

1 **Mid-Piacenzian variability of Nordic Seas surface circulation linked to**
2 **terrestrial climatic change in Norway**

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13 **Key Points:**

- 14 • Late Pliocene marine and terrestrial climate in the Norwegian Sea region is controlled by
15 Norwegian Atlantic Current and obliquity changes
- 16 • Warmer-than-present intervals characterized by strong Norwegian Atlantic Current
17 influence and high obliquity
- 18 • During colder late Pliocene intervals, oceanic and terrestrial conditions were comparable
19 to the present

20
21 **Index Terms:**

22 0473 Paleoclimatology and paleoceanography

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27
28 **Keywords:**

29 Dinoflagellate cysts, Norwegian Atlantic Current, Arctic Front, northward heat transport,
30 obliquity forcing, Late Pliocene

31 Abstract

32 During the mid-Piacenzian, Nordic Seas sea surface temperatures (SSTs) were higher than today.
33 While SSTs provide crucial climatic information, on their own they do not allow a reconstruction
34 of potential underlying changes in water masses and currents. A new dinoflagellate cyst record
35 for Ocean Drilling Program (ODP) Site 642 is presented to evaluate changes in northward heat
36 transport via the Norwegian Atlantic Current (NwAC) between 3.320 and 3.137 Ma. The record
37 is compared with vegetation and SST reconstructions from Site 642 and SSTs from ODP Site
38 907, Iceland Sea, to identify links between SSTs, ocean currents and vegetation changes. The
39 dinocyst record shows strong Atlantic water influence via the NwAC corresponds to higher-than-
40 present SSTs and cool temperate vegetation during Marine Isotope Stage (MIS) transition M2–
41 M1 and KM5. Reduced Atlantic water inflow relative to the warm stages coincides with near-
42 modern SSTs and boreal vegetation during MIS M2, KM6 and KM4–KM2. During most of the
43 studied interval, a strong SST gradient between sites 642 and 907 indicates the presence of a
44 proto-Arctic Front (AF). An absent gradient during the first half of MIS KM6, due to reduced
45 Atlantic water influence at Site 642 and warm, presumably Atlantic water reaching Site 907, is
46 indicative of a weakened NwAC and EGC. We conclude that repeated changes in Atlantic water
47 influence directly affect terrestrial climate and that an active NwAC is needed for an AF to
48 develop. Obliquity forcing may have played a role, but the correlation is not consistent.

49 1 Introduction

50 The mid-Piacenzian (3.264–3.025 Ma) is the most recent prolonged warm period in
51 Earth's history that exhibits similarities to climatic conditions predicted for the end of the 21st
52 century [IPCC, 2013; Dowsett *et al.*, 2016]. As such, this time interval has been the focus of
53 proxy reconstructions and climate modelling to compile a comprehensive picture of the
54 magnitude and spatial scale of climatic changes and their drivers [Dowsett *et al.*, 2016; Haywood
55 *et al.*, 2016]. During the mid-Piacenzian, global annual surface temperatures are estimated to
56 have been 2–3°C higher than present, with reconstructed atmospheric CO₂ concentrations
57 ranging between 270–410 ppm [Seki *et al.*, 2010; Bartoli *et al.*, 2011; Badger *et al.*, 2013;
58 Haywood *et al.*, 2013a; Martínez-Botí *et al.*, 2015]. The most recent environmental
59 reconstruction of this time interval, the Pliocene Research Interpretation and Synoptic Mapping
60 (PRISM) 4 paleoenvironmental reconstruction, highlights the need for high-resolution multi-
61 proxy records with a regional and process-oriented approach [Dowsett *et al.*, 2013b, 2016]. Such
62 studies are needed to provide more complete paleoenvironmental reconstructions and to gain a
63 better understanding of the climate variability within the mid-Piacenzian [McClymont *et al.*,
64 2015]. Furthermore, there is significant disagreement between data and models over the
65 magnitude of warming during the mid-Piacenzian, highlighting the need for further
66 investigations [Dowsett *et al.*, 2013a; Haywood *et al.*, 2013b; Salzmann *et al.*, 2013].

67 In the Nordic Seas, some proxy-based reconstructions reveal an enhanced sea surface
68 temperature (SST) increase when compared to low-latitude sites during the mid-Piacenzian
69 [Dowsett *et al.*, 2013a]. This has been ascribed to increased northward heat transport via a
70 stronger Atlantic Meridional Overturning Circulation (AMOC) [Raymo *et al.*, 1996; Ravelo and
71 Andreasen, 2000; Sarnthein *et al.*, 2009], radiative forcing due to increased greenhouse gas
72 levels [Zhang *et al.*, 2013a, 2013b; Bachem *et al.*, 2016] and paleogeographic changes in the
73 Arctic [Hill, 2015; Otto-Bliesner *et al.*, 2017]. In fact, the magnitude of warming is not uniform
74 over the Nordic Seas and varies between proxies and sites. At Ocean Drilling Program (ODP)

75 Site 907 (69°N) in the Iceland Sea (Figure 1), the reconstruction of summer SSTs using the
76 Mg/Ca ratio yields values 3–5°C higher than present [Robinson, 2009], and an estimate of annual
77 SSTs derived from alkenones at the same site is around 3°C higher than today [Schreck *et al.*,
78 2013]. At ODP Site 909 (79°N) northwest of Svalbard, summer SSTs using alkenones and the
79 Mg/Ca ratio have been estimated to be ~11–18°C higher than present [Robinson, 2009].
80 However, the full variability may not be recorded due to low resolution of the data sets and the
81 estimates might only represent brief pulses of warmth advecting into the Arctic [Robinson,
82 2009]. At the nearby Site 910 (80°N), a rise of annual SSTs of 3–4°C is inferred from the
83 distribution of glycerol dialkyl glycerol tetraethers (GDGTs) [Knies *et al.*, 2014b]. The warming
84 is least pronounced in the Norwegian Sea. There, alkenone-derived summer SST estimates for
85 the mid-Piacenzian show a warming in the order of 2–3°C in comparison to the Holocene
86 average, with an obliquity-driven SST variability of up to 4°C [Bachem *et al.*, 2016]. Bachem *et*
87 *al.* [2016] suggest that the inflow of warm Atlantic water into the Norwegian Sea via the North
88 Atlantic Current (NAC) was similar to present. However, these estimates are only based on SST
89 reconstructions and the large variety in reconstructed temperatures between sites emphasizes the
90 need for better documentation of the mid-Piacenzian oceanographic conditions and climate
91 variability in the Nordic Seas.

92 In the North Atlantic, variations in strength and position of the NAC recorded in
93 dinoflagellate cyst (dinocyst) and SST records have been suggested to have had a strong impact
94 on high-latitude climate during glacial Marine Isotope Stage (MIS) M2 (c. 3.3 Ma) and the
95 subsequent establishment of warmer climatic conditions during the mid-Piacenzian [De Schepper
96 *et al.*, 2013]. A weakened NAC appears to have halted northward heat transport prior to the
97 global ice volume expansion during MIS M2, whereas the re-establishment of an active, modern-
98 like NAC corresponds to the onset of mid-Piacenzian warm conditions [De Schepper *et al.*,
99 2013]. In northern Norway, the continuous presence of cool temperate and boreal forests on land
100 indicates that mid-Piacenzian climate was too warm for the persistence of sea-terminating
101 glaciers, even during MIS M2 [Panitz *et al.*, 2016]. It remains unclear whether the Scandinavian
102 terrestrial realm and Nordic Seas SST changes are linked to variations in the inflow of Atlantic
103 water into the Norwegian Sea or can merely be explained by orbitally forced insolation changes.
104 In particular, evidence for changes in the inflow of Atlantic water and its effects on terrestrial
105 climate is missing for the Norwegian Sea – a region crucial for heat transport from the North
106 Atlantic to the Arctic Ocean via the Norwegian Atlantic Current (NwAC).

