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A reference data set for similar Cenozoic systems

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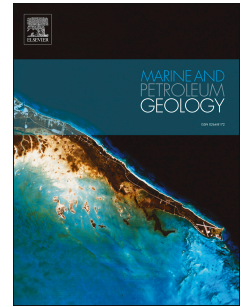
1 **Running head: PALYNOFACIES REFERENCE DATA SET FOR THE LOWER MIOCENE IN THE NORTH**

2 **SEA BASIN**

3

4 **Title: A PALYNOFACIES STUDY OF PAST FLUVIO-DELTAIC AND SHELF ENVIRONMENTS, THE**

5 **OLIGOCENE-MIOCENE SUCCESSION, NORTH SEA BASIN: A REFERENCE DATA SET FOR SIMILAR**

6 **CENOZOIC SYSTEMS**

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18 Key words: Palynofacies, depositional environments, fluvio-deltaic, Miocene, North Sea Basin
19
20 **ABSTRACT**
21
22 Correct interpretations of depositional environments are fundamental for evaluating the

23 geological history of a sedimentary basin. Palynofacies analyses are a valuable supplement to

24 sedimentological and seismic studies. In order to develop a palynofacies reference dataset for

25 fluvio-deltaic and shelfal successions, a study of the assemblages of sedimentary organic particles

26 from seven different well-defined depositional environments within the uppermost Oligocene –

27 lower Miocene succession onshore Denmark (eastern North Sea Basin) has been performed. The

28 study deals with the following environments; floodplain, lagoon, washover-fan flat, prodelta,

29 shoreface, offshore transition and shelf.

30

31 The sedimentary organic particles were grouped into four major categories; 1) Structured wood

32 particles, 2) Amorphous organic matter (AOM, in the present study mainly consisting of partly

1

33 degraded vitrinite), 3) Cuticle and membranes and 4) Palynomorphs. The palynomorphs were

34 grouped into eight subcategories; 1) Microspores, 2) Non-saccate pollen, 3) Bisaccate pollen, 4)

35 *Botryococcus*, 5) Other freshwater algae, 6) Fungal hyphae and –spores, 7) Acritarchs and 8)

36 Organic-walled dinoflagellate cysts.

37

38 A combination of a univariate box plots and a multivariate Principal Component Analysis (PCA) of

39 the palynofacies data clear revealed the quantitative characteristics and variations within each

40 discrete environment as well as their principal similarities and differences. In spite of some natural

41 overlaps, for example between the lagoon and offshore transition environments, the data

42 revealed distinct characteristics, e.g. a strong dominance of wood particles in the shoreface

43 environment, a strong dominance of bisaccate pollen in the washover-fan flat environment and a

44 near absence of dinocysts in the floodplain environment. An overall increase in relative

45 abundances of dinocysts and a decrease in abundances of non-saccate pollen in the proximal-

46 distal trend were also outlined.

47

48 This study outlines a palynofacies reference dataset that can be used as a tool for interpreting

49 depositional environments in equivalent settings, preferentially combined with other information

50 such as seismic data, well logs, and/or lithology.

51

52   **1 INTRODUCTION**

53

54 During the last 15 years the uppermost Oligocene to Miocene succession onshore Denmark has

55 been studied intensively, with main the purpose to develop a 3-dimensional model for the fluvio-

56 deltaic sand layers within the succession, as they are important groundwater reservoirs (aquifers).

57 A huge dataset from more than 50 boreholes, 25 outcrops and a number of seismic profiles has

58 been generated and the geological development in the area is therefore very well known (Fig. 2)

59 and well documented through a series of papers, e.g. Rasmussen (2004a; 2004b; 2014),

60 Rasmussen and Dybkjær (2005), Rasmussen et al. (2006; 2010), Hansen and Rasmussen (2008) and

61 Dybkjær and Piasecki (2010).

62

2

63   The assemblage of sedimentary organic particles (the palynofacies) in a sediment sample reflects

64   the depositional environment in which the sediment was deposited. Different depositional

65   environments will have a different composition of organic particles, e.g. lagoonal clay will have a

66   higher content of terrestrial palynomorphs (spores and pollen) and of freshwater algae than for

67   example clay deposited in an offshore setting. In contrast, offshore clay will contain higher relative

68   abundances of marine algae, e.g. dinoflagellate cysts (dinocysts) – see also the comprehensive

69   evaluations of this matter by Traverse (1994) and Tyson (1995) and references therein.

70

71   Palynofacies studies are therefore a good tool for interpreting the depositional history of a study

72   area, providing information about; i) The type of sedimentary setting (i.e. either marine, brackish

73   or freshwater) (Traverse 1994; Tyson 1995). ii) Deepening or shallowing upwards trends for a

74   succession. Increase in e.g. non-saccate pollen, microspores and/or freshwater algae and fungal

75   hyphae and spores in a succession otherwise interpreted to be fully marine, may be a good

76   indication of a prograding coastline, either due to a eustatic sea-level fall or to increased

77   sedimentation rates. In contrast, an increase in abundance of dinocysts and of bisaccate pollen is a

78   good indicator of deepening/flooding events (Tyson 1995; de Vernal 2009). iii) Positions and types

79   of stratigraphic surfaces such as sequence boundaries, flooding surfaces and other surfaces

80   important for subdividing into system tracts and thus strengthening the predictive tool of

81   sequence stratigraphy (Tyson 1995). Sequence boundaries may be identified as a break in the

82   natural succession of environments, indicating an unconformity (Catuneanu et al. 2011). Flooding

83   surfaces may, in the distal parts of a fluvio-deltaic system, be recognized as levels with increased

84   abundances of dinocysts. In more proximal portions, a flooding surface may be indicated by a

85   sudden influx of dinocysts into an otherwise fluvial succession (Tyson 1995). iv) Positions and types

86   of system tracts, e.g. forced regression and transgressive system tracts. The former should be

87   identified by a dominance of floodplain environments and the latter by the dominance of lagoonal

88   and estuarine environments (Rasmussen 2009a). Good reservoirs are commonly associated with

89   forced regression; clean and thick sand deposits have for instance been found on the delta

90   platform of the Billund Formation (Rasmussen and Bruun-Petersen 2010). Well-developed basin-

91   floor fans are also commonly associated with forced regression (Hunt and Tucker 1992). Tidal bars

3

92 and barrier complexes are the typical reservoirs found in transgressive system tracts (Catuneanu

93 et al. 2011).

