm; Slide 14G400 A;
1471		W33.
1472	14	<i>Svalbardella</i> sp. 3; Sample U1406 A19 H 3 84-86 cm; Slide 14G398
1473		A; U14.
1474	15	<i>Palaeocystodinium golzowense</i> Alberti, 1961; Sample U1411 B15 H4
1475		0-2 cm; Slide 15A78 A; Q23/4.
1476		
1477		Plate VIII: Scale bar = 20 μ m applies to all figures; all photographs taken using
1478		differential interference contrast.
1479	1	<i>Selenopemphix crenata</i> Matsuoka and Bujak, 1988; Sample U1411
1480		C8 H4 146-148 cm; Slide 15A180 A; England Finder coordinates F33.
1481	2	<i>Selenopemphix nephroides</i> Benedek, 1972; Sample U1411 C8 H4
1482		146-148 cm; Slide 15A180 A; N33/4.
1483	3, 4	<i>Tectatodinium pellitum</i> Wall, 1967; Sample U1406 A17 H4 84-86 cm;
1484		Slide 14G394 B; T39/4; specimen in high and low focus.
1485	5	<i>Thalassiphora delicata</i> Williams and Downie, 1966c; Sample U1411
1486		C8 H4 146-148 cm; Slide 15A180 B; W22.
1487	6	<i>Wetzeliiella gochtii</i> Costa and Downie, 1976; Sample U1406 A19 H3
1488		84-86 cm; Slide 14G398 B; V42.
1489	7	<i>Wetzeliiella symmetrica</i> Weiler, 1956; Sample U1406 A19 H4 80-83
1490		cm; N32.
1491	8, 9	<i>Thalassiphora pelagica</i> (Eisenack, 1954b) Eisenack and
1492		Gocht, 1960; Sample U1406 A17 H5 84-86 cm; Slide 14G395 C; Q34;
1493		specimen in high and low focus.