107 Here, we integrate a new high-resolution dinoflagellate cyst record from ODP Hole
108 642B in the Norwegian Sea with pollen [Panitz *et al.*, 2016], alkenone-derived SSTs and ice
109 rafted debris (IRD) records from the same site [Bachem *et al.*, 2017] over a ~180-kyrs time
110 interval (3.320–3.137 Ma). This multi-proxy approach allows us to document surface water mass
111 changes in the Norwegian Sea throughout the mid-Piacenzian, and investigate land-ocean
112 interactions, as well as oceanographic and atmospheric forcings. ODP Site 642 represents one of
113 two PRISM4 time series in the North Atlantic region that allow a comparison of marine and
114 terrestrial environmental changes during the mid-Piacenzian [Dowsett *et al.*, 2016].

115 2 Geographical Setting

116 The Nordic Seas consist of the Greenland Sea, Iceland Sea and Norwegian Sea and are
117 characterized by steep zonal and meridional climatic gradients. ODP Site 642 is located on the
118 outer Vøring Plateau in the Norwegian Sea, about 400–450 km west off the Norwegian coast

119 (67°13.2'N, 2°55.8'E, 1286 m water depth; *Shipboard Scientific Party*, 1987; Figure 1). The site
 120 is situated in the path of the northward-flowing NwAC, with one branch on either side of the
 121 plateau. The eastern branch follows the Norwegian continental slope and the western branch
 122 flows around the Vøring Plateau [*Nilsen and Nilsen*, 2007]. The NwAC is a continuation of the
 123 NAC, with Atlantic waters entering the Norwegian Sea through the Iceland-Faroe Ridge and
 124 Faroe-Shetland Channel, resulting in the presence of warm and saline (6–10°C, 35.1–35.3 psu in
 125 summer) waters [*Swift*, 1986; *Blindheim and Østerhus*, 2005]. The warm, nutrient-enriched
 126 waters of the NAC are associated with relatively high primary production in the Norwegian Sea
 127 [*Skogen et al.*, 2007]. The NwAC gradually releases its excess heat along its way towards the
 128 Arctic Ocean. In the eastern Nordic Seas, cooler and fresher polar water from the Arctic (<0°C,
 129 30–34 psu in summer) is transported southward within the East Greenland Current (EGC) [*Swift*,
 130 1986]. Along its path, some of the EGC water is diverted to the east into the adjacent Boreas
 131 Basin, Greenland Basin and Iceland Sea [*Blindheim and Østerhus*, 2005]. Polar and Atlantic
 132 water masses mix in the central part of the Nordic Seas, forming a distinct Arctic water mass (0–
 133 4°C, 34.6–34.9 psu in summer) [*Swift*, 1986]. The water masses are separated by fronts, with the
 134 Polar Front following the southward flowing EGC, separating Polar and Arctic water, and the
 135 Arctic Front (AF), marking the boundary between Arctic and Atlantic water and running from
 136 SW to NE north of Iceland (Figure 1) [*Swift*, 1986].

137 Climate and vegetation of Norway change along latitudinal and altitudinal gradients as
 138 well as with increasing continentality. Due to the presence of Atlantic water, the climate of
 139 Norway is relatively mild when compared with areas at comparable latitudes [*Diekmann*, 1994].
 140 The modern vegetation of Norway is characterized by boreal forests, with alpine tundra
 141 prevailing at the higher altitudes of the Scandinavian mountains (Figure 1). Deciduous forest is
 142 found at the far southern coast of Norway (Figure 1) [*Moen*, 1987, 1999].

143 **3 Materials and Methods**

144 3.1 Age model

145 The Pliocene age model for ODP Hole 642B is based on an updated magnetic
 146 stratigraphy [*Bleil*, 1989; *Hilgen et al.*, 2012] and the correlation of the benthic oxygen isotope
 147 curve from Hole 642B to the global LR04 benthic oxygen isotope stack between 4.147 and 3.137
 148 Ma (Figure 2) [*Lisiecki and Raymo*, 2005; *Risebrobakken et al.*, 2016]. A hiatus is present in the
 149 younger part (<3.14 Ma) of the Pliocene section [*Jansen and Sjøholm*, 1991]. All records
 150 presented from Hole 642B follow the same age model [*Risebrobakken et al.*, 2016].

151 3.2 Samples and sample preparation

152 Marine palynomorphs (dinocysts and acritarchs) were analyzed in 44 samples from ODP
 153 Hole 642B between 68.45 and 66.95 meters below sea floor (mbsf), or 3.32 and 3.14 Ma
 154 [*Shipboard Scientific Party*, 1987; *Risebrobakken et al.*, 2016], with three samples taken from
 155 *De Schepper et al.* [2015]. The <63- μ m sediment fraction was used for palynomorph analysis as
 156 the samples were pre-sieved in Bergen, Norway to retain foraminifera for oxygen isotope
 157 analysis [*Risebrobakken et al.*, 2016]. The samples were prepared at the Palynological
 158 Laboratory Services Ltd, North Wales and Northumbria University, Newcastle, using standard
 159 palynological techniques [details in *De Schepper et al.*, 2017]. One *Lycopodium clavatum* spore
 160 tablet was added to each sample to calculate pollen concentrations [*Stockmarr*, 1971]. The
 161 sediment was treated with HCl (20%) followed by concentrated HF (48%) to remove carbonates

162 and silicates, respectively. Fluorosilicates were removed with an additional wash of hot (c. 80°C)
 163 HCl (20%). The sediment was sieved through a 10 µm screen and the back-sieved residue was
 164 mounted on glass slides using glycerol-gelatin jelly.

165 Marine [this study] and terrestrial [*Panitz et al.*, 2016] palynomorphs were studied in the same
 166 samples, with both records having a temporal resolution of 1000 to 14,000 years. Alkenone-
 167 derived SSTs from Hole 642B have been estimated in 87 samples between 3.138 and 3.330 Ma
 168 [*Bachem et al.*, 2016, 2017]. For six of the 44 samples analyzed for palynomorphs, SSTs are
 169 available from exactly the same sample.

170 Alkenone-derived SSTs from ODP Hole 907A (Figure 1) were obtained using the method
 171 described in *Schreck et al.* [2017]. The age model for Hole 907A is based on *Jansen et al.*
 172 [2000]. The raw data is available at <https://doi.pangaea.de/10.1594/PANGAEA.877309>.