94

95 In order to interpret the palynofacies data from a specific sediment sample, or a series of samples,

96 it is helpful to have a robust and synoptic reference dataset from a comparable and coeval

97 succession; same time-interval, similar climate (humid, warm-temperate), similar tectonic regime

98 – ideally from the same basin. The purpose of the present study was to develop a robust reference

99 dataset of palynofacies that documents the characteristic assemblages of organic particles within

100 seven sedimentologically well-constrained shallow-marine depositional paleo-environments. The

101 palynofacies data are obtained from sediment samples collected from the uppermost Oligocene –

102 lower Miocene succession onshore Denmark (eastern North Sea Basin). The succession covers

103 seven environments; Floodplain, lagoon, washover-fan flat, prodelta, shoreface, offshore

104 transition and shelf (Fig. 1). The distribution of palynofacies is presented in univariate box plots.

105 The data are also analysed using multivariate data analysis, Principal Component Analysis (PCA),

106 targeting the palynological data in the conventional format using relative frequencies based on the

107 total number of counts, see further below. The PCA approach reveals simultaneous discriminating

108 trends and correlations between all characterizing variables used in the study, both discriminating

109 features *between* the depositional environments as well as the dominant *within*-environment

110 specifics. As part of the PCA a small number of distinct *outliers* were identified, which were

111 carefully documented and investigated. Comprehensive arguments are presented for why these

112 were removed from analysis of the coherent core of the data corpus. The reference dataset

113 presented here will provide an important supplementary help for interpretation depositional

114 environments from coeval successions.

115

116

117   *1.1 Previous studies*

118

119 Studies of the distribution of sedimentary organic particles in recent environments have formed

120 the base for interpreting palynofacies data obtained from older deposits. In the classical study

121 from the Orinoco delta, Muller (1959) studied the distribution of sedimentary organic particles in

4

122 different parts of the delta, especially the dispersal of pollen grains. His results illustrated the

123 gradual settling of pollen in the marine environment during transport away from the source area

124 (the local swamp areas and the river mouths). Muller (1959) concluded that "palynology, in

125 conjunction with sedimentological studies, can make a valuable contribution to paleogeographic

126 interpretation". Mudie (1982) studied the spore- and pollen distribution in recent marine

127 sediments off eastern Canada. She concluded that the overall pollen and spore concentrations

128 decreased offshore as a function of distance from vegetation sources (and northwards as a

129 function of lower vegetation density north of the summer Arctic Frontal Zone). In addition, she

130 registered a selective offshore transport of bisaccate pollen, which she interpreted as reflecting

131 wind transport combined with the floating abilities of bisaccate pollen ("Neves effect") (Traverse

132 1994).

133

134 One of the studies dealing with the palynofacies analysis in a geological record was published by

135 Roncaglia and Kuijpers (2006). They studied palynofacies assemblages from the last 1500 years in

136 sediments from Greenland, in the Faroe Islands fjords and from North Atlantic deep-water sites.

137 They concluded that the distribution of particulate organic matter at high latitudes is controlled by

138 the distance from the shore and water depth.

139

140 One example of a combined palynofacies and palynological study from the Cenozoic in the North

141 Atlantic region comprise the study of Eldrett and Harding (2009) in which they reconstructed the

142 subsidence history of the Eocene–Oligocene transition on the Outer Vøring Plateau (the

143 Norwegian - Greenland Sea).

144

145 Palynofacies studies and studies of pollen assemblages of the late Eocene to Miocene succession

146 at the New Jersey margin, were used to interpret changes in vegetation, climate and relative sea-

147 level (e.g. McCarthy et al. 2013; Kotthoff et al. 2014; Prader et al. 2017).

148

149 In a series of three recent publications McArthur et al. (2016a, 2016b, 2017) presented a

150 palynofacies classification scheme aiming to assist the interpretation of submarine fan

151 environments. Their study is based on samples from the well-studied outcrops of the Miocene

152 Marnoso-Arenacea Formation, Appenines, northern Italy.

153

154 Previous (traditional) palynofacies studies from the upper Oligocene – Miocene in the North Sea

155 Basin are confined to Dybkjær (2004); Rasmussen and Dybkjær (2005), Rasmussen et al. (2006)

156 and Śliwińska et al. (2014). These studies all present palynofacies analysis closely corresponding to

157 the one presented here, aiming to supply data useful for the interpretation of the depositional

158 environments. Larsson et al. (2010) studied the spore- and pollen assemblages in the uppermost

159 Oligocene – lowermost Miocene successions in the Dykær and Hindsgavl outcrops in the eastern

160 part of Jylland, and included the relative abundances of *Botryococcus* and the marine versus

161 terrestrial palynomorph-ratio in addition. An increase in the relative abundance of bisaccate

162 pollen was interpreted to indicate an increase in relative sea-level (the "Neves-effect") rather than

163 a change towards a colder climate. In a study from the southern part of the North Sea Basin

164 Donders et al. (2009) applied the relative amount of terrestrial palynomorphs for indicating

165 variations in terrestrial run-off. Furthermore, they used variations in the dinocyst assemblages for

166 interpreting variations in sea surface temperatures and variations in the pollen records for

167 interpreting variations in terrestrial temperatures.

168

169

170

171   **2 GEOLOGICAL SETTING**

172

173 The eastern North Sea Basin area was formed as a result of Mesozoic rifting and subsequent

174 thermal sagging (Ziegler 1990). In the late Mesozoic and Tertiary inversion tectonism dominated

175 the development of the basin (Ziegler 1990; Mogensen and Kortsgård 1993; Rasmussen 2009b;

176 2013). One of these inversion pulses was in the Miocene. The overall compressional regime

177 formed by the Alpine Orogeny and the opening of the North Atlantic, also resulted in uplift of the

178 Fennoscandian Shield during the Neogene (Japsen et al. 2007; Gabrielsen et al. 2010). Due to uplift

179 of the shield, sediments were shed into the basin from the north and northeast.

6

180 In the Late Oligocene a shelf setting dominated. The water depth was more than 200 m (e.g.

181 Rasmussen et al 2010). The basin was sediment starved which resulted in the formation of

182 glaucony rich sediments. Associated with inversion of the Norwegian-Danish Basin in the latest

183 Oligocene, transient progradation of the shoreline occurred, but the shoreline only reached the

184 easternmost part of the study area.