Fig. 1

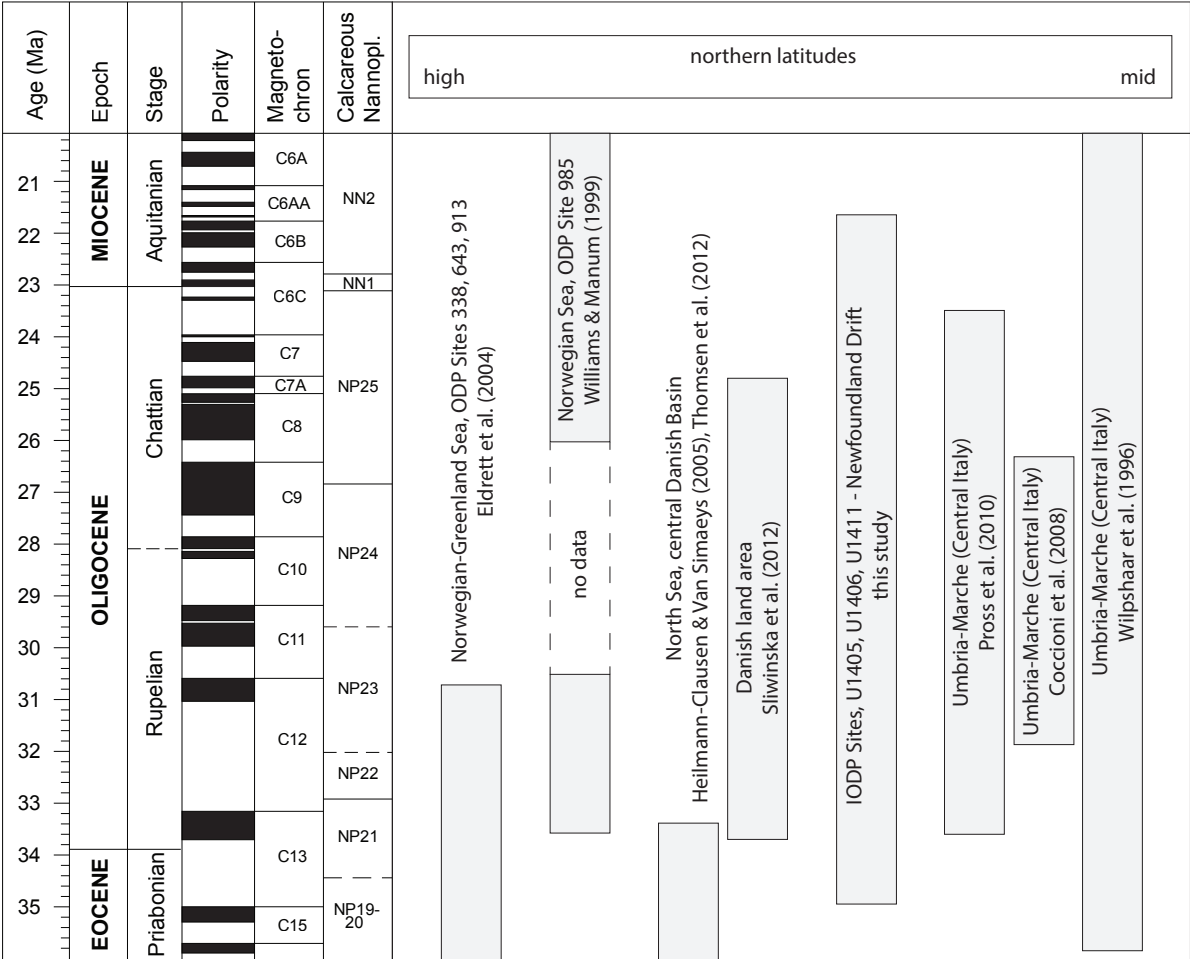


Fig. 2

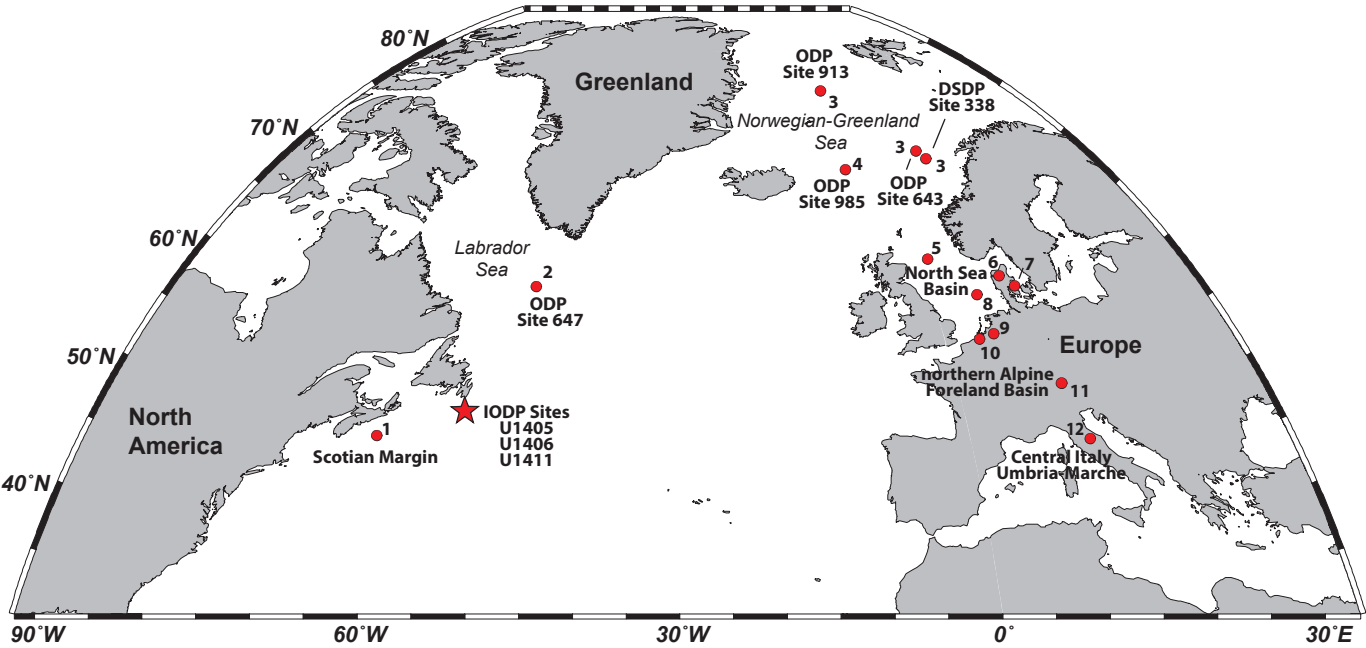


Fig. 3

Site U1405

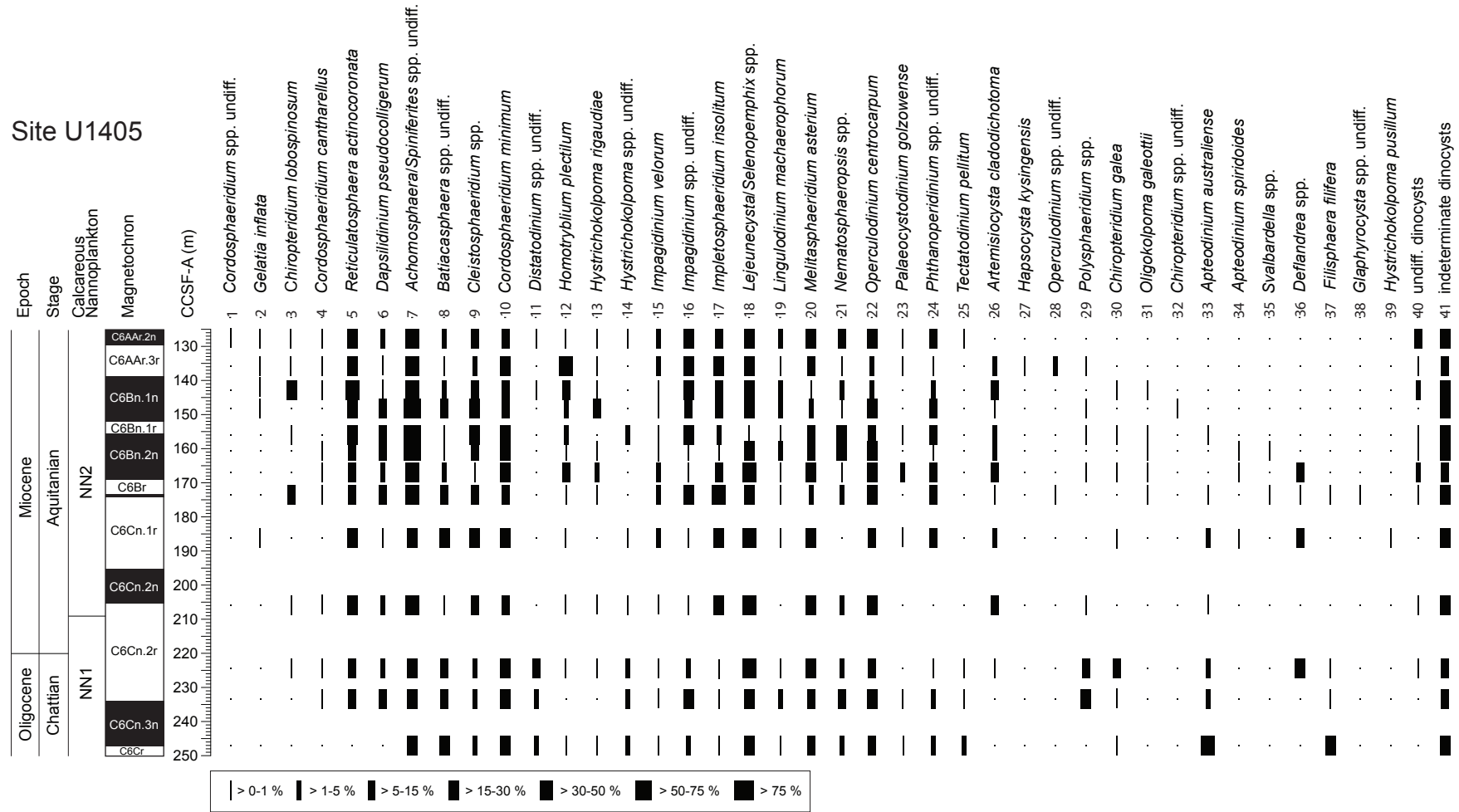


Fig. 4