173 3.3. Analysis of marine palynomorphs

174 3.3.1 Dinoflagellate cysts

175 At least 300 dinocysts were identified for each sample, and Table 1 provides a taxonomic
 176 list of species encountered in the Piacenzian sediments of ODP Hole 642B with full authorial
 177 citations. Cysts of *Protoceratium reticulatum* (also known as *Operculodinium centrocarpum*
 178 sensu Wall and Dale, 1966; see *Paez-Reyes and Head*, 2013) with processes smaller than 2 µm
 179 [cf. *Rochon et al.*, 1999] were counted separately in 34 samples (the morphotype was not
 180 differentiated in the remaining ten samples). *Brigantedinium* spp. comprises all (sub)spherical
 181 brown protoperidinioid cysts with an intercalary (sub)polygonal archeopyle and without
 182 processes [*Reid*, 1977]. Round brown cysts (RBCs) include (sub)spherical brown
 183 protoperidinioid cysts with neither processes nor a visible polygonal archeopyle. Round brown
 184 spiny dinocysts without a visible archeopyle are included in *Echinidium* spp. Species within the
 185 genus *Spiniferites* were differentiated if possible, depending on orientation and preservation. The
 186 relative abundance of taxa was described as dominant (>60%), abundant (60–30%), common
 187 (30–10%), rare (10–1%) or present (1–0%).

188 The dinocyst burial flux (DBF) was calculated based on the dinocyst concentrations using
 189 the following formula:

$$190 \quad (1) \quad \text{DBF} = C_D \times \rho \times S$$

191 with DBF in cysts/(cm² ka). C_D is the dinocyst concentration (cysts/g), ρ the dry bulk
 192 density (g/cm³) [*Shipboard Scientific Party*, 1987] and S the sedimentation rate (cm/ka)
 193 [*Risebrobakken et al.*, 2016]. The comparison of DBF with dinocyst concentrations gives an
 194 indication of the influence of productivity and/or sedimentation rate on the observed fluctuations.
 195 If DBF and dinocyst concentration show the same pattern, the changes in concentrations can be
 196 interpreted to reflect changes in productivity [*Hennissen et al.*, 2014].

197 3.3.2 Acritarchs

198 Acritarchs are indicators for marine productivity, stratification and/or water temperature
 199 [*de Vernal and Mudie*, 1989a, 1989b; *Schreck et al.*, 2013; *De Schepper and Head*, 2014]. The
 200 acritarch burial flux was calculated based on the formula:

$$201 \quad (2) \quad \text{ABF} = C_A \times \rho \times S$$

202 with ABF in acritarchs/(cm² ka), C_A representing the acritarch concentration (cysts/g), ρ
203 the dry bulk density (g/cm³) and S the sedimentation rate (cm/ka).

204 4 Results

205 4.1 Dinoflagellate cyst assemblages

206 In ODP Hole 642B, 71 dinocyst taxa were encountered in the Piacenzian sediments, with
207 the eleven most abundant taxa always comprising at least 80% of the assemblage in any sample
208 (Figure 2). The number of taxa in any one sample ranges between 19 and 34. Four taxa, namely
209 cysts of *Protoceratium reticulatum*, *Filisphaera filifera*, *Habibacysta tectata* and
210 *Spiniferites/Achomosphaera* spp. constitute between 52 to 87% of the assemblages. Other rare to
211 common species include *Bitectatodinium raedwaldii*, *B. tepikiense*, *Lingulodinium*
212 *machaerophorum*, *Impagidinium pallidum*, *Nematosphaeropsis labyrinthus*, *Pyxidinosia braboi*
213 and Round Brown Cysts.

214 Cysts of *P. reticulatum*, *F. filifera* and *H. tectata* show marked relative abundance
215 changes over the studied time interval (3.320 and 3.137 Ma), covering MIS M2 to the early part
216 of MIS KM2 (Figure 2). During MIS M2, relative abundances of cysts of *P. reticulatum* are
217 relatively constant between ~25–40%. Proportions of *F. filifera* are higher in the first half of MIS
218 M2, with values around 10–15%, and decline to values of <10% after 3.284 Ma. Relative
219 abundances of cysts of *P. reticulatum* decline throughout MIS M1, before reaching minimum
220 values of 8% in the first half of MIS KM6. At the start of MIS M1, percentages of *F. filifera*
221 show a marked increase from 4 to 12% with values increasing to a maximum of 25% at 3.228
222 Ma within the early part of MIS KM6. Proportions of *H. tectata* are very low (<4%) during MIS
223 M2 but gradually increase throughout MIS M1 and reach values of up to 29% in the first half of
224 MIS KM6. In the middle of MIS KM6 between 3.225 and 3.222 Ma, a sharp increase in the
225 relative abundances of cysts of *P. reticulatum* from 13 to 48% occurs, which is accompanied by
226 a marked decline in the relative abundances of *F. filifera* and *H. tectata*. Subsequently, relative
227 abundances of cysts of *P. reticulatum* gradually increase to maximum values of 64% at 3.205 Ma
228 within MIS KM5 while *F. filifera* and *H. tectata* both show proportions of less than 7%. After
229 3.205 Ma, relative abundances of cysts of *P. reticulatum* continuously decline. Proportions of *F.*
230 *filifera* peak at 3.189 and 3.179 Ma and stay around 5–10% until values drop to <3% at 3.142 Ma
231 within MIS KM2. A clear increase in the relative abundance of *H. tectata* occurs at 3.185 Ma at
232 the end of MIS KM5, continuing throughout MIS KM4 and reaching highest values of 32% at
233 3.159 Ma in the middle of MIS KM3. Afterwards, proportions of *H. tectata* decline and those of
234 *L. machaerophorum* increase to up to 16%.

235 Cyst concentrations range between 500 and 5500 cysts/g in the majority of samples
236 (Figure 2). Highest concentrations occur between 3.222 and 3.197 Ma with maximum values of
237 13,000 cysts/g at 3.203 Ma. The DBF shows the same pattern as the cyst concentrations
238 throughout most of the interval. However, the DBF declines sharply between 3.214 and 3.207
239 Ma while cyst concentrations remain high until 3.197 Ma (Figure 2).

240 4.2 Acritarch assemblages

241 In the analyzed samples, the total counts of acritarchs range between 28 and 1099 and the
242 proportion of acritarchs in the total marine palynological assemblage (dinocysts and acritarchs)
243 varies between 7 and 74%. Twelve taxa and taxa groups are differentiated, with seven taxa

244 having been formally described (Table 1). Five taxa, namely *Cymatiosphaera? icenorum*, *C.?*
245 *invaginata*, *Lavradosphaera crista*, *Nannobarbophora walldalei* and small spiny acritarchs are
246 abundant to dominant in Hole 642B. Acritarch concentrations are comparable to dinocyst
247 concentrations for most of the studied interval with values fluctuating between ~140 and 1400
248 acritarchs/g. Maximum concentrations of ~16,400–21,300 acritarchs/g are reached between
249 3.217 and 3.205 Ma (Figure 3). The ABF shows a good correlation to the acritarch concentration
250 with the exception of the early part of MIS KM5, when the ABF declines before the
251 concentration decreases (Figure 2).