185 In the early Miocene the North Sea was a restricted basin, with only a narrow connection to the

186 North Atlantic between the Shetland Islands and present day Norway. The lower Miocene

187 succession comprise three periods of shoreline progradation (Fig. 2). The first two prograding

188 systems, the Billund and Bastrup formations (Fig. 3), consist of wave-dominated deltas. The delta

189 progradation occurred into water depth of up to 100 m. Due to the location in the westerly

190 dominated wind-belt, spit and barrier systems with lagoons formed southeast of the main deltas

191 (Rasmussen and Dybkjær 2005; Rasmussen et al. 2010). In the initial phase, associated with

192 inversion tectonism, braided fluvial river-systems dominated, but later in the early Miocene, the

193 rivers were predominantly meandering river-systems (Rasmussen 2009b; 2015; Rasmussen et al.

194 2010). The third prograding system, the Odderup Formation, was formed in shallow water and

195 thus characterized by coastal plains with widespread lagoons and swamps. The three prograding

196 systems are separated by marine mud referred to the Vejle Fjord, Klintinghoved and Arnum

197 formations. This overall pattern of progradation and transgression was controlled strongly by

198 eustatic sea-level changes and correlate with the so-called Mi glaciations (Miller et al 1991;

199 Rasmussen 2004a). The climate was warm temperate to subtropical and humid, ca. 1500 mm

200 annual precipitation (Larsson et al. 2011; Rasmussen et al. 2013). The coastal areas were

201 dominated by Taxodium swamp forests also hosting other angiosperms such as *Alnus*, *Betula*,

202 *Nyssa* and *Salix*. A mixed deciduous-evergreen forest hosting e.g. *Areacaceae*, *Carya*, *Engelhardia*,

203 *Fagus*, *Ilex*, *Liquidambar*, *Podocarpus*, *Sabal* and *Ulmus* prevailed further inland, while

204 gymnosperm conifer forests of *Abies*, *Cathaya*, *Larix*, *Picea*, *Pinus*, *Sequoia* , *Sciadopitys* and *Tsuga*

205 grow in the more well-drained hinterland and in elevated areas (Larsson et al. 2010; 2011).

206

207   **3 DEPOSITIONAL ENVIRONMENTS**
208

7

209 The samples included in the palynofacies study come from one of the following seven well-

210 documented depositional environments; floodplain, lagoon, washover-fan flat, prodelta,

211 shoreface, offshore transition and shelf (Fig. 1). In the following, the criteria for identifying each of

212 these environments/facies associations, based on sedimentology and seismic data, will be

213 presented. Samples were preferentially taken from outcrops. Outcrops provide the most reliable

214 identification of the depositional environments. However, the prodelta and shelf environments

215 were not represented in outcrops and samples from these environments thus had to be collected

216 from boreholes. See Figure 4 for the location of outcrops and boreholes. In the boreholes, the

217 seismic patterns combined with lithology formed the basis for identifying the depositional

218 environments. A correlation of the studied outcrops and boreholes is presented in Figure 5. This

219 correlation shows how the interpretations of the outcrops and borehole successions have

220 supported each other. No samples have been analysed from the "delta plain" and the "fluvial sand

221 and gravel" environments. Samples from the former environment have never been sampled for

222 palynology, while deposits from the latter environment does not contain any organic

223 microparticles due to the very high energy level in this environment. Each of the sampled

224 boreholes are located close to a seismic line and the depositional environment of the intersected

225 successions has been interpreted based on a combination of the seismic data and the borehole

226 log/lithology (Rasmussen and Dybkjær 2005; Hansen and Rasmussen 2008; Rasmussen 2009a;

227 2014) (Fig. 6). The interpretations of the depositional environments in the outcrops are based on

228 detailed sedimentological studies, including studies of lithology variations, sedimentary structures

229 and tracefossils (Friis et al. 1998; Rasmussen and Dybkjær 2005; Rasmussen 2014) (Figure 7a-h).

230 The tracefossils terminology applied in our study is described in McIlroy (2004).

231 The abbreviations indicated in parentheses after each subheading below are those

232 used for the depositional environment/facies association in question in the PCA analysis (Figs. 10-

233 20; Appendices 1a,b). Each abbreviation is followed by a color denoting the polygon representing

234 the specific depositional environment/facies association in the PCA-plots.

235

236 **Flood-plain Facies Association (F; green);** The flood-plain facies association is composed of dark

237 brown mud alternating with sand layers up to 10 cm in thickness (Fig. 7a). The sand layers are

238 homogenous to inverse graded and interpreted as crevasse splays (Rasmussen 2014). Rootlets are

8

239 found in the upper part of crevasse splays. Thin coal-layer and scattered macro-scale wood

240 particles are common (Fig. 7b).

241

242 **Lagoonal Facies Association (L; purple);** The lagoonal facies association consists of dark brown

243 mud with an organic content of 5 to 10 % (Fig. 7c). The facies association is normally heavily

244 bioturbated, but discrete wave-ripples and tidal rhytmites may be visible (Rasmussen and Dybkjær

245 2005). Lignite occurs especially in the upper part of the facies. A lag of lignite may occur capping

246 the facies.

247

248 **Washover-fan flat Facies Association (W; orange);** The washover-fan flat facies association (NCSS

249 2005) is dominated by fine-grained, yellowish to white sand deposited as washover fans

250 (Rasmussen and Dybkjær 2005; Rasmussen et al 2010; Fig. 7c). The succession formed gently

251 dipping clinoforms. The trace fossil assemblage is characterized by *Macaronichnus* (Fig.7d), but

252 *Ophiomorpha* and *Diplocraterion* may occur.

253

254 **Shoreface Facies Association (SF; yellow);** The shoreface facies association (i.e. Dashtgard 2012) is

255 composed of white, fine- to medium-grained sand. Hummocky -, swaley cross-stratified sand and

256 other tempestites, dominate the facies association (Fig. 7e). Thin, light brown mud beds occur in

257 isolated troughs in the distal part of the facies or associated with fair-weather wave ripples

258 (Rasmussen and Dybkjær 2005; Rasmussen et al. 2010). The trace fossil assemblage is dominated

259 by *Ophiomorpha* (Fig. 7f), but *Skolithos* and *Diplocraterion* has also been found.