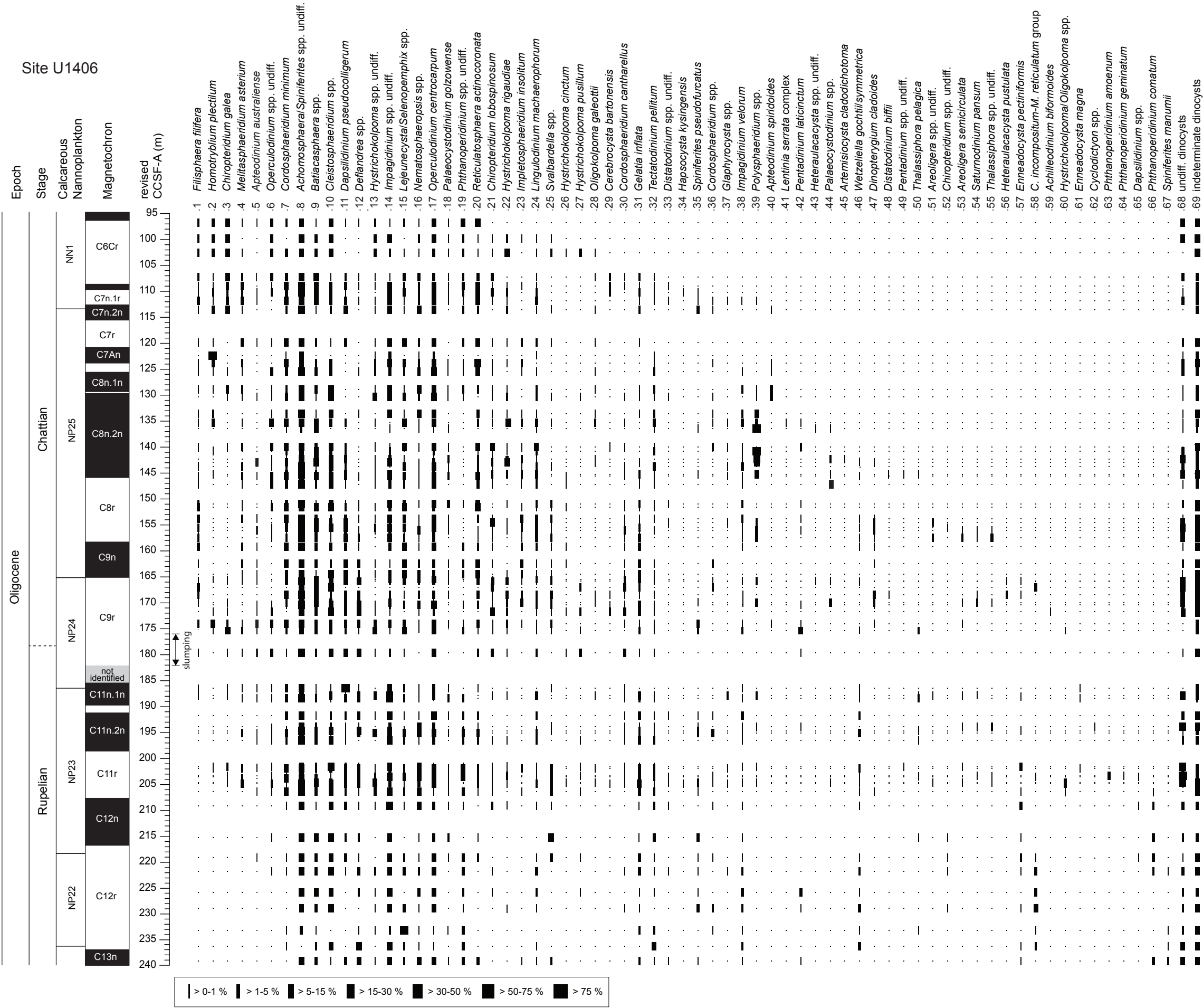


Fig. 5

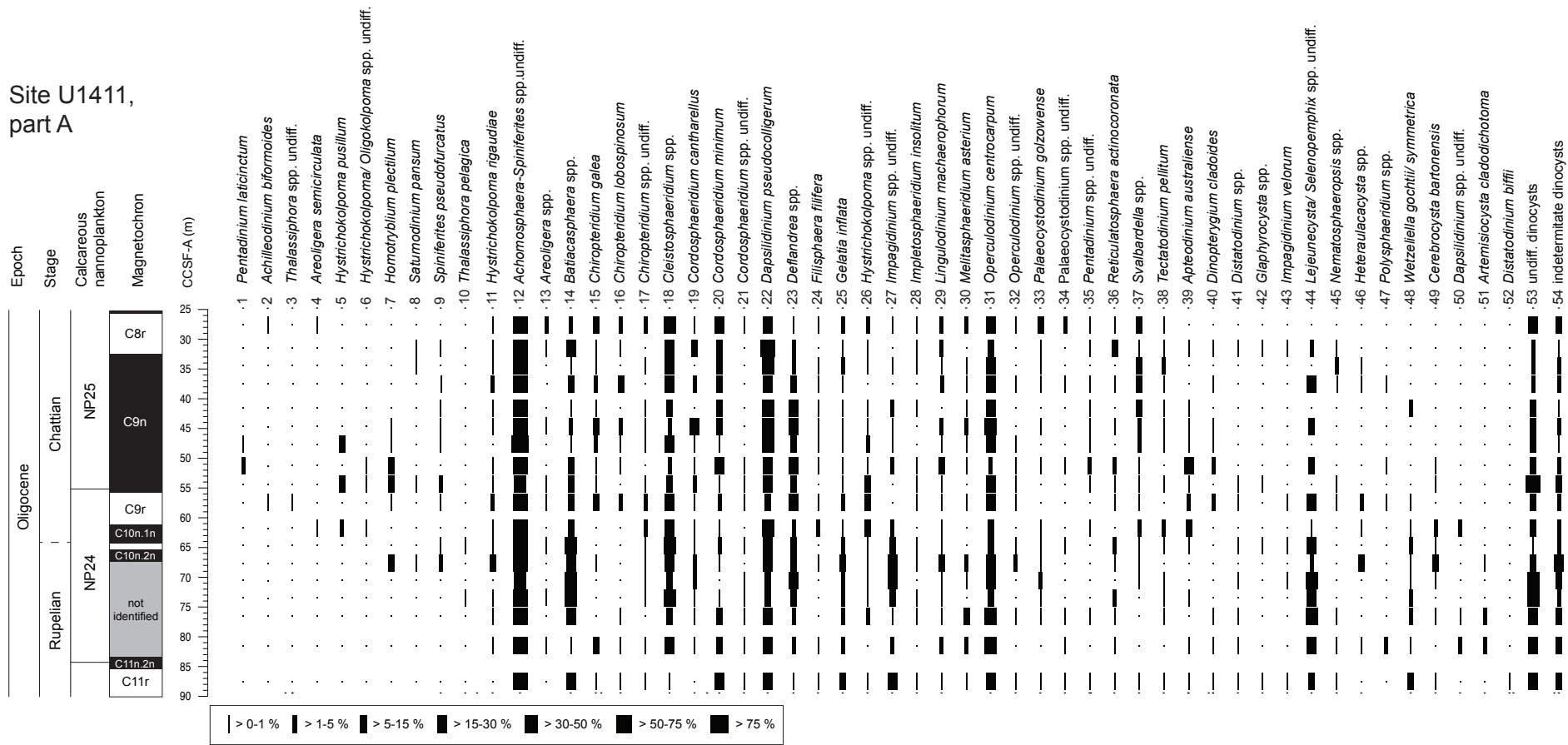


Fig. 6

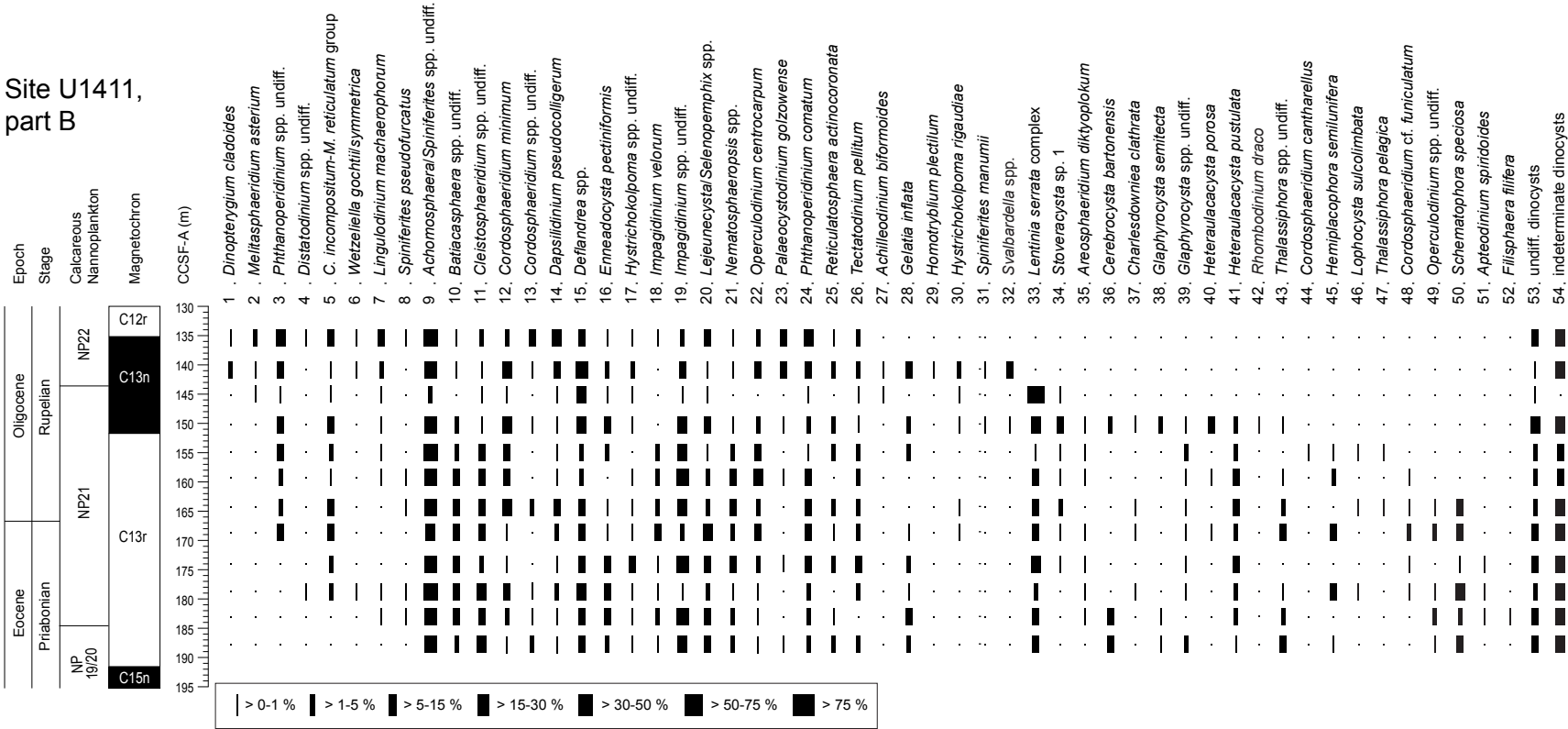
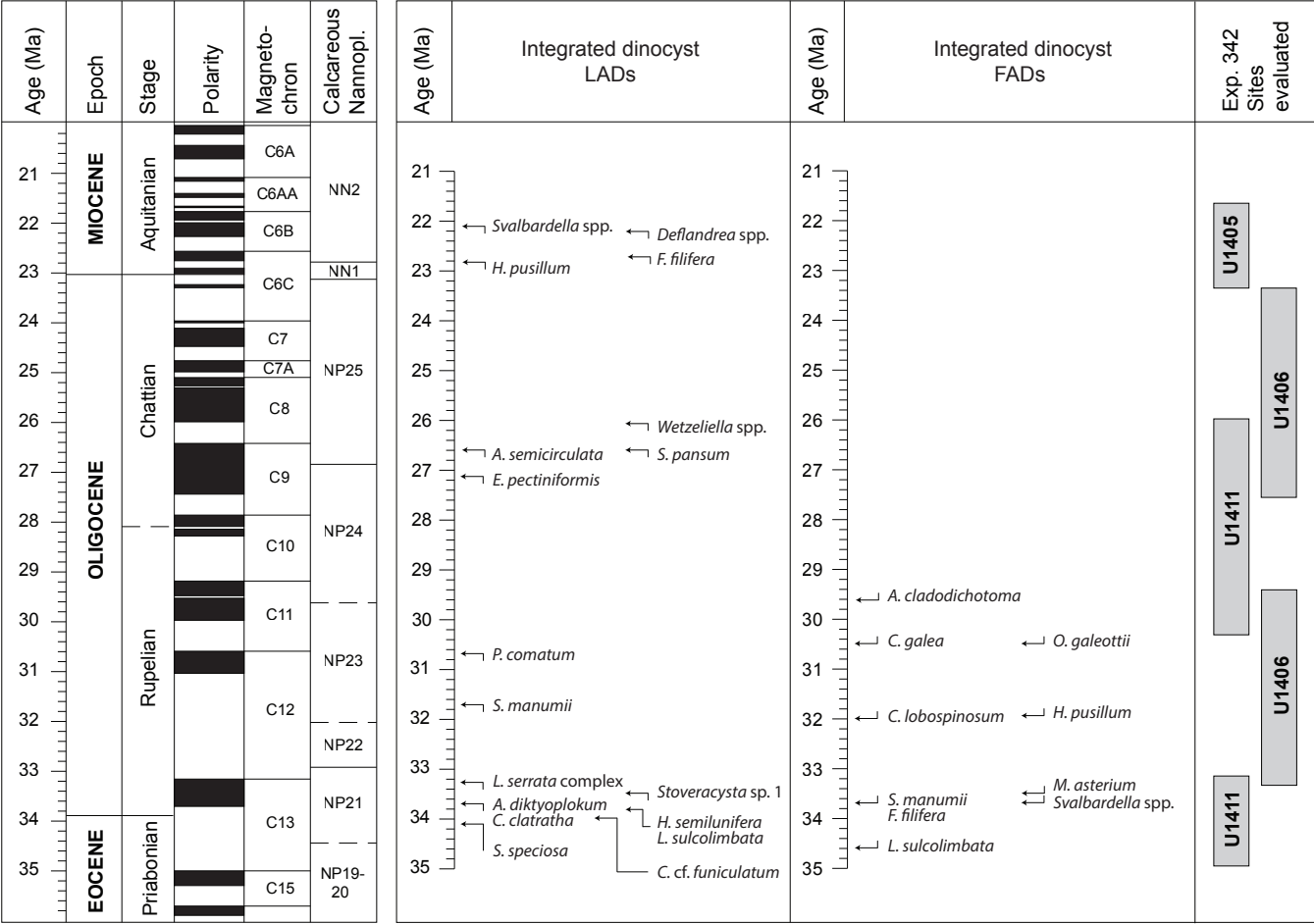