252 5 Discussion

253 5.1 Paleocology of the dominant dinoflagellate cyst species in ODP Hole 642B

254 Of the three most abundant dinocyst species (cysts of *P. reticulatum*, *F. filifera* and *H.*
255 *tectata*) in the mid-Piacenzian sediments of Hole 642B, only cysts of *P. reticulatum* are still
256 extant. This species is cosmopolitan, tolerates a wide range of temperature and salinity
257 [Zonneveld *et al.*, 2013], can be abundant near shelf edges [Wall *et al.*, 1977; Dale and Dale,
258 2002], and is usually over-represented in fossil assemblages due to high cyst production [Dale,
259 1976; Bolch and Hallegraeff, 1990]. Nevertheless, in the modern North Atlantic, cysts of *P.*
260 *reticulatum* are recorded in high abundance (up to 91%) along the path of the NAC [Rochon *et*
261 *al.*, 1999; Zonneveld *et al.*, 2013]. Atlantic water flows into the Nordic Seas via the NwAC,
262 which is reflected in abundances of this species above 60% in modern dinocyst assemblages in
263 the Norwegian Sea [Matthiessen, 1995]. In pre-Quaternary paleoceanographic reconstructions in
264 the North Atlantic and Nordic Seas, cysts of *P. reticulatum* have been used as a tracer of Atlantic
265 water because of their modern association with the NAC and NwAC [Grøsfjeld *et al.*, 2009; De
266 Schepper *et al.*, 2013, 2015; Hennissen *et al.*, 2014; Knies *et al.*, 2014a]. Given that the major
267 transport of Atlantic water in the Norwegian Sea occurs via the northward-flowing NwAC,
268 distinct variations in the abundances of cysts of *P. reticulatum* in Hole 642B are interpreted to
269 indicate changes in the inflow of Atlantic water into the Norwegian Sea.

270 Both *F. filifera* and *H. tectata* became extinct during the Pleistocene [Head, 1996].
271 According to their stratigraphic records, these species have previously been classified as cold-
272 water tolerant species as they are common elements of Pliocene high-latitude sites in the
273 Northern Hemisphere [Head, 1994, 1996]. However, the high latitudes were markedly warmer
274 than today during the Pliocene [De Schepper *et al.*, 2015; Herbert *et al.*, 2016; Bachem *et al.*,
275 2017], suggesting that these species could live in relatively mild SSTs. During the
276 Pliocene/Pleistocene, percentages of *F. filifera* above 5% are associated with Mg/Ca-based
277 (*Globigerina bulloides*) spring-summer SSTs of >11°C and abundances of *H. tectata* >30% with
278 spring-summer SSTs between 10 and 16°C (Mg/Ca, *G. bulloides*) in the eastern North Atlantic
279 [De Schepper *et al.*, 2011; Hennissen *et al.*, 2017]. At DSDP Site 610 in the eastern North
280 Atlantic, *F. filifera* occurs in higher abundances (up to 8%) during glacial MIS M2 [De Schepper
281 *et al.*, 2009a], reflecting its affinity for cool waters. During the intensification of Northern
282 Hemisphere Glaciation across the Pliocene/Pleistocene transition, higher abundances (up to
283 53%) of *H. tectata* are recorded during cooler intervals when proportions of cysts of *P.*
284 *reticulatum* are relatively low due to shifts in the NAC [Hennissen *et al.*, 2014, 2017]. In Hole
285 642B, *F. filifera* and *H. tectata* might be characteristic elements of the dinocyst assemblage
286 during the Piacenzian given their continuous presence throughout the studied interval and the
287 location of the site just north of the Arctic Circle.

288 Other potential cool-water indicators that are continuously present in low abundances in
 289 the Hole 642B record include the extant species *Bitectatodinium tepikiense* and *Impagidinium*
 290 *pallidum* (Figure 2). In the modern ocean, *B. tepikiense* is restricted to subarctic to temperate
 291 waters [Zonneveld *et al.*, 2013]. During the Pliocene/Pleistocene, the relationship between
 292 abundances of *B. tepikiense* and Mg/Ca based (*G. bulloides*) spring-summer paleo-SSTs in the
 293 North Atlantic compares closely to present [De Schepper *et al.*, 2011; Hennissen *et al.*, 2017]. At
 294 present, *I. pallidum* is a bi-polar species mostly encountered in cold surface waters but its
 295 presence at North Atlantic sites during the Pliocene suggests a tolerance of a wide temperature
 296 range, limiting the use of this species as a paleotemperature indicator [De Schepper *et al.*, 2011;
 297 Hennissen *et al.*, 2017].

298 Species of *L. machaerophorum* are presently mainly found in coastal temperate to
 299 equatorial regions with summer temperatures above 10°C [Zonneveld *et al.*, 2013]. During the
 300 late Piacenzian, *L. machaerophorum* is a common element in the palynomorph assemblages
 301 deposited in the southern North Sea Basin, where it has been used as an indicator for warm
 302 temperate conditions [Head, 1998; De Schepper *et al.*, 2009b]. The species tolerates a broad
 303 range of salinity and also occurs in high abundances near upwelling cells, below river plumes or
 304 in highly stratified waters [Zonneveld *et al.*, 2013]. In Norwegian fjords, higher numbers of this
 305 species have been associated with increased eutrophication [Thorsen and Dale, 1997; Dale *et al.*,
 306 1999].

307 To better interpret the dinocyst assemblage response to surface circulation changes and
 308 particularly to SST changes associated with variations in the influence of Atlantic and Arctic
 309 water at Site 642, we calculated the gradient between SSTs from Site 642 [Bachem *et al.*, 2017]
 310 and Site 907 in the Iceland Sea [this study] (Figure 1 and 3). The reconstruction of this gradient
 311 is limited by the lower sampling resolution in Hole 907A but the absolute values as well as the
 312 trend in SST changes is supported by a low-resolution alkenone SST record from the same site
 313 [Herbert *et al.*, 2016]. A strong gradient can be seen as an indication for the presence of a proto-
 314 Arctic Front (AF) between the Iceland and Norwegian Sea comparable to the modern situation,
 315 while a weak or absent gradient suggests the absence of a proto-AF between both sites. For most
 316 of the studied interval, the SST gradient fluctuates around or exceeds ~5–8°C, suggesting that a
 317 proto-AF was present (Figure 3). Under these conditions, abundances of cysts of *P. reticulatum*
 318 fluctuate between ~25 and 45%, while the combined proportions of *F. filifera* and *H. tectata* do
 319 not exceed ~25% (Figure 3). Around 3.24 Ma, the gradient drops to ~0°C, mainly due to
 320 warming in the Iceland Sea (Figure 3), indicating an AF likely did not exist between the sites.
 321 This is associated with the lowest percentages (~10%) of cysts of *P. reticulatum* within the
 322 studied interval and highest abundances (~50%) of *F. filifera* and *H. tectata*.

323 5.2 Mid-Piacenzian paleoceanography of the Norwegian Sea and links to terrestrial
 324 environmental changes

325 5.2.1. MIS M2 to MIS M1 (3.312–3.264 Ma): from glacial to interglacial conditions

326 During MIS M2, relative abundances of cysts of *P. reticulatum* around ~30–40% indicate
 327 a constant influence of Atlantic and/or shelf water (Figure 2). Abundances of *F. filifera* reach up
 328 to 17% during the first half of MIS M2. At the same time, SSTs in Hole 642B are low for the
 329 Pliocene and comparable to the Holocene average, with values around 12–13°C (Figure 3)
 330 [Bachem *et al.*, 2017], suggesting that *F. filifera* is a common element of the Piacenzian dinocyst

331 assemblage under conditions similar to today. A proto-AF was present between sites 642 and
332 907 as indicated by a gradient of ~6–10°C (Figure 3). The predominance of *Pinus* pollen and
333 *Sphagnum* spores in the pollen assemblages of Hole 642B suggests the prevalence of boreal
334 forests and an extensive distribution of peatlands under subarctic, near-modern climatic
335 conditions in northern Norway (Figure 3) [Panitz *et al.*, 2016]. Terrestrial climatic conditions
336 might have been cold enough for the establishment of mountain glaciers despite the lower-than-
337 present height of the Scandinavian mountains [Anell *et al.*, 2009; Knies *et al.*, 2014a; Panitz *et*
338 *al.*, 2016].