260

261 **Prodelta Facies Association (P; brown);** This facies association, corresponding to delta platform

262 slope facies, is limited to successions covered by seismic data and boreholes (Fig. 6). It consists of

263 alternating dark brown mud and white, medium to cross-grained sand. Amalgamation of sand is

264 common in the upper part of the delta platform succession and dominates the down drift portion

265 of the delta platform (Rasmussen and Bruun-Petersen 2010). Pebbles occur as lags at the base of

266 discrete sand beds and clasts up to 4 cm are found scattered within the succession. On seismic

267 data, the prodelta facies is characterized by clinoforms dipping 2 to 7 degrees and migration

268 azimuths of 135° to 225°. The clinoform height is commonly between 50-100 m.

269

270 **Offshore Transition Facies Association (O; dark blue);** Offshore transition facies association

271 consists of alternating brown to dark brown mud and wave-rippled sand. Hummocky cross-

272 stratified sand layers (Fig.7g) are common in the proximal part of the offshore mud. The trace

273 fossil assemblage is characterized by *Scolicia, Schaubcylindrichnus* and *Chondrites* (Fig. 7h).

274

275 **Shelf Facies Association (S; light blue);** A shelf is defined by a depositional package with a low

276 gradient surface (< 0.1 degree) and formed at water depths of more than 70 m (Fig. 1). The shelf

277 facies association is represented only in successions covered by seismic data and boreholes (Fig.

278 6). It is composed of dark brown and dark gray mud. The pyrite content is between 1 and 10 %

279 (Rasmussen and Larsen 1989; Rasmussen 1995) and at certain levels glaucony is common. The

280 organic content varies from 2 to 5 %. Shells are present but mostly dissolved.

281

282   **4 MATERIAL AND METHODS**

283

284 Spreading, transport and deposition of organic particles is a complex story with many influencing

285 factors. The origin of the organic particles (terrestrial vs. marine) and the transport mechanisms

286 (e.g. wind, water) are important. The depositional energy-level has a strong sorting effect and

287 post-depositional degradation has different impact on selected particles. For more detailed

288 discussions of these effects, see e.g. Traverse (1994), Tyson (1995) and Appendices 2a,b.

289   During the latest Oligocene – early Miocene time, swamp forests, covering large

290 parts of the coastline, delivered large amounts of wood particles, partly degraded vitrinite (here

291 referred to as amorphous organic matter, AOM, see example in Fig. 8 D) and cuticle to the

292 lagoonal and nearshore marine depositional settings. Terrestrial palynomorphs (spores and pollen)

293 were deposited on land and in ponds and lakes, and some of them were transported to the sea by

294 wind, streams and rivers. Some of the terrestrial palynomorphs were probably deposited directly

295 into lagoons and in the sea from the swamp forest covered shorelines. Limnic/fluvial

296 palynomorphs (freshwater algae, e.g. *Pediastrum*, *Mougeotia laetevirens*, *Pseudokomewuia* aff.

297 *granulata* and the brackish-water tolerant freshwater algae *Botryococcus*) thrived in freshwater

298 and brackish-water environments (floodplains, ponds, lakes, lagoons) and were transported into

299 the sea via the large rivers and delta-systems (e.g. Friis 1975, 1977, 1978; Koch 1989; Larsson

300 2006; 2010; Rasmussen et al. 2010). At the same time marine algae, especially dinoflagellates,

301 thrived in the marine depositional environment (Rasmussen and Dybkjær 2005; Dybkjær and

302 Piasecki 2010; Śliwińska et al. 2014). The variations through time, in the studied succession, in the

303 relation between the terrestrial/fluvial and the marine palynomorphs probably reflect the global

304 climatic variations in the latest Oligocene – early Miocene and the resulting variations in eustatic

305 sea-level (e.g. Miller et al. 2005).

306   In the following collection of a series of samples representing the fluvio-deltaic and

307 shelf environments in the uppermost Oligocene – lower Miocene succession in the western part of

308 Denmark was carried out. The preparation and counting methods are outlined and the methods

309 used for data analysis are presented.

310

311   *4.1 Sampling*

312

313 The present study is based on a total of 169 sediment samples, collected from 6 boreholes and 11

314 outcrops (Figs. 4, 5). All analysed samples are listed in Appendices 1a,b.

315

316 Outcrop samples were collected during a total of 17 years of fieldwork campaigns in the period

317 1999-2016. The samples were selected randomly from each of the well-defined depositional

318 environments in an attempt to represent the environment facies as objectively as possible. The

319 palynological analyses of the borehole samples were performed in the same period.

320

321 The samples were collected from a succession deposited between 25 and 21 Ma, i.e. representing

322 the uppermost Oligocene – lower Miocene. At any specific field location, the depositional

323 environment varied through this timespan as the relative sea-level changed, partly due to

324 tectonism and partly due to changes in the global climate (Zachos et al. 2001; Miller et al. 2005)

325 (Figs. 2, 3). Therefore, the sampled succession (as observed in sediment cores and outcrops)

326 represent different, but generically related parts of the geological history of the study area (Fig. 5).

327

328 In order to gain enough palynomorphs to make a proper data analytical analysis, all samples were

329 selected from clayey sediment. In e.g. the sand-dominated shoreface environment, palynomorphs

330 are generally rather sparse due to sorting effects. Therefore, only the thin clay-laminae

331 representing fair weather conditions were selected for the present study (Fig. 7f).

332

333 The aim of the present study is to provide a reference dataset which is useful for a wide group of

334 palynologists, not necessarily experts in Miocene dinocysts – or multivariate data analysis for that

335 matter - and simultaneously not too time-consuming. Therefore, the dinocysts were not separated

336 into different taxa, although finer resolution variations in the dinocyst assemblages could perhaps

337 have been useful in characterising the different depositional environments in even more detail

338 than the present, see further the discussion. This would however require some degree of expertise

339 in identification of the uppermost Oligocene to Miocene dinocysts. For the present purpose,

340 grouping all dinocysts in one classification unit is considered sufficient.

341

342 This sampling approach makes the relative frequency of the sedimentary organic particles and

343 palynological variables used in data analysis contingent upon the assumption that random samples

344 from the clay-containing layers can be viewed as representative of the full variability of the

345 influencing depositional environments.

346

347

348   *4.2 Preparation of samples*

349 In order to extract the organic particles for the palynofacies study, all sediment samples were

350 processed in the Palynological Laboratorium at GEUS. The preparation included the following

351 steps:

352 1) Drying the sediment sample and crushing it to all particles are <2mm. Approximately 20 gr. of

353   the well-mixed, dried sediment sample were extracted and used for further treatment.