Fig. 7



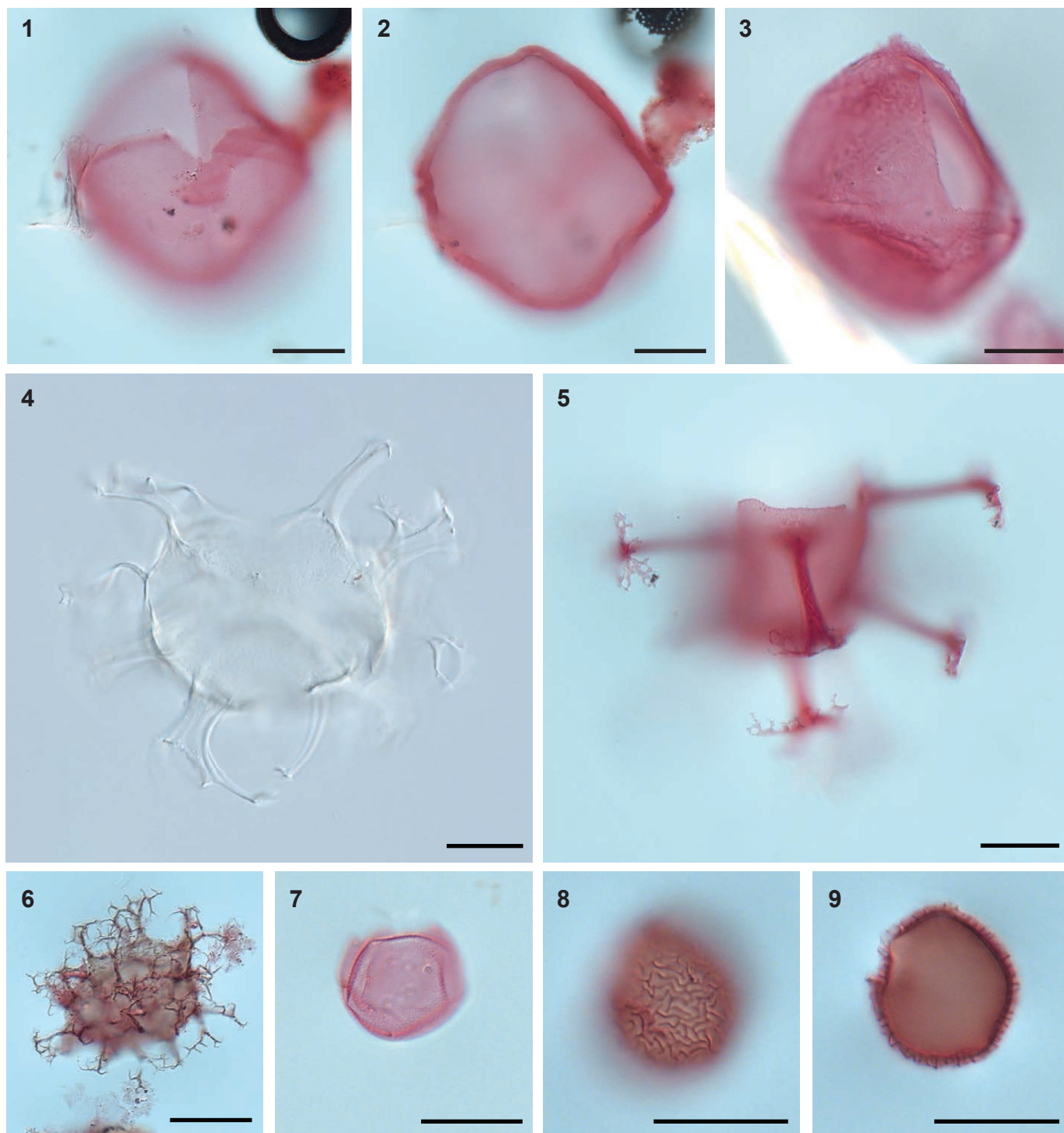


Plate II

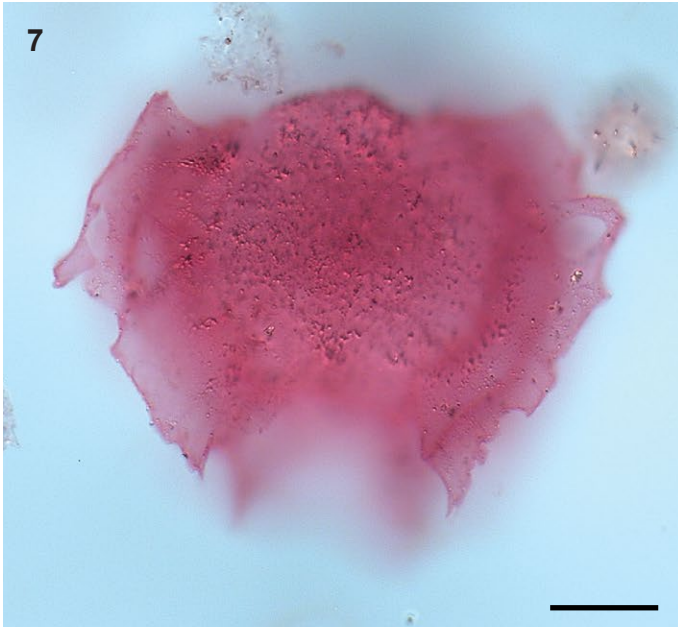
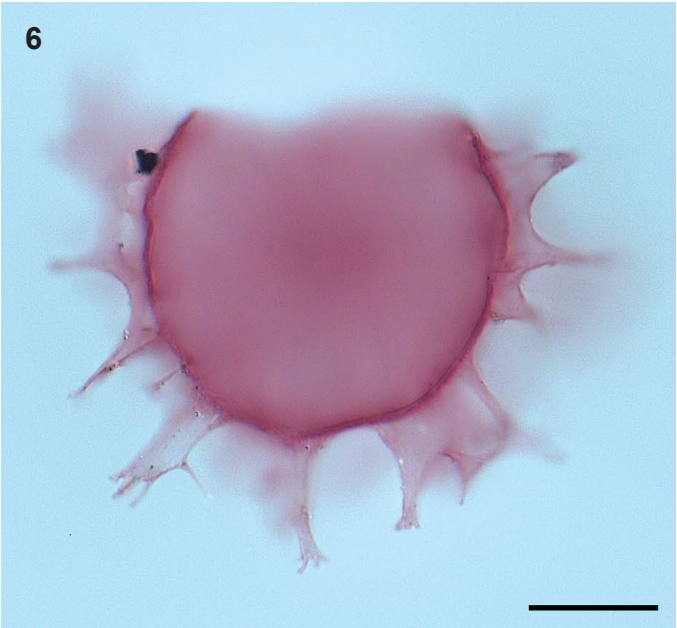
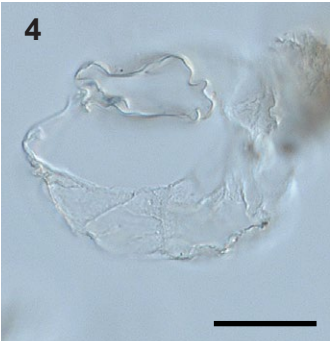
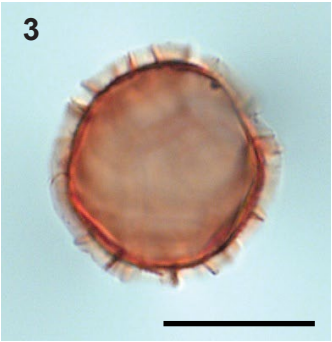
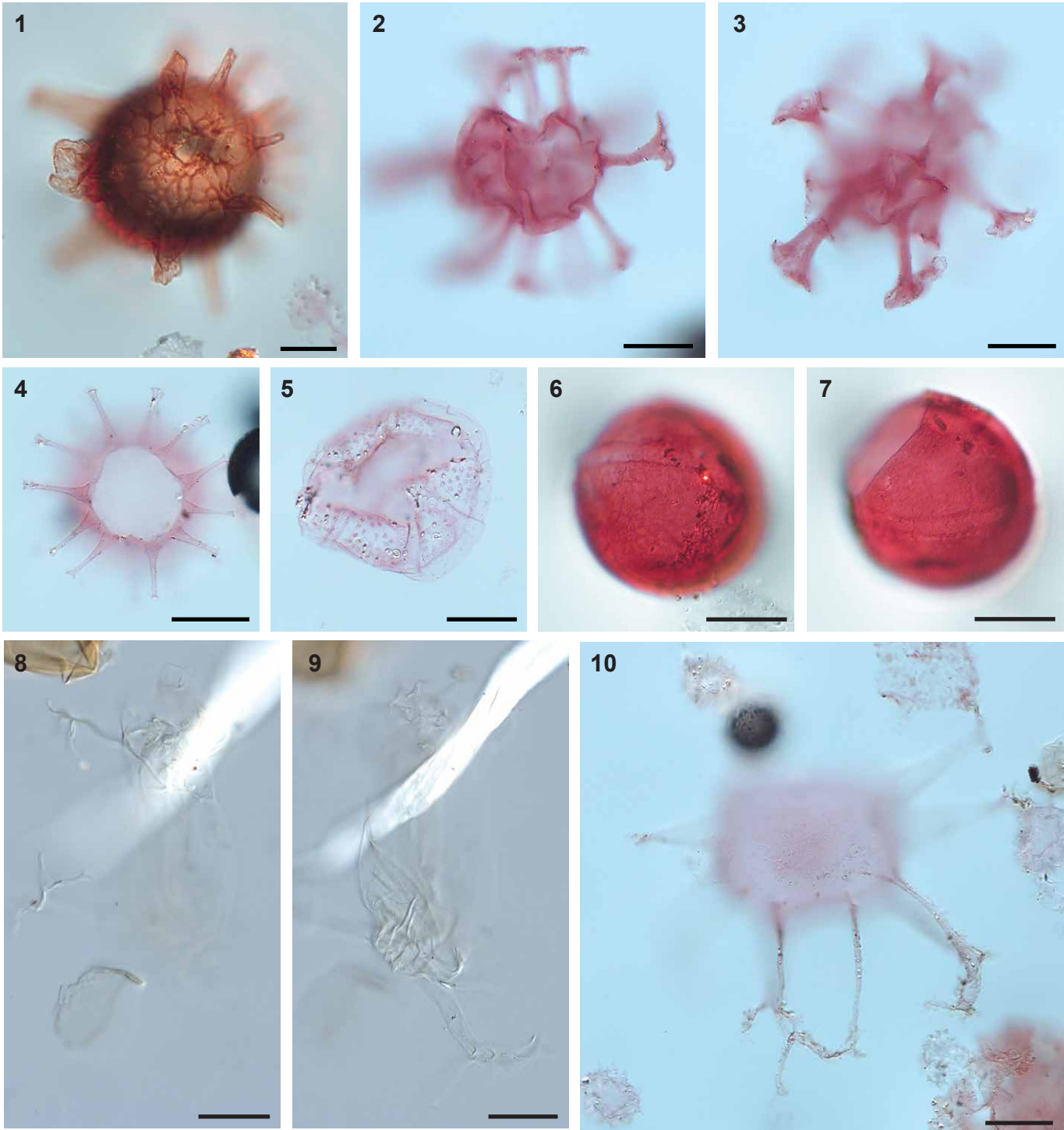
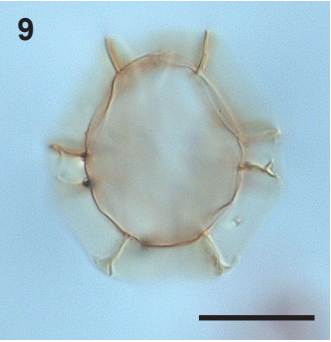
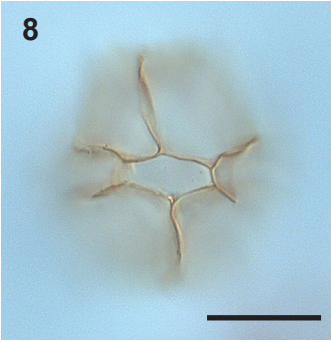
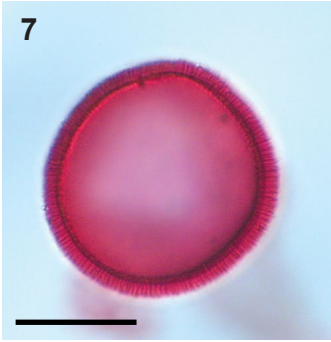
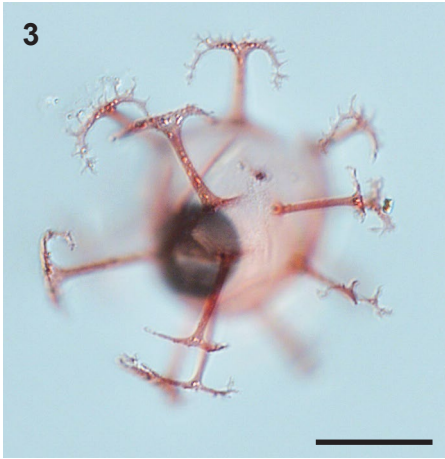
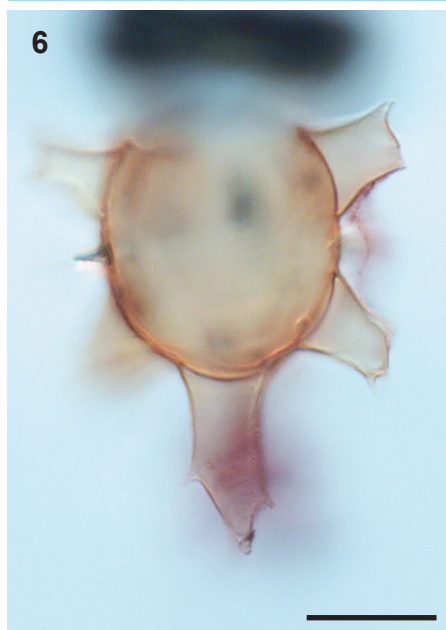
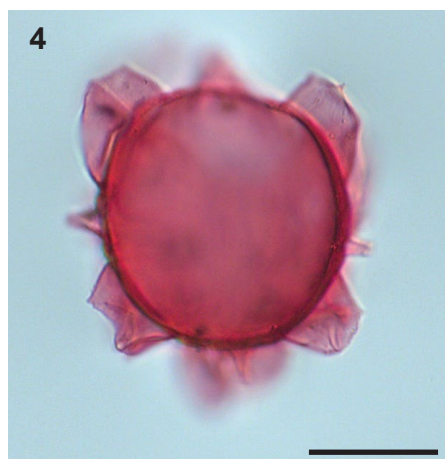