339 Glacial MIS M2 has been globally recognized in benthic oxygen isotope and other
340 marine and terrestrial proxy records as a pronounced cooling event during the warmer-than-
341 present Piacenzian [Lisiecki and Raymo, 2005; Mudelsee and Raymo, 2005; Brigham-Grette *et*
342 *al.*, 2013; De Schepper *et al.*, 2013, 2014]. In Hole 642B, MIS M2 is not as distinctly recorded as
343 at other sites in neither environmental changes derived from dinocysts, SSTs and pollen nor in
344 the benthic oxygen isotope signal (Figure 2 and 3), which suggests that the event might have
345 been less pronounced in the Norwegian Sea area. However, it is likely that the most extreme part
346 of MIS M2 is missing due to a minor hiatus (≤ 10 ky) [Risebrobakken *et al.*, 2016] and more
347 records are needed to assess the impact of this global cooling event on the Nordic Seas and
348 Norwegian environment. The marine and terrestrial proxy records from Hole 642B are indicative
349 of Holocene-like climatic conditions in the Norwegian Sea region during the early part of MIS
350 M2, which supports the inference of a similar-to-present Northern Hemisphere ice sheet/glacier
351 volume [De Schepper *et al.*, 2014]. At Site 907, the presence of IP₂₅ indicates seasonal sea ice
352 cover around 3.3 Ma; an interpretation which is supported by low concentrations of marine
353 biomarkers and SSTs [Clotten *et al.*, 2018]. In addition, a pronounced IRD peak suggests that
354 glaciers reached the coastline, calving icebergs in the ocean [Jansen *et al.*, 2000]. During the
355 second half of MIS M2, SSTs and productivity increases while the influence of Atlantic water
356 remains unchanged. A decline in the relative abundance of *F. filifera* is observed between 3.284
357 and 3.281 Ma (Figure 3). This is interpreted to reflect the warming of surface waters as recorded
358 in a rise in SSTs of ~5°C to highest values (~15–16°C) within the studied interval between 3.285
359 and 3.283 Ma, tracing the obliquity cycle (Figure 3) [Bachem *et al.*, 2017]. The ABF also
360 increases between 3.287 and 3.284 Ma, suggesting enhanced marine productivity (Figure 3) [de
361 Vernal and Mudie, 1989b; Schreck *et al.*, 2013]. The warming in the Norwegian Sea coincides
362 with a distinct increase in the proportions of thermophilous conifer taxa, such as *Sciadopitys* and
363 *Tsuga*, from 12 to 42% between 3.283 and 3.281 Ma (Figure 3). This is indicative of the
364 establishment of diverse, cool temperate mixed forests and warmer-than-present climatic
365 conditions in northern Norway [Panitz *et al.*, 2016]. With the warming being most pronounced in
366 the SST record from Hole 642B and vegetation changes in northern Norway [Panitz *et al.*, 2016;
367 Bachem *et al.*, 2017], it is likely a response to increased obliquity forcing, which strengthened
368 the seasonal contrast and led to warm summers [e.g. Haug *et al.*, 2001].

369 5.2.2. MIS M1 towards KM6: Establishment of cooler climatic conditions

370 At c. 3.260 Ma, the abundance of *F. filifera* increases and is comparable to the first half
371 of MIS M2, suggesting similar-to-present oceanographic conditions established (Figure 2). This
372 is supported by the presence of a proto-AF as indicated by a SST gradient of ~6°C between sites
373 642 and 907 (Figure 3). The increase in proportions of *F. filifera* is accompanied by an increase
374 in the relative abundance of *Sphagnum* spores and low proportions of thermophilous conifers,
375 indicating an expansion of peatlands at the expense of forests and the establishment of subarctic

376 climatic conditions in northern Norway [Panitz *et al.*, 2016]. For the middle section of MIS M1
377 no sediment was available for analysis. Above the sampling gap, the relative abundance of cysts
378 of *P. reticulatum* declines towards MIS KM6 which is interpreted as a reduction of Atlantic
379 water influence via the NwAC. This is supported by low concentrations and influxes of
380 dinocysts, and acritarchs (Figure 2 and 3), indicating reduced marine productivity and a cooling
381 of surface waters at Site 642 (Figure 3). The decrease of SSTs after 3.247 Ma traces the obliquity
382 cycle [Bachem *et al.*, 2016], suggesting that the weakened seasonality and warmer winters might
383 have contributed to a reduction in the NwAC influence. At the same time, relatively high
384 abundances of *Sphagnum* spores and *Pinus* pollen are indicative of subarctic climatic conditions
385 on land (Figure 3). While SSTs decrease in the Norwegian Sea, a pronounced warming of
386 surface waters is recorded in the Iceland Sea, suggesting a collapse of the SST gradient and the
387 absence of a proto-AF between sites 642 and 907 (Figure 3). This is indicative of a weakened
388 NwAC and EGC in the Nordic Seas, with Site 907 being influenced by warmer, presumably
389 Atlantic waters, entering through the Denmark Strait. It also suggests that an active NwAC is
390 needed for an AF to develop between the Norwegian and Iceland Sea. The good correlation of
391 dinocyst and pollen assemblage changes suggests that a reduced Atlantic water influence due to
392 the absence of the NwAC had a direct impact on terrestrial climate.

393 5.2.3. MIS KM6 (3.238–3.212 Ma): Increased inflow of warm Atlantic waters

394 The cooling that commenced within MIS M1 culminates during the first half of MIS
395 KM6, which is evident in peaks in the abundances of *F. filifera* and *H. tectata* (Figure 2),
396 following the reduction of NwAC influence. This is also reflected in Holocene-like SSTs in Hole
397 642B (Figure 3) [Bachem *et al.*, 2016]. Between 3.225 and 3.222 Ma, a distinct increase in the
398 relative abundance (up to ~48%) and concentrations of cysts of *P. reticulatum* takes place
399 (Figure 2), indicating increased inflow of Atlantic waters into the Norwegian Sea. The increase
400 in abundance of cysts of *P. reticulatum* also corresponds to an increase in the total DBF and ABF
401 (Figure 2 and 3), suggesting that nutrient-rich water influenced the site and led to enhanced
402 productivity. An increase in SSTs in Hole 642B by ~2.5°C is recorded at 3.223 Ma (Figure 3)
403 [Bachem *et al.*, 2016]. Bachem *et al.* [2016] note that the rise in SSTs coincides with an increase
404 in obliquity, indicating that the warming might be a response to orbital forcing. However, the
405 abrupt increase in the abundance of cysts of *P. reticulatum* prior to a rise in SSTs suggests that
406 the latter is at least partly, if not entirely, controlled by water mass changes not linked to
407 obliquity changes. The oceanographic change coincides with an increase in the proportions of
408 *Pinus* and other conifer pollen, reflecting a change from boreal to cool temperate climatic
409 conditions. The contemporaneous change of water masses and vegetation is indicative of an
410 immediate response of the latter to oceanographic changes.