354   2) Dissolution of carbonates using HCl 3.5% to end of reaction followed by HCl 17.5% for 24

355   hours. Followed by treatment with 70°C warm, mild solution of citric acid.

356   3) Dissolution of silicates using cold HF (40%) for a minimum of 6 days, followed by treatment

357   with 70°C warm, mild solution of citric acid.

358   4) Brief oxidation with concentrated HNO_3 and KOH 5%.

359   5) Heavy liquid separation with ZnBr (2.3 g/ml).

360   6) Filtering on 11 µm nylon mesh.

361   7) The acid-resistant organic particles larger than 11 um are mounted in glycerine gel on glass

362   slides and studied using a normal light microscope.

363

364

365   *4.3 Counting*

366   In each sample a minimum of 200 sedimentary organic particles were identified and referred to

367   one of the four major categories; 1) Structured wood particles, 2) non-structured, partly degraded

368   vitrinite (AOM) (see below), 3) cuticle and 4) palynomorphs. Subsequently, a minimum of 300

369   palynomorphs were identified and referred to one of the following subcategories; Microspores,

370   bisaccate pollen, non-saccate pollen, *Botryococcus*, other freshwater algae, fungae (-hyphae and -

371   spores), acritarchs and dinocysts (marine algae).

372

373   Information on the origin, distribution and preservation for each of these categories is presented

374   in Appendices 2a,b. Examples of palynofacies composition from the seven depositional

375   environments are presented in Figure 8.

376   In this way, a minimum of 500 sedimentary organic particles were identified and categorized in

377   each sample, in accordance with the recommendation by Tyson (1995). In total more than 85.000

378   organic particles are included in the study. The resulting relative abundances are shown in

379   Appendices 1a,b.

380

381   The counted particles comprise both whole particles, e.g. whole pollen grains, and fragments, e.g.

382   of bisaccate pollen. Due to the preparation procedure, including sieving on 11 µm filters, all

383   counted particles are larger than 11 µm. When a category or subcategory is shown to represent

384   1%, it may just indicate that the category/subcategory is present (= minimum 1 particle referable

385   to that category/subcategory was recorded during counting).

386

387   Prasinophycean algae were recorded very rarely (below 0.5% of the total assemblage) and limited

388   to the shelf environment, and were therefore not included in the summary statistics.

389

390   Palynofacies data from the Harre-1 borehole, from 58.25m-48.25m, were previously published in

391   Śliwińska et al. (2014). Palynofacies data from the Dykær profile, from lagoonal deposits, were

392   previously published in Rasmussen and Dybkjær (2005) and these are the data used here.

393   However, in these previous studies only 200 palynomorphs were counted in each sample. For the

394   present study, counting was therefore resumed and continued until an additional 100

395   palynomorphs had been encountered to make the reference data set fully consistent.

396

397

398   *4.4 Data Analysis*

399

400   Based on the complete reference data matrix, Appendices 1a,b, this study employs Principal

401   Components Analysis (PCA) which transforms and visualizes matrices of observational/measured

402   numerical data from a series of samples (N) characterized by a number of variables (P) into sets of

403   projection sub-spaces used for visualization of 'hidden' data structures. In the present study

404   N=169 and P = 4 for the data set MVDA-I, P=12 for data set MVDA-II and P=8 for MVDA-III (see

405   further below). PCA makes use of 'principal components' which are variance-maximized

406   interrelationships between samples and variables respectively. The principal components are used

407   as a new coordinate system. Full methodological description can be found in the extensive

408   literature e.g. Esbensen and Swarbrick (2018), Esbensen and Geladi (2009), Martens and Næs

409   (1992).

410

411

412   Operationally PCA constructs 'super-variables' which are linear combinations of the P original

413   variables, used for displaying the data structure (i.e. "patterns") in the data. There can be derived

414   any number of principal components (up to P) in order to model the dominant proportions of the

415   total data variance, but often the first two (three ..) principal components capture a dominant

416   major fraction hereof, allowing a comprehensive overview of the full multivariate data structure in

417   just one or two cross-plots (see below). In this fashion, what was originally a P-dimensional issue,

418   becomes a projected, two or three-dimensional, version of the data structure, reducing the

419   complexity of the original data to a manageable few new dimensions which are much easier to

420   interpret. Thus PCA score-plots display groupings, clusters and trends between samples based on

421   the degrees of compositional similarities and differences, as described by the variable correlations

422   which are shown in accompanying loading-plots. PCA also quantifies the proportion (%) of total

423   data set variance that can be modelled by each PC-component. Thus a score plot shows the major

424   similarity, or dissimilarity, between groups of samples (for example groups of samples coming

425   from specific depositional environments) that can be delineated individually and discriminated

426   from other groups. PCA score plots comprise an easy-to-interpret, visualization tool with which to

427   overview complex within- and between-sample as well as within- and between-group

428   relationships even when expressed by a relatively high dimensionality (in the present work P

429   reaches 12). In addition, complementary scores- and loading plots easily identify aberrant

430   samples, *outliers* and/or variables displaying aberrant behavior not always constructive to analyze

431   together with the gamut of all other samples; examples are presented and described below.

432

433   With PCA, each score plot is accompanied by a complementary loading plot; the latter is a visual

434   rendition of the correlation relationships between all original P variables. The loading plot

435   represents the same reduction in dimensionality from P to the small number of new dimensions

436   (number of principal components) developed as for the score relationships. This model

437   dimensionality is a function of the objective data structure of the original data matrix (X). Some

438   data matrices can be of a particularly simple data structure requiring perhaps only two

439   components, while other data may require additional components before a satisfactory

440   proportion of the total data variance has been included in the PC-model (3,4,5.. components). The

441   effective data structure is a reflection of the complexity of the geological/palynofacies context and

442   the specific problem investigated. Model dimensionality is not a function of the number of original

443   variables, P, in fact each principal component is a linear combination of all original P variables.

444

445 By a careful inspection of pairs of complementary scores and loadings plots it is possible to

446 formulate descriptions of the visualized data patterns, often opening up for more direct scientific

447 interpretation and hypothesis generation. Such patterns usually manifest themselves as

448 prominent *between* - vs. *within* - group discriminability. E.g. individual sample clusters (data

449 groups) with appreciable (separable) in-between distances – <u>either</u> as elongated groups spanning

450 large compositional ranges while still retaining a defining data group coherence – or as *outlying*

451 *samples* (singular, or more) often signifying particularly interesting, or particularly irrelevant,

452 samples. Data groups may show little, or substantial overlaps, all as a reflection of the depositional

453 environments and their constitutent assemblages.