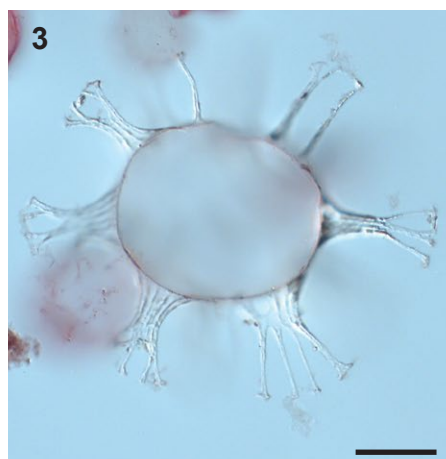
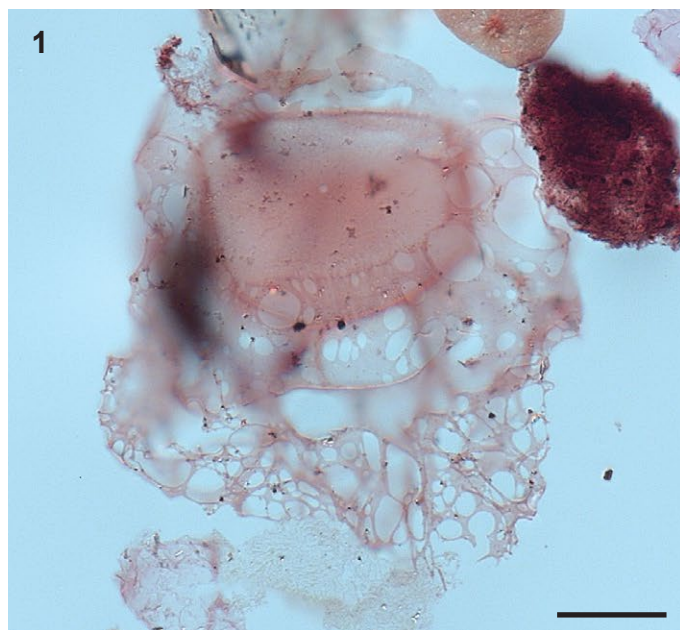
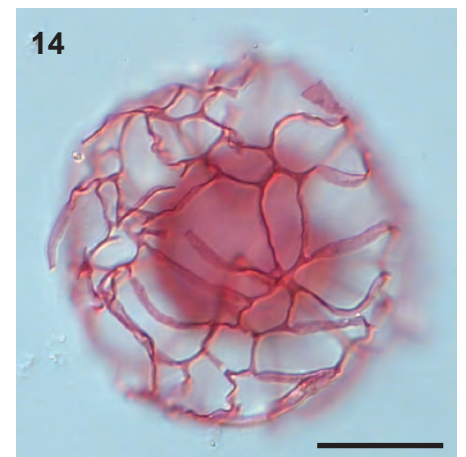
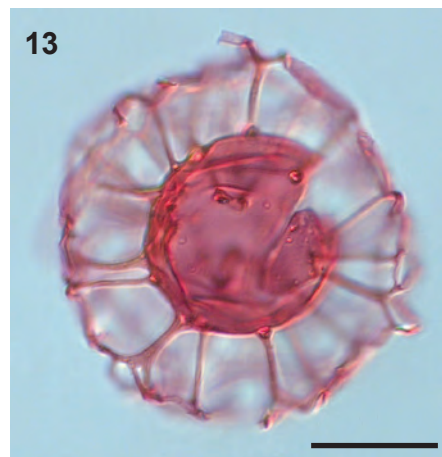
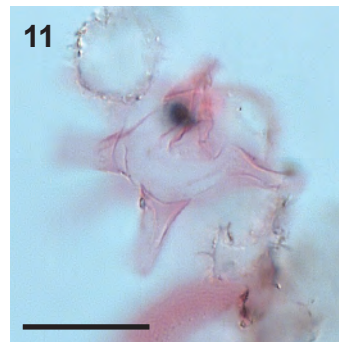
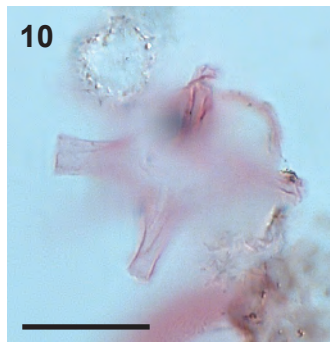
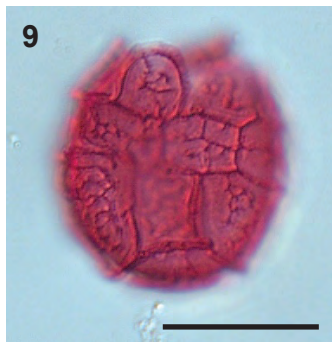
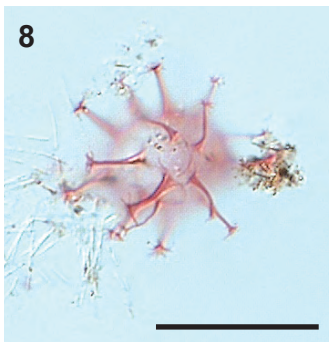
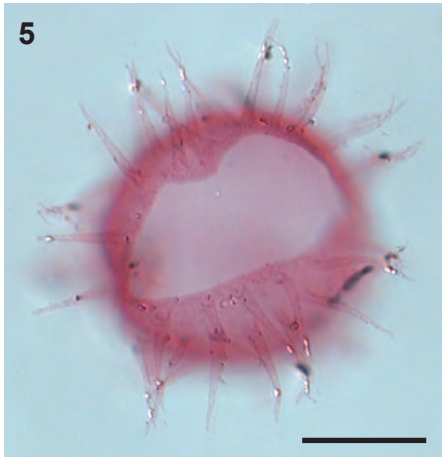
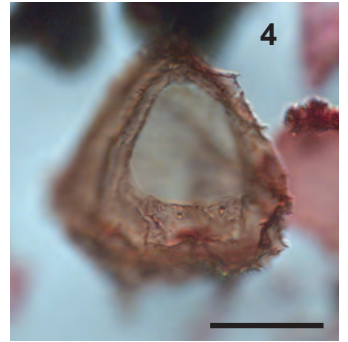
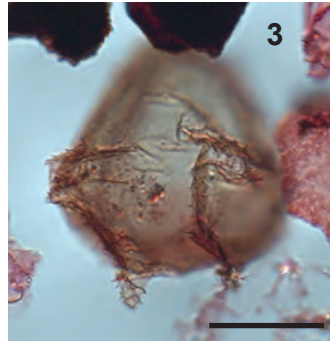
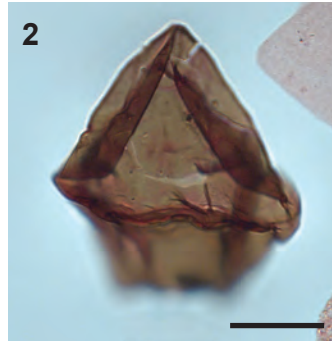
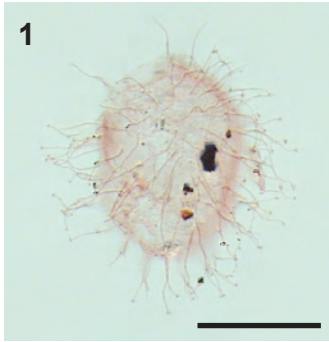