411 5.2.4. MIS KM5 (3.212–3.184 Ma): Warmer-than-present interglacial conditions

412 Relative abundances of cysts of *P. reticulatum* increase continuously to maximum values
413 of ~64% at 3.205 Ma, with high proportions predominating until 3.197 Ma, suggesting an
414 increased influence of Atlantic water via a well-established NwAC (Figure 2). This is supported
415 by the low proportions of the cold-water tolerant taxa *F. filifera* (<11%) and *H. tectata* (<9%).
416 Increased Atlantic water influence in the Norwegian Sea and SSTs ~2°C higher when compared
417 to the Holocene average [Bachem *et al.*, 2016] coincide with relatively low SSTs in the Iceland
418 Sea [this study], resulting in a strong SST gradient and thus the presence of a proto-AF between

419 sites 642 and 907 (Figure 3). The overall high percentages of cool temperate pollen taxa are in
420 line with warmer-than-present climatic conditions (Figure 3).

421 At the end of MIS KM5, the relative abundance of conifer taxa excluding *Pinus* declines
422 after peaking at 3.189 Ma (Figure 3), indicating a shift towards predominantly boreal forests and
423 subarctic climatic conditions in northern Norway. This cooling corresponds to a drop in SSTs of
424 ~2°C in Hole 642B between 3.189 and 3.185 Ma and a contemporaneous increase in IRD, most
425 likely originating from sea-terminating ice masses on Greenland (Figure 3) [Bachem *et al.*,
426 2016]. This cooling on land is not reflected in the dinocyst assemblage changes, indicating stable
427 water masses and a change in marine and terrestrial surface temperature, possibly driven by
428 weakened obliquity and insolation forcing (Figure 2 and 3). However, while SSTs return to
429 values comparable to those before the cooling event, abundances of cool temperate pollen taxa
430 remain low, suggesting that subarctic climatic conditions persisted in northern Norway.

431 5.2.5. MIS KM4–KM2 (3.184–3.137 Ma): Cooling of the sea and land

432 Declining abundances of cysts of *P. reticulatum* and increasing proportions of *H. tectata*
433 are indicative of a reduced influence of Atlantic water after 3.189 Ma (Figure 3). During MIS
434 KM4 and KM3, a freshening of the water masses, when compared to the previous intervals, may
435 be inferred from higher proportions of cysts of *P. reticulatum* with short processes (Figure 3). In
436 the modern North Atlantic Ocean, the process length of this species shows a positive correlation
437 to sea surface salinity and density [Mertens *et al.*, 2010, 2012; Jansson *et al.*, 2014]. Hole 642B
438 SSTs only show low-amplitude changes, with values fluctuating between 12 and 14°C (Figure 3)
439 [Bachem *et al.*, 2016]. Both pollen of *Pinus* and other conifer taxa show low (<13%) and
440 decreasing abundances throughout MIS KM4 to KM2, reflecting the prevalence of boreal forest
441 and a continuous decline in forest cover in northern Norway. Proportions of *Sphagnum* spores
442 reach values as high as those during the early part of MIS M2 but are still variable, indicating a
443 repeated expansion of peatlands at the expense of forest under subarctic climatic conditions
444 (Figure 3) [Panitz *et al.*, 2016].

445 During MIS KM2, the increase in the abundances of *L. machaerophorum* suggests an
446 influence of an additional water mass, or change in taphonomy (Figure 2). The higher
447 abundances of *L. machaerophorum* are unlikely to be linked to increased nutrient availability due
448 to the contemporaneous low proportions of cysts of *P. reticulatum*, RBCs and low DBF and ABF
449 rates (Figure 2). As *L. machaerophorum* is a typical neritic species, restricted to the coastal
450 regions and vicinity of continental margins [Zonneveld *et al.*, 2013], the higher abundances in
451 Hole 642B during MIS KM2 might be an indication of an increased influence of water from the
452 inner shelf area. The process length of *L. machaerophorum* has also been correlated with salinity
453 [Mertens *et al.*, 2009; Verleye *et al.*, 2009]. In this study, specimens with reduced processes were
454 identified in the samples with high abundances of this species but not quantified. Thus, the cysts
455 might have been produced in fresher, inner shelf water and transported to the site.

456 5.3 Norwegian Sea – North Atlantic water mass exchange during the MIS M2/M1 457 transition

458 In the eastern North Atlantic, Piacenzian oceanographic changes have been inferred from
459 dinocyst assemblage changes at DSDP Site 610, IODP Site U1308 and IODP Site U1313 (Figure
460 1) [De Schepper *et al.*, 2013; Hennissen *et al.*, 2014]. The transition between full-glacial
461 conditions during MIS M2 and interglacial MIS M1 has been suggested to represent a climatic

462 evolution from glacial, similar-to-modern to warmer-than-present conditions driven by a re-
463 invigoration of the NAC in the North Atlantic around 3.285 Ma and accompanied increase in
464 northward heat transport [Naafs *et al.*, 2010; De Schepper *et al.*, 2013]. During MIS M2, cysts of
465 *P. reticulatum* are present in very low abundances at Site 610 and Site U1308, indicating the
466 absence of northward warm water transport via the NAC [De Schepper *et al.*, 2013]. If a hiatus
467 over parts of MIS M2 can be excluded in Hole 642B, relatively high proportions of this species
468 during MIS M2 (Figure 2) suggest either that Atlantic water influence prevailed or that its local
469 representation is affected by other factors than the influence of Atlantic water. These factors
470 include influx of cysts from the shelf edge [Dale and Dale, 2002] and/or higher cyst productions
471 in comparison to other species [Dale, 1976]. During the first half of MIS M2, cool climatic
472 conditions persisted in the Norwegian Sea, with high abundances of *F. filifera*, Holocene-like
473 SSTs [Bachem *et al.*, 2016] and a strong SST gradient between sites 642 and 907 (Figure 3),
474 indicating the presence of a proto-AF and similar-to-present oceanographic conditions. At the
475 same time, the presence of boreal vegetation in northern Norway also resembles modern climatic
476 conditions (Figure 3) [Panitz *et al.*, 2016].

477 In the eastern North Atlantic, warming at 3.285 Ma is seen in SST reconstructions as well
478 as an increase in the relative abundance of cysts of *P. reticulatum* at Site 610 and Site U1308 [De
479 Schepper *et al.*, 2013]. In Hole 642B, the warming is not associated with an increase in the
480 proportions of this species, but is instead evident in a decline in the abundances of *F. filifera*. The
481 warming is particularly pronounced in an increase of SSTs in the Norwegian Sea [Bachem *et al.*,
482 2017], which barely affects the SST gradient between sites 642 and 907 due to a
483 contemporaneous warming in the Iceland Sea (Figure 3). In northern Norway, cool temperate
484 climatic conditions establish at 3.283 Ma. Together, the changes suggest that the prevalence of
485 cysts of *P. reticulatum* is an expression of constant Atlantic water influence and possibly the site
486 location close to the Norwegian shelf edge. In addition, the SST increase and vegetation changes
487 mainly seem to be a response to obliquity forcing which does not affect the NwAC. Thus, the
488 warming in the Norwegian Sea, marking the MIS M2/M1 transition, is presumably mainly the
489 result of a strengthened seasonal contrast with warmer summers due to increased obliquity [e.g.
490 Haug *et al.*, 2005]. With the inflow of Atlantic water into the Nordic Seas being constrained to
491 the Iceland-Faroe Ridge and Faroe-Shetland Channel, changes in the position of the NAC during
492 the MIS M2/M1 transition might be restricted to the North Atlantic [De Schepper *et al.*, 2013].