454

455 The reason for samples being recognizable as outliers is crucial: these may (i) represent true

456 unique events, e.g. occurrences of critical importance in the interpretation, (ii) be the result of

457 either sampling or measurement errors, identification mishaps, laboratory handling; or (iii)

458 possibly, but always difficult to prove, singular "freak" events in nature. Inclusion of outliers of the

459 latter categories in the data analytical interpretation may obscure distribution trends for the

460 majority of samples. For this reason, outliers from the second category must be removed from the

461 analysed data set. Then, the repeated PCA is better equipped to reveal the relevant data structure.

462 Outliers representing "end-members" within a recognized sample group can be excluded from

463 part of the data analysis, but should be included in the overall interpretations as they carry

464 important information about the variability within the dataset. Therefore, the first step in any

465 multivariate data analysis is to perform a careful outlier screening. For more details concerning the

466 PCA method and identification of outliers see e.g. Esbensen & Swarbrick (2018); Martens and Næs

467 (2002); Esbensen and Geladi (2009) and Esbensen et al (2015).

468 **5 DISTRIBUTION OF SEDIMENTARY ORGANIC PARTICLES - BOX PLOTS**

469

470 In Figure 9 the results from the palynofacies analysis are presented as univariate box plots. The

471 data are presented as relative abundances with a minimum and a maximum value, 25% and 75%

472 values and a median value of each category/subcategory. These data are further shown in

473 Appendices 1 a and b. Two plots are presented for the lagoonal environment due to the two

474 outliers with extremely high relative percentages of AOM; one plot includes the outliers (end-

475 members), while the other presents the data with these outliers excluded. Also for the floodplain

476 environment two plots are presented, one includes the data from the two outlier samples (end-

477 members) with extremely high relative abundances of microspores and one where data from

478 these two outlier samples have been excluded.

479 Looking at the relative abundances across the major categories, it is evident that in six out of the

480 seven environments most samples are dominated by palynomorphs (median values between 50

481 and 87%), especially the floodplain, wash-over fan flat and the offshore transition environments

482 which are characterized by medium values above 85% palynomorphs. Only the shore-face

483 environment differs from this trend, with a medium abundance of palynomorphs of only 35% -

484 most samples in this environment are dominated by wood particles (medium abundance of 57%).

485 In none of the other six environments the medium percentages of wood particles exceed 16%.

486 This dominance of wood particles probably reflects a higher wave energy, effectively sorting the

487 organic particles and prohibiting the low-density palynomorphs from settling.

488 The highest relative abundances of AOM are found in the pro-delta and shelf

489 environments (medium values of 31% and 23%, respectively), and in the lagoonal environment

490 (including the two outlier samples with 86 and 94% AOM, respectively).

491 The relative abundances of cuticle are generally very low, with the highest maximum

492 values of 12 % found in a sample from the floodplain environment.

493

494 Among the subcategories (palynomorphs), bisaccate pollen dominates in most samples and show

495 higher medium values than non-saccate pollen in all environments except for the lagoonal

496 environment. The relatively high abundances of non-saccate pollen in the lagoonal samples

497 possibly reflects the presence of Taxodium swamp vegetation (producing mostly non-saccate

498 pollen) along the shoreline forming the landwards/inner part of the lagoon.

499 In the offshore transition environment the medium values are nearly equal (25% non-saccate and

500 32% bisaccate), while there is a clear difference in the shelf and pro-delta environments (17% non-

501 saccate and 50% bisaccate in the shelf environment, and 20% and 56% in the prodelta

502 environment). This difference may reflect the so-called "Neves-effect" – according to which the

503 higher floating ability of the bisaccate pollen results in a gradually higher bisaccate/non-saccate

504 ratio in a distal direction (Traverse 1994; Tyson 1995 and references therein, Armstrong and

505 Brasier, 2005). The relatively high bisaccate/non-saccate ratio in the shoreface environment may

506 reflect that these deposits are mainly storm-deposits and thus do not reflect a normal proximal-

507 distal transport direction. The extremely high relative abundances of bisaccate pollen in the

508 washover-fan flat environment may indicate (i) either the "Neves-effect" with preferentially

509 bisaccate pollen being transported from the vegetation growing along the inner coastline of the

510 lagoon before reaching the washover-fan flats, or (ii) it may reflect that the vegetation growing on

511 the (sandy) barrier islands mainly was composed of bisaccate-producing plants, rather than

512 Taxodium swamp vegetation producing mainly non-saccate pollen. The strong dominance of

513 bisaccate pollen from the floodplain samples may be interpreted as reflecting sandy, nutrient poor

514 soil, see further discussion. The two outlier samples showing extremely high abundances of

515 microspores probably reflect the local flood-plain vegetation. Microspore-producing plants (e.g.

516 ferns) often act as pioneer plants and thus microspores are common in unstable environments

517 including e.g. flood-plain areas.

518

519 The relative abundances of dinocysts show a clear pattern with an increase in medium

520 abundances in a proximal-distal trend. The samples from the floodplain environment show very

521 low abundances of dinocysts (medium of 0.5 % and a maximum of 1%), the washover-fan flat

522 samples show a medium of 1% and maximum abundances of 2%, the shoreface samples show a

523 medium of 4%, the samples from lagoonal deposits show a medium of 10%, the prodelta samples

524 show a medium of 15%, the samples from offshore transition environments show a medium of 16

525 % and, finally, show the shelf samples a medium of 26 % dinocysts.

526

18

527 *Botryococcus* show the highest medium values and the highest maximum values in the offshore

528 transition and the floodplain environments (8% medium value in offshore transition and 3% in the

529 floodplain; maximum relative abundance of 35% in the offshore transition, 40% in the floodplain

530 plot incl. outliers and 30% excl. outliers, respectively).

531

532 The medium value for freshwater algae does not exceed 1% in any environment. The highest

533 relative abundances (17%) are found in samples from the floodplain environment in the plot incl.

534 outliers, while samples with 10% freshwater algae were found in the lagoonal environment.

535

536 Fungal hyphae and spores follows the same trend, with a medium value not exceeding 1 %, and

537 the maximum relative abundances (12%) in the floodplain environment (the plot incl. outliers) and

538 maximum values of 10% in the lagoonal environment.