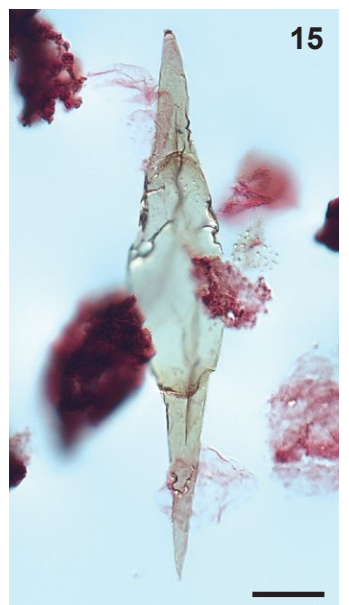
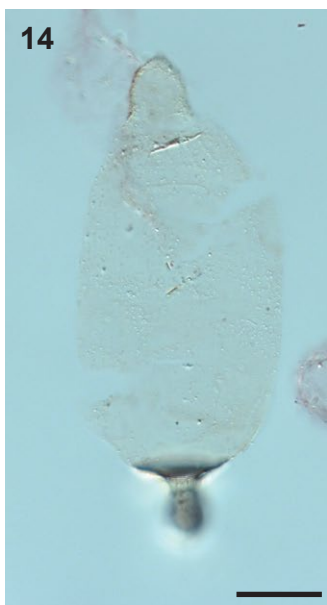
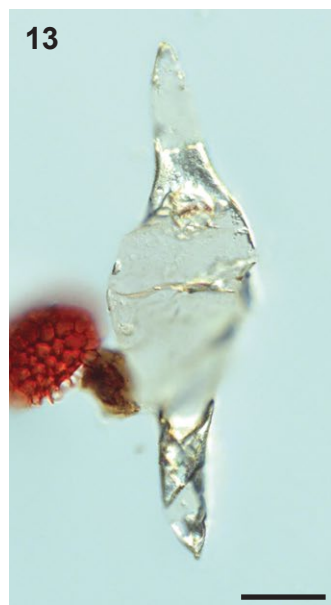
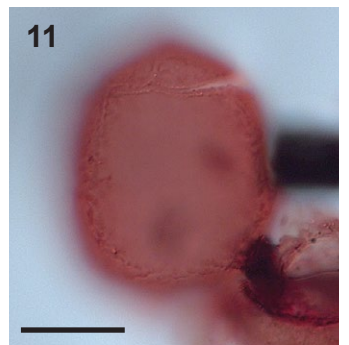
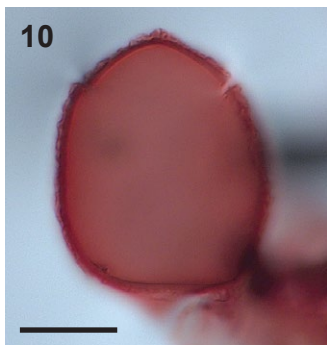
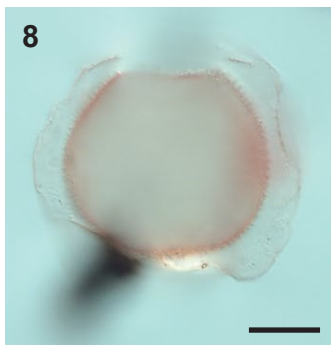
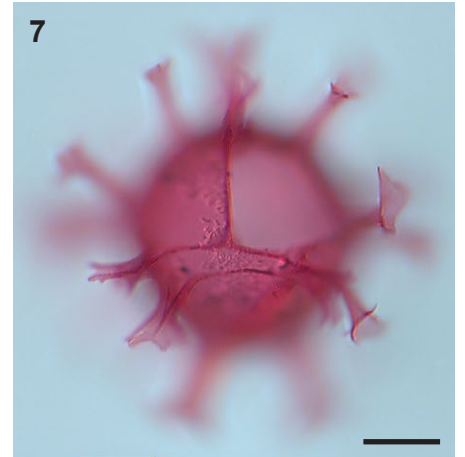
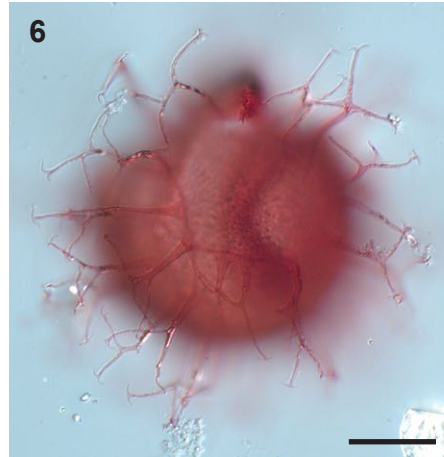
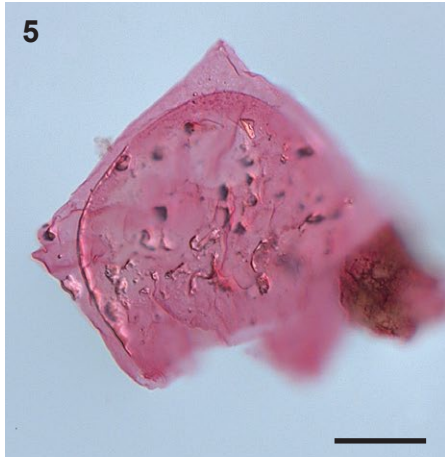
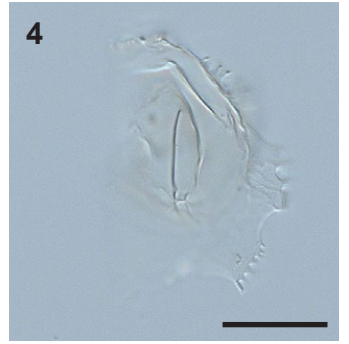
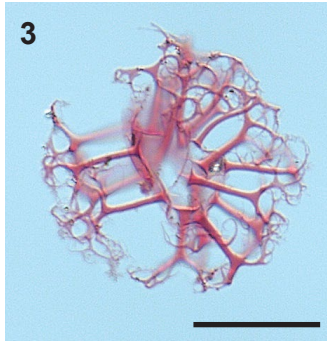
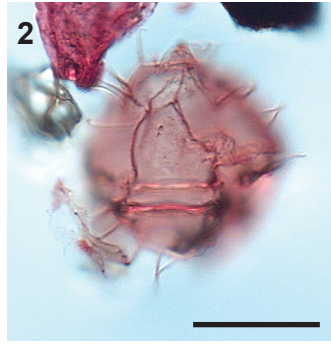
Plate III