493 5.4 Paleoenvironmental conditions during the Pliocene time slice (3.205 Ma)

494 To address the discrepancy in the magnitude of warming between proxy-based climate
495 reconstructions and model simulations during the mid-Piacenzian, a time slice centered on
496 3.205 Ma (3.204–3.207 Ma) has been chosen within the warm period to overcome the problem
497 of warm peak averaging [Haywood *et al.*, 2013b]. The time slice falls on a prolonged negative
498 isotope excursion (MIS KM5c) to ensure warmer-than-present climatic conditions and coincides
499 with an interval characterized by relatively stable orbital forcing, comparable to the preindustrial,
500 to reduce the influence of other forcings than higher atmospheric CO₂ concentrations [Haywood
501 *et al.*, 2013b].

502 In Hole 642B, highest abundances of cysts of *P. reticulatum* within the studied interval
503 occur at 3.205 Ma (Figure 2), indicating the presence of a well-established NwAC and maximum
504 influence of Atlantic water. At the same time, SSTs are relatively high and stable, fluctuating
505 around 14°C (Figure 3), which is in line with low-amplitude changes in obliquity [Bachem *et al.*,

506 2016]. Cool temperate pollen taxa show relatively high abundances between 3.207 and 3.205 Ma
507 (Figure 3), suggesting the presence of mixed forests and warmer-than-present climatic conditions
508 in northern Norway. A pronounced SST gradient between sites 642 and 907 (Figure 3) is
509 indicative of the presence of a proto-AF and strong surface circulation in the Nordic Seas, that is
510 a well-established NwAC and EGC. It is notable, however, that the time slice only stands out in
511 the dinocyst record relative to the signal seen during the other mid-Piacenzian interglacials
512 (Figure 3).

513 The high-resolution, multi-proxy record from Hole 642B highlights high-frequency, low-
514 amplitude climate variability during the mid-Piacenzian, with climatic conditions fluctuating
515 between warmer-than-present and similar-to-modern in the Norwegian Sea region. This study
516 underlines the value of focusing on a time slice for data-model comparison to reduce
517 uncertainties related to regional climate variability.

518 **6 Conclusions**

519 This study integrates a new mid-Piacenzian record of dinocyst assemblage changes from
520 ODP Hole 642B in the Norwegian Sea with an alkenone and pollen and spore record from the
521 same site to investigate the link between surface water masses, SSTs and terrestrial climate. Our
522 study shows regional climate changes in response to variations in northward heat transport via
523 the NwAC and/or obliquity forcing. We identified five major climate changes in the Norwegian
524 Sea and on the Scandinavian mainland:

525 1) MIS M2/M1: Similar-to-present oceanographic and terrestrial conditions prevail
526 during the first half of MIS M2. The end of MIS M2 is characterized by warming of surface
527 waters at c. 3.283 Ma which is accompanied by a change from boreal to cool temperate
528 vegetation in northern Norway. The dinocyst record indicates no change of the NwAC,
529 suggesting a constant inflow of Atlantic water into the Norwegian Sea and obliquity changes as
530 the main driver of the warming.

531 2) MIS M1: During the early part of MIS M1, cooling leads to the re-establishment
532 of climatic conditions comparable to present and boreal vegetation in northern Norway.

533 3) MIS KM6/KM5: The cooling recorded in the dinocyst and pollen record that
534 commenced at the beginning of MIS M1 culminates in the first half of MIS KM6. A weak
535 surface ocean circulation appears to prevail in the Nordic Seas as seen in the absence of a zonal
536 gradient between the Norwegian and Iceland Sea. The NwAC might have weakened in response
537 to warmer winters as a result of reduced obliquity. A strong increase in marine and terrestrial
538 surface temperatures at c. 3.222 Ma correlates with strengthened obliquity forcing. However, the
539 dinocyst record indicates that a contemporaneous increase in northward heat transport via the
540 NwAC may have also played an important role.

541 4) MIS KM5c: The influence of the NwAC is strongest within the studied time
542 interval, resulting in a strong SST gradient between the Norwegian and Iceland Sea and thus a
543 enhanced surface ocean circulation. Alkenone-derived SSTs in the Norwegian Sea are $\sim 2^{\circ}\text{C}$
544 higher than the Holocene average and warmer-than-present climatic conditions prevail in
545 northern Norway.

546 5) MIS KM4–KM2: A reduced influence of the NwAC is accompanied by relatively
547 cool SSTs and the establishment of boreal vegetation and subarctic climatic conditions in
548 northern Norway.

549 Our study demonstrates the importance of using assemblage studies and linking evidence
550 from both marine and terrestrial proxies to better understand how ocean currents and orbital
551 forcing control climate variability of the high latitudes in a warmer-than-present world.

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814

815 **Tables**

816 **Table 1.** Taxonomic names with full authorial citations of dinoflagellate cyst and acritarch taxa
 817 [following *Williams et al.*, 2017] from the mid-Piacenzian of ODP Hole 642B.

Dinoflagellate cysts

Achomosphaera andalouisiensis Jan du Chêne 1977 emend. Jan du Chêne and Londeix 1988
Achomosphaera andalouisiensis subsp. *andalouisiensis* Jan du Chêne 1977 emend. Jan du Chêne and Londeix 1988
Achomosphaera andalouisiensis subsp. *suttonensis* Head 1997
Achomosphaera ramulifera (Deflandre 1937) Evitt 1963
Amiculosphaera umbraculum Harland 1979
Ataxiodinium choane Reid 1974
Ataxiodinium Reid 1974
Ataxiodinium zevenboomii Head 1997
Barssidinium Lentin, Fensome and Williams 1994
Barssidinium graminosum Lentin, Fensome and Williams 1994
Barssidinium pliocenicum (Head 1993) Head 1994 emend. De Schepper and Head 2004
Batiacasphaera micropapillata complex sensu Schreck and Matthiessen (2013)
Bitectatodinium raedwaldii Head 1997
Bitectatodinium? *serratum* Head, Norris and Mudie 1989
Bitectatodinium sp. A of De Schepper et al. (2017)
Bitectatodinium Wilson 1973
Bitectatodinium tepikiense Wilson 1973
Brigantedinium Reid 1977 ex Lentin and Williams 1993
 cf. *Cerebrocysta?* *namocensis* Head, Norris and Mudie 1989
Corrudinium harlandii Matsuoka 1983
Corrudinium? *labradori* Head, Norris and Mudie 1989
Corrudinium Stover and Evitt 1978
 Cyst of *Pentapharsodinium dalei* Indelicato and Loeblich III 1986
 Cysts of *Protoceratium reticulatum* (Claparède and Lachmann, 1859) Bütschli 1885
Dapsilidinium pseudocolligerum Stover 1977
Echinidinium Zonneveld 1997 ex Head, Harland and Matthiessen 2001
Filisphaera filifera Bujak 1984
Filisphaera microornata (Head, Norris and Mudie 1989) Head 1994
Filisphaera Bujak 1984
Habibacysta tectata Head, Norris and Mudie 1989
Heteraulacacysta sp. A of Costa and Downie (1979)
Impagidinium aculeatum (Wall 1967) Lentin and Williams 1981
Impagidinium pallidum Bujak 1984
Impagidinium paradoxum (Wall 1967) Stover and Evitt 1978
Impagidinium patulum (Wall 1967) Stover and Evitt 1978