539

540 Acritarchs occur sporadically and the medium value does not exceed 1% in any environment. The

541 highest relative abundances were found in samples from the offshore transition (7%) and the

542 lagoon (5%).

543

544 Two outlier samples with more than 88% microspores were found in the floodplain environment.

545 Except for those, and a few samples from the shoreface environment with 9% microspores, the

546 maximum abundance does not exceed 3%.

547

548

549   **6 PRINCIPAL COMPONENT ANALYSIS OF THE PALYNOFACIES**

550

551 The raw data, i.e. absolute numbers/values of the four main categories of organic particles and

552 the eight palynomorph subcategories within the 169 sediment samples is presented in Appendices

553 1a, b. The data are treated statistically using Principle Component Analysis (PCA) (Figs. 10-20),

554 based on a series of increasingly inclusive data sets in order to 'zoom in' and allow appreciation of

555 the full complex relationships. On each of these figures the facies associations are delineated with

556 convex polygons, allowing for detailed discrimination as commented upon for each plot. No PCA

557 needed more than 4 components; data structures delineated by e.g. PC3 and PC4 represent

558 objective relationships that are revealed after the more dominant PC1 and PC2 have been

559 modelled.

560

561 The first step in the present Multivariate Data Analysis (MVDA-I) consists of a PCA based on the

562 four major categories (P=4): Wood (WO), Amorphous organic matter (AOM), cuticle and

563 membranes (CU) and palynomorphs (PM) (Fig. 10). The four categories are reported in relative

564 abundances summing to 100%.

565

566 In the second step (MVDA-II), the palynomorph (PM) category is subdivided into its eight

567 subcategories, these adding up to 100 %; microspores (MS), non-saccate pollen (NSP), bisaccate

568 pollen (BP), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and –spores (FU), acritarchs

569 (AC) and dinocysts (DI). In this step there are thus 12 variables (P=12); the first four major

570 categories and the eight palynomorph subcategories (Figs. 11-14). The purpose of subdividing the

571 palynomorph category was to delineate the internal relationships between all depositional facies

572 with maximum clarity. Summing up both of these categories to 100%, allow the major organic

573 particles categories and the palynomorph subcategories both to be expressed as relative

574 abundances. For the ensuing data analysis, the X matrix is therefore auto-scaled to allow for

575 simultaneous interpretation (Esbensen and Swarbrick 2018; Esbensen and Geladi 2009).

576

577

578 The final PCA is carried out on the eight palynomorph subcategories alone (MVDA-III); (P=8). The

579 aim was to elucidate still more subtle relationships within this overall category (Figs. 15-20).

20

580 *6.1 MVDA-I: Four Main Categories*

581

582

583 On the score cross plot PC1 vs. PC2 (Fig. 10) the two components collectively model 99% of the

584 total data variance. In this analysis the shoreface (SF, yellow)- and washover-fan flat (W, orange)-

585 facies are completely overlapping, and both are characterized by extreme compositional ranges

586 due to highly varying relative abundances of wood (WO) (Fig. 10b). The lagoonal (L, purple)-facies

587 is of even more variable composition, dominated by highly varying relative abundances of

588 amorphous organic matter (AOM) (Fig. 10b). Two samples (marked orange on Figure 10a) are

589 characterized by extremely high AOM abundances. The prodelta (P, brown)- and shelf (S, light

590 blue)-facies (stippled polygons) are extensively overlapping each other within the lagoonal-facies.

591

592 The loading plot PC1 vs. PC2 (Fig. 10b) shows that effectively only three major categories

593 (amorphous organic matter (AOM), wood (WO) and palynomorphs (PM) are responsible for the

594 overall facies disposition shown in Figure 10a. While palynomorphs are present in all facies

595 associations in average abundances (red ellipsoid), wood and amorphous organic matter vary

596 extensively in the lagoonal- and shoreface-facies (as well as the prodelta- and shelf-facies),

597 extending their compositional ranges to the left quadrants of the plot. Cuticle (CU) abundances

598 are very low in the reference data set, and do not contribute to the disposition shown in Figure

599 10a.

600

601 In this lead-in data-analysis, it is apparently only samples with higher than average abundances

602 that discriminate between facies. Three of these four major categories discriminate the washover-

603 fan flat (W)- and shoreface (SF)-facies from the lagoonal (L)- , prodelta (P)- and shelf (S)-facies, due

604 to the "influencing variables" wood (WO) and amorphous organic matter (AOM), as evidenced by

605 Figure 10b. At low and intermediate abundance for these categories, all facies overlap and occupy

606 the same location (red transparent ellipse in Figure 10a.). Palynomorphs (PM) pools the facies

607 along the PC1, but does not differentiate them. For this reason, the palynomorph (PM) category is

608 subdivided into eight relevant subcategories below, anticipating more sensitive discriminations.

609

610   *6.2 MVDA-II: Main Categories + Palynomorph Subcategories*

611

612   The score plot PC1 vs. PC2 (Fig. 11a) reveals the relationship between the flood-plain (F, green)-

613   and lagoonal (L, purple)-facies in relation to all other facies associations. The palynofacies

614   assemblage from the flood-plain (F)- facies is highly variable and isolated from marine influence,

615   which distinguishes it from remaining facies. The flood-plain (F) facies is especially well

616   discriminated from the lagoonal (L)- facies along PC2. The flood-plain (F)-facies display high

617   palynomorph (PM) and microspore (MS) abundances, while the lagoonal (L)-facies is characterized

618   by high abundances of amorphous organic matter (AOM) and dinocysts(DI), cfr. Appendices 1a, b.

619

620   The three rightmost samples (end-members: red color on Figure 11a) of the flood-plain (F)-facies

621   along PC1 are characterized by exceptionally high proportions of cuticle (CU), *Botryococcus* (BO),

622   fungal hyphae and spores (FU) and freshwater algae (FA) (black ellipse) (Fig. 11b). The lagoonal (L)-

623   facies is partially characterized by the same variables (BO, FU and FA), also extending this group in

624   the PC1 direction. The two prominent L-outliers (orange color on Figure 11a) are dominated by

625   AOM (Fig. 11b), explaining their marked deviating location in the plot. Except for these

626   discriminating features, there is an extensive overlap between all other facies (center and left side

627   of Figure 11a).

628

629   Due to the highly variable character of the palynofacies assemblages of the flood-plain (F)-facies -

630   driven by high abundances of microspores (MS) and elevated abundances of *Botryococcus* (BO),

631   freshwater algae (FA) and fungal hyphae and spores (FU) - this easily discriminated environment is

632   removed from the following analysis of MVDA-II (Figs. 12-14). Removing the F-facies improved

633   discrimination between the remaining six facies (see below).

634

635   The score plot of PC1 vs. PC3 reveals some discrimination of five of the six remaining facies. In this

636   analysis the shelf (S, light blue)-facies is not clearly distinguished from the other five

637   environments.

638

639   The lagoonal (L, purple)- and prodelta (P, brown)-facies occupy opposite positions along the PC1

640   component (with a minor overlap at low PC1-scores, Figure 12a). This can be explained by the

641   marked negative correlation between freshwater algae (FA), fungal hyphae and spores (FU),

642   *Botryococcus* (BO) and non-saccate pollen (NSP) vs. bisaccate pollen (BP) (Fig. 12b). The shoreface

643   (SF, yellow)- and washover-fan flat (W, orange)-facies are discriminated with respect to the

644   prodelta (P, brown)-, lagoonal (L, purple)- and offshore transition (O, dark blue)-facies in the

645   negative PC3 direction, notably because of very high bisaccate pollen (BP) abundances with

646   simultaneous low dinocyst (DI) abundances. There is some overlap between the offshore

647   transition (O, dark blue)- and the lagoonal (L, purple)-facies. However, the offshore transition (O,

648   dark blue)-facies is extended in the PC3 direction due to high(er) dinocyst (DI) abundances., while

649   The prodelta (P, brown)-facies manifests itself as a kind of "mixed bag", which is understandable

650   because of its depositional position in a fully marine environment but with a high influx of material

651   from <u>both</u> terrestrial and fluvial sources.

652

653   The score plot of PC3 vs. PC4 reveals that the shoreface (SF, yellow)- and the offshore transition

654   (O, dark blue)- facies separate almost completely along the PC3 axis (Fig. 13a). Thus the PC3 vs.

655   PC4 cross plot reveals a proximal-distal trend manifested along and modelled by the PC3 axis.

656   Marine palynomorphs (dinocysts, DI) (rightmost) correlate negatively with fluvial and terrestrially

657   derived palynomorphs (non-saccate pollen, NSP, microspores, MS, and bisaccate pollen, BP) and

658   particles (cuticle, CU and wood, W) (leftmost). *Botryococcus* (BO) and acritarchs (AC), which are

659   located in the central part of the PC3 axis with relative small loadings, are probably representing

660   nearshore marine depositional regimes. Amorphous organic matter (AOM) appear to be

661   correlated with acritarchs (AC), but this is only a reflection of the two end-members of the

662   lagoonal (L)-facies that were identified above (Fig. 10a). The shelf (S, light blue)-facies that falls

663   within the offshore transition (O, dark blue)-facies is discussed further below.

664

665   When PC2 is plotted versus PC3 (Fig. 14a), the washover-fan flat (W, orange)-facies is entirely

666   overlapping the shoreface (SF, yellow)-facies but only for high palynomorph/wood (PM/WO)-

667   ratios. The very large compositional extension of the shoreface (SF)-facies is due to the marked

668   palynomorph (PM) *vs.* wood (WO) anti-correlation. The shoreface (SF)-facies has markedly higher

669   relative abundances of wood particles in one end of the facies association (rightmost), while the

670   opposite end is indistinguishable from the washover-fan flat (W)-facies. Both facies plot along the

23

671 negative part of PC3, possibly due to low relative abundances of dinocysts (DI) and high relative

672 abundances of bisaccate pollen (BP) and notably higher relative abundances of cuticle (CU) than in

673 most other environments.

674

675

676 *6.3 MVDA-IlI: Palynomorph Subcategories*

677

678 In this final step of data analysis data matrix from all seven facies are included. By correlating PC1

679 vs. PC2 (Fig. 15) we observe two outliers in the flood-plain (F)-facies. These samples (marked by

680 green) are high in freshwater algae (FA) and fungal hyphae and spores (FU). After removing these

681 two datapoints, a repeated PCA results in the pattern shown in Figure 16.

682

683 The facies succession from floodplain (F, green), via shoreface (SF, yellow) to shelf (S, light

684 blue)/offshore transition (O, dark blue) (Fig. 16 a) delineate a grading relationship from right to

685 left, as indicated by the black arrow. Geologically this is interpreted to represent a proximal-distal

686 spectrum of depositional environments, each with their distinctive palynomorphic characteristics.

687 The apparent "reverse" location of the offshore transition (O)- in relation to the shelf (S)-facies

688 (Fig. 16a) is most probably caused by extreme high dinocyst abundances in some of the offshore

689 transition (O)-facies samples. We observe relatively high abundances of dinocysts (DI) in the shelf

690 samples with the highest median of dinocysts (DI) among all seven environments, but very

691 variable abundances of dinocysts (DI) in the offshore transition (O)-facies (Fig. 9; Appendix 1b).

692 The offshore transition (O)-facies stretches along the PC2 axis with dinocysts (DI) as the end

693 member to the far left and non-saccate pollen (NSP) to the far right. This may suggest that the

694 offshore transition (O)-facies is influenced by pulses of dinocyst blooms ("red-tide" situations) (e.g.

695 Millie et al. 1997; Hall et al. 2012) and/or pulses in the influx of non-saccate pollen, see further

696 discussion below. Some of the most influential variables revealed by the multivariate approach,

697 will also be amenable to univariate data analysis and interpretation, e.g. by box-plot

698 characterization.

699

700 As expected, there is a marked overlapping along this gradation. The lagoonal (L, purple)- and the

701 shoreface (SF, yellow)- facies associations are intermediate along this trend, in fact overlapping

702 with the most distal part of the flood-plain (F)-facies and the most proximal parts of the offshore

703 transition (O, dark blue) - and the shelf (S, light blue)-facies.

704

705 From the disposition shown in Figure 16a, the lagoonal (L, purple)-facies is closest to the flood-

706 plain (F, green)- and shoreface (SF, yellow)-facies, probably reflecting that the organic particles

707 found here mainly originates from fluvial and shoreface sources – with occasional contributions

708 from shelf (S, light blue) and offshore transition (O, dark blue) marine influences (storm activity

709 and /or high tide).

710

711 For the further analysis, the other two end-members (outliers) of the flood-