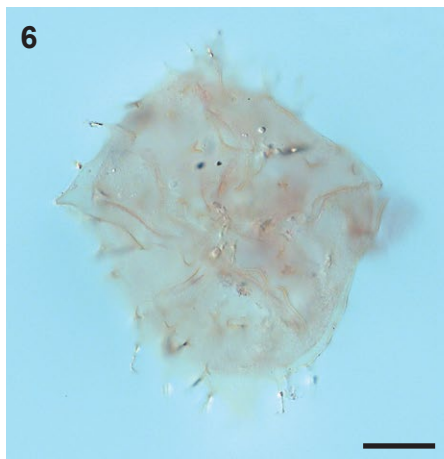
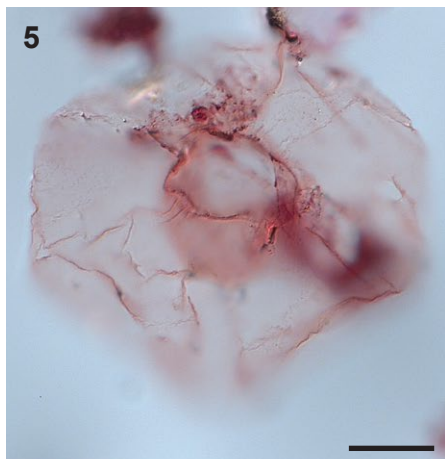
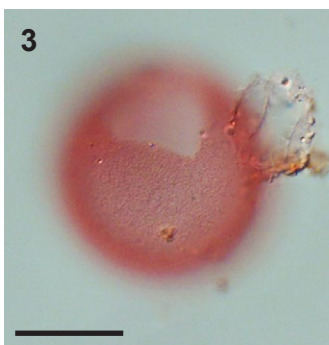


Table 1

Taxon	Age (Ma)				
	Newfound- land Drift Exp. 342	Norwegian -Greenland Sea	Norwegian Sea	North Sea/Danish land area	Umbria- Marche (Italy)
<i>Artemisiocysta cladodichotoma</i>	29.6				
<i>Chiropteridium galea</i>	30.5	33.5			
<i>Oligokolpoma galeottii</i>	30.5				31.3
<i>Chiropteridium lobospinosum</i>	32.0	33.5			32.5
<i>Hystrichokolpoma pusillum</i>	32.0				32.3
<i>Melitasphaeridium asterium</i>	33.5				
<i>Filisphaera filifera</i>	33.7				
<i>Spiniferites manumii</i>	33.7	33.0	31.4		
<i>Svalbardella</i> spp.	33.7	42.2			29,1
<i>Lophocysta sulcolimbata</i>	34.6		21,1		

Table 2

Taxon	Age (Ma)				
	Newfound- land Drift Exp. 342	Norwegian -Greenland Sea	Norwegian Sea	North Sea/Danish land area	Umbria-Marche (Italy)
<i>Svalbardella</i> spp.	22.1	33.5	30.4		27.1
<i>Deflandrea</i> spp.	22.2				
<i>Filisphaera filifera</i>	22.7				
<i>Hystriocholpoma pusillum</i>	22.8				23.6
<i>Wetzeliiella gochtii/symmetrica</i> group	26.1				26.9 (<i>W. gochtii</i>)
<i>Areoligera semicirculata</i>	26.6		30.4	C8r	27.4
<i>Saturnodinium pansum</i>	26.6			C8r	24.5
<i>Enneadocysta pectiniformis</i>	27.1				27.9
<i>Phthanoperidinium comatum</i>	30.7				27.9
<i>Spiniferites manumii</i>	31.7	30.8		C12r	
<i>Lentinia serrata</i> complex	33.3				32.4
<i>Stoveracysta</i> sp. 1	33.5				30.9 (<i>S. spp.</i>)
<i>Areosphaeridium diktyoplokum</i>	33.7	33.5		C12r	33.4
<i>Charlesdowniea clathrata</i>	33.7				32.4
<i>Hemiplacophora semilunifera</i>	33.8				33.6*
<i>Cordosph. cf. funiculatum</i>	34.0				
<i>Schematophora speciosa</i>	34.1				34.5*
<i>Lophocysta sulcolimbata</i>	34.6				

Appendix, Table A.1

Taxon	Key to range charts				Micro- photographs
	Fig. 3	Fig. 4	Fig. 5	Fig. 6	
<i>Achomosphaera</i> spp.	7	8	12	9	
<i>Achilleodinium biformoides</i> (Eisenack, 1954b) Eaton, 1976		59	2	27	
<i>Apteodinium australiense</i> (Deflandre and Cookson, 1955) Williams, 1978	33	5	39		Pl. I, Figs. 1-2
<i>Apteodinium spiridoides</i> Benedek, 1972		40		51	Pl. I, Fig. 3
* <i>Areoligera semicircularata</i> (Morgenroth, 1966b) Stover and Evitt, 1978		53	4		Pl. I, Fig. 4
<i>Areoligera</i> spp. (undiff.)		51	13		
* <i>Areosphaeridium diktyoplokum</i> (Klumpp, 1953) Eaton, 1971				35	Pl. I, Fig. 5
* <i>Artemisiocysta cladodichotoma</i> Benedek, 1972	26	45	51		Pl. I, Fig. 6
<i>Batiacasphaera micropapillata</i> Stover, 1977					Pl. I, Fig. 7
<i>Batiacasphaera sphaerica</i> Stover, 1977					
<i>Batiacasphaera</i> spp. (undiff.)	8	9	14	10	
<i>Cerebrocysta bartonensis</i> Bujak in Bujak et al., 1980		29	49	36	Pl. I, Figs. 8-9
* <i>Charlesdowniea clathrata</i> (Eisenack, 1938b) Lentin and Vozzhennikova, 1989				37	Pl. IV, Fig. 2
* <i>Chiropteridium galea</i> (Maier, 1959) Sarjeant, 1983	30	3	15		Pl. II, Figs. 5-6
* <i>Chiropteridium lobospinosum</i> Gocht, 1960	3	21	16		Pl. II, Figs. 7-8
<i>Chiropteridium</i> spp. (undiff.)	32	52	17		
<i>Cleistosphaeridium ancyreum</i> (Cookson and Eisenack, 1965b) Eaton et al., 2001					
<i>Cleistosphaeridium diversispinosum</i> Davey et al., 1966					
<i>Cleistosphaeridium</i> spp. (undiff.)	9	10	18		
<i>Cordosphaeridium cantharellus</i> (Brosius, 1963) Gocht, 1969	4	30	19	44	Pl. III, Figs. 2-3
* <i>Cordosphaeridium</i> cf. <i>funiculatum</i> of Biffi and Manum, 1988				48	Pl. III, Fig. 1
<i>Cordosphaeridium minimum</i> (Morgenroth, 1966a) Benedek, 1972		7	20	12	Pl. II, Fig. 1
<i>Cordosphaeridium</i> spp. (undiff.)	1	36	21	11	
<i>Corrudinium incompositum</i> (Drugg, 1970b) Stover and Evitt, 1978		58		5	Pl. II, Figs. 2-3
<i>Cribroperidinium</i> sp. 1					Pl. III, Figs. 6-7
<i>Cyclodictyon</i> spp.		62			Pl. II, Fig. 4
<i>Dapsilidinium pseudocolligerum</i> (Stover, 1977) Bujak et al., 1980	6	11	22	14	Pl. III, Fig. 4
<i>Dapsilidinium</i> spp.		65	50		
<i>Deflandrea phosphoritica</i>					Pl. IV, Fig. 1
<i>Deflandrea</i> spp. (undiff.)	36	12	23	15	
<i>Dinopterygium cladoides</i> Deflandre, 1935		47	40	1	Pl. III, Fig. 5
<i>Diphyes colligerum</i> (Deflandre and Cookson, 1955) Cookson, 1965a					
<i>Distatodinium biffii</i> Brinkhuis et al., 1992		48	52		Pl. III, Figs. 8-9
<i>Distatodinium craterum</i> Eaton, 1976					
<i>Distatodinium ellipticum</i> (Cookson and Eisenack, 1965a) Eaton, 1976					
<i>Distatodinium</i> spp. (undiff.)		33	41	4	
* <i>Enneadocysta pectiniformis</i> (Eaton, 1971) Stover and Williams, 1995		57		16	Pl. IV, Fig. 3
<i>Enneadocysta magna</i> Fensome et al., 2006		61			Pl. III, Fig. 10
* <i>Filisphaera filifera</i> Bujak, 1984	37	1	24	52	Pl. IV, Figs. 6-7
<i>Gelatia inflata</i> Bujak, 1984	2	31	25	28	Pl. IV, Fig. 4
<i>Glaphyrocysta intricata</i> (Eaton, 1971) Stover and Evitt, 1978					
<i>Glaphyrocysta semitecta</i> (Bujak in Bujak et al., 1980) Lentin and Williams, 1981				38	Pl. V, Fig. 1
<i>Glaphyrocysta</i> spp. (undiff.)	38	37	42	39	Pl. V, Fig. 2
<i>Hapsocysta kysingensis</i> Heilmann-Clausen and Van Simaey, 2005	27	34			
* <i>Hemiplacophora semilunifera</i> Cookson and Eisenack, 1965a				45	Pl. IV, Fig. 5
<i>Heteraulacacysta porosa</i> Bujak in Bujak et al., 1980		56		40	
<i>Heteraulacacysta pustulata</i> Jan du Chêne and Adediran, 1985				41	
<i>Heteraulacacysta</i> spp. (undiff.)		43	46		
<i>Homotryblum plectilum</i> Drugg and Loeblich Jr., 1967	12	2	7	29	Pl. V, Fig. 3
<i>Hystrichokolpoma cinctum</i> Klumpp, 1953					Pl. V, Fig. 8
* <i>Hystrichokolpoma pusillum</i> Biffi and Manum, 1988	39	27	5		Pl. V, Fig. 4
<i>Hystrichokolpoma rigaudiae</i> Deflandre and Cookson, 1955	13	22	11	30	Pl. V, Figs. 6-7
<i>Hystrichokolpoma salacia</i> Eaton, 1976					
<i>Hystrichokolpoma</i> sp. sensu Biffi and Manum 1988					
<i>Hystrichokolpoma truncata</i> Biffi and Manum, 1988					
<i>Hystrichokolpoma</i> spp. (undiff.)	14	13	26	17	
<i>Hystrichokolpoma/Oligokolpoma</i> spp.		60	6		
<i>Hystrichosphaeropsis obscura</i> Habib, 1972					
<i>Impagidinium dispertitum</i> (Cookson and Eisenack, 1965a) Stover and Evitt, 1978					
<i>Impagidinium maculatum</i> (Cookson and Eisenack, 1961b) Stover and Evitt, 1978					
<i>Impagidinium paradoxum</i> (Wall, 1967) Stover and Evitt, 1978					
<i>Impagidinium torsium</i> Stover and Hardenbol, 1993					
<i>Impagidinium velorum</i> Bujak, 1984	15	38	43	18	
<i>Impagidinium</i> spp. (undiff.)	16	14	27	19	Pl. IV, Figs. 8-9

Appendix, Table A.1

<i>Impletosphaeridium insolitum</i> Eaton, 1976	17	23	28		Pl. VI, Fig. 1
<i>Lejeunecysta fallax</i> (Morgenroth, 1966b) Artzner and Dörhöfer, 1978					Pl. VI, Fig. 2
<i>Lejeunecysta hyalina</i> (Gerlach, 1961) Artzner and Dörhöfer, 1978					
<i>Lejeunecysta</i> spp.	18	15	44	20	
* <i>Lentinia serrata</i> Bujak in Bujak et al., 1980		41		33	Pl. VI, Figs. 3-4
<i>Lingulodinium machaerophorum</i> (Deflandre and Cookson, 1955) Wall, 1967	19	24	29	7	Pl. VI, Fig. 5
* <i>Lophocysta sulcolimbata</i> Manum, 1979				46	Pl. VI, Figs. 6-7
* <i>Melitasphaeridium asterium</i> (Eaton, 1976) Bujak et al., 1980	20	4	30	2	Pl. VI, Fig. 8
<i>Microdinium reticulatum</i> Vozzhennikova, 1967		58		5	Pl. VI, Fig. 9
<i>Nematosphaeropsis reticulensis</i> (Pastiels, 1948) Sarjeant, 1986					
<i>Nematosphaeropsis labyrinthus</i> (Ostenfeld, 1903) Reid, 1974					Pl. VI, Figs. 12-14
<i>Nematosphaeropsis</i> spp. (undiff.)	21	16	45	21	
* <i>Oligokolpoma galeottii</i> Pross et al., 2010	31	28			Pl. VI, Figs. 10-11
<i>Oligokolpoma</i> spp.					Pl. V, Fig. 5
<i>Operculodinium centrocarpum</i> (Deflandre and Cookson, 1955) Wall, 1967	22	17	31	22	Pl. VII, Fig. 1
<i>Operculodinium</i> spp. (undiff.)	28	6	32	49	
<i>Palaeocystodinium golzowense</i> Alberti, 1961	23	18	33	23	
<i>Palaeocystodinium</i> spp. (undiff.)		44	34		Pl. VII, Fig. 15
<i>Pentadinium laticinctum</i> Gerlach, 1961		42	1		Pl. VII, Fig. 8
<i>Pentadinium</i> spp. (undiff.)		49	35		
<i>Phthanoperidinium amoenum</i> Drugg and Loeblich Jr., 1967		63			
* <i>Phthanoperidinium comatum</i> (Morgenroth, 1966b) Eisenack and Kjellström, 1972		66		24	Pl. VII, Fig. 2
<i>Phthanoperidinium filigranum</i> (Benedek, 1972) Benedek and Sarjeant, 1981					
<i>Phthanoperidinium geminatum</i> Bujak in Bujak et al., 1980		64			
<i>Phthanoperidinium</i> spp. (undiff.)	24	19		3	
<i>Polysphaeridium</i> spp.	29	39	47		
<i>Reticulatosphaera actinocoronata</i> Benedek, 1972	5	20	36	25	Pl. VII, Fig. 3
<i>Rhombodinium draco</i> Gocht, 1955				42	Pl. VII, Fig. 5
* <i>Saturnodinium pansum</i> (Stover, 1977) Brinkhuis et al., 1992		54	8		Pl. VII, Fig. 4
* <i>Schematophora speciosa</i> Deflandre and Cookson, 1955				50	Pl. VII, Fig. 9
<i>Selenopemphix crenata</i> Matsuoka and Bujak, 1988					Pl. VIII, Fig. 1
<i>Selenopemphix nephroides</i> Benedek, 1972					Pl. VIII, Fig. 2
<i>Selenopemphix</i> spp. (undiff.)	18	15	44	20	
* <i>Spiniferites manumii</i> (Lund, 2002) Schiøler 2005		67		31	Pl. VII, Fig. 6
<i>Spiniferites pseudofurcatus</i> (Klumpp, 1953) Sarjeant, 1970		35	9	8	Pl. VII, Fig. 7
<i>Spiniferites</i> spp. (undiff.)	7	8	12	9	
* <i>Stoveracysta</i> sp. 1				34	Pl. VII, Figs. 10-11
* <i>Svalbardella</i> spp.	35	25	37	32	Pl. VII, Figs. 12-14
<i>Tectatodinium pellitum</i> Wall, 1967	25	32	38	26	Pl. VIII, Figs. 3-4
<i>Thalassiphora delicata</i> Williams and Downie, 1966c					Pl. VIII, Fig. 5
<i>Thalassiphora fenestrata</i> Liengjaren et al., 1980					Pl. VIII, Fig. 8
<i>Thalassiphora gracilis</i> Heilmann-Clausen and Van Simaëys, 2005					
<i>Thalassiphora pelagica</i> (Eisenack, 1954b) Eisenack and Gocht, 1960		50	10	47	Pl. VIII, Figs. 9-10
<i>Thalassiphora</i> spp. (undiff.)		55	3	43	
* <i>Wetzeliiella gochtii</i> Costa and Downie, 1976		46	48	6	Pl. VIII, Fig. 6
* <i>Wetzeliiella symmetrica</i> Weiler, 1956		46	48	6	Pl. VIII, Fig. 7
undiff. dinocysts	40	68	53	53	
indeterminate dinocysts	41	69	54	54	
*dinocysts used for biostratigraphy					