Impagidinium solidum Versteegh and Zevenboom in Versteegh 1995
Impagidinium sp. 2 of De Schepper and Head (2009)
Impagidinium Stover and Evitt 1978
Invertocysta lacrymosa Edwards 1984
Invertocysta sp. 1
Invertocysta Edwards 1984 /*Amiculosphaera* Harland 1979
Lejeunecysta catomus ? Harland et al. 1991
Lingulodinium machaerophorum (Deflandre and Cookson 1955) Wall 1967
Melitasphaeridium choanophorum (Deflandre and Cookson, 1955) Harland and Hill 1979
Melitasphaeridium sp. A of De Schepper and Head (2008)
Melitasphaeridium (Deflandre and Cookson, 1955) Harland and Hill 1979
Nematosphaeropsis labyrinthus (Ostenfeld 1903) Reid 1974
Nematosphaeropsis lativittata Wrenn 1988
Nematosphaeropsis Deflandre and Cookson 1955 emend. Williams and Downie 1966
Operculodinium? *eirikianum* var. *eirikianum* Head 1997
Operculodinium centrocarpum s.s. (Deflandre and Cookson, 1955) Wall 1967/*Operculodinium israelianum* (Rossignol 1962) Wall 1967
Operculodinium janduchenei Head, Norris and Mudie 1989
Operculodinium Wall 1967 emend. Matsuoka, McMinn and Wrenn 1997
Pyxidinopsis braboi De Schepper, Head and Louwye 2004
Round brown cysts
Selenopemphix conspicua de Verteuil and Norris 1992
Selenopemphix dionaeacysta Head, Norris and Mudie 1989
Selenopemphix cf. *islandensis* Verhoeven and Louwye 2012
Selenopemphix nephroides (Benedek 1972) Bujak in Bujak et al. 1980
Selenopemphix nephroides - small variety (c. 20µm)
Selenopemphix Benedek 1972 emend. Bujak in Bujak et al. 1980
Spiniferites elongatus Reid 1974
Spiniferites falcipediis Warny and Wrenn 1997
Spiniferites mirabilis (Rossignol 1964) Sarjeant 1970
Spiniferites membranaceus (Rossignol 1964) Sarjeant 1970
Spiniferites ramosus (Ehrenberg 1838) Mantel 1854
Spiniferites Mantell 1850 emend. Sarjeant 1970 /*Achomosphaera* Evitt 1963
Tectatodinium pellitum (Wall 1967) Head 1994
Trinovantedinium glorianum (Head, Norris and Mudie 1989) de Verteuil and Norris 1992
Trinovantedinium Reid 1977 emend. de Verteuil and Norris 1992
Tuberculodinium vancampoe (Rossignol 1962) Wall 1967
Dinocyst spp.

Acritarchs

Cymatiosphaera? aegirii De Schepper and Head 2014
Cymatiosphaera? fensomei De Schepper and Head 2014
Cymatiosphaera? icenorum De Schepper and Head 2014
Cymatiosphaera? invaginata Head, Norris and Mudie 1989
Lavradosphaera canalis De Schepper and Head 2014
Lavradosphaera crista De Schepper and Head 2008
Nannobarbophora walldalei Head 1996

819 **Figure captions**

820 **Figure 1.** Modern oceanographic setting and vegetation of Norway. Location of (A) Ocean
 821 Drilling Program (ODP) Site 642 in the Norwegian Sea (green circle, this study), Site 907
 822 (yellow circle, this study) in the Iceland Sea, Deep Sea Drilling Project Site (DSDP) 610 and
 823 International Ocean Drilling Program (IODP) sites U1308 and U1313 in the North Atlantic
 824 (black circles). (B) Modern vegetation of Norway modified after *Moen* [1987]. In (A), color
 825 gradient of currents from red to light orange indicates decreasing water temperatures and blue
 826 designates cold currents. EGC = East Greenland Current, NAC = North Atlantic Current and
 827 NwAC = Norwegian Atlantic Current.

828 **Figure 2.** Dinoflagellate cyst (dinocyst) assemblages from ODP Hole 642B in the Norwegian
 829 Sea. (a) Global benthic oxygen isotope stack from *Lisiecki and Raymo* [2005] and the 5-point
 830 smoothed benthic oxygen isotope curve for Hole 642B from *Risebrobakken et al.* [2016]; (b–c)
 831 orbital solutions for mean daily insolation and obliquity from *Laskar et al.* [2004]; (d–f) relative
 832 abundance (colored lines) and concentration (black lines) of the dinocyst species *H. tectata*, *F.*
 833 *filifera* and cysts of *P. reticulatum*; (g) dinocyst burial flux (DBF, line with gray dots) and total
 834 dinocyst concentration (line with vertical bars); and (h) Dinocyst assemblage composition in
 835 Hole 642B. Dark gray vertical bar indicates the possible presence of an hiatus over the most
 836 extreme part of marine isotope stage M2 [*Risebrobakken et al.*, 2016]. Light red bar marks the
 837 time slice chosen for data-model comparison [*Haywood et al.*, 2013b].

838 **Figure 3.** Paleoceanographic and paleoterrestrial proxy records from ODP Hole 642B in the
 839 Norwegian Sea. (a) Obliquity after *Laskar et al.* [2004]; (b–c) conifer taxa excluding *Pinus*
 840 (green), relative abundances of *Pinus* pollen (gray) and *Sphagnum* spores (blue); (d) acritarch
 841 burial flux (ABF, line with gray dots) and total acritarch concentration (line with vertical bars);
 842 (e) ice rafted debris (IRD) concentrations; (f) alkenone-based sea surface temperature (SST)
 843 estimates for ODP Hole 642B (orange, solid line) [*Bachem et al.*, 2017] and Holocene mean SST
 844 at nearby Site MD95–2011 (orange, dashed line) [*Calvo et al.*, 2002], and alkenone-based SSTs
 845 for ODP Hole 907A (brown, solid line) [this study] and Holocene mean SST at nearby Site
 846 GS15-198-62 MC-A (brown, dashed line) [*Bachem et al.*, 2017]; (g) SST gradient (gray shading)
 847 between Site 642 and 907 calculated by subtracting the records after interpolating to 1 kyr
 848 resolution. Black line is the 5-point running average; (h) relative abundance of cysts of *P.*
 849 *reticulatum* (yellow line), cysts of *P. reticulatum* with short processes (filled yellow area), *F.*
 850 *filifera* (light blue) and *H. tectata* (dark blue). Dark gray vertical bar indicates the possible
 851 presence of an hiatus over the most extreme part of marine isotope stage M2 [*Risebrobakken et*
 852 *al.*, 2016]. Light red bar marks the time slice chosen for data-model comparison [*Haywood et al.*,
 853 2013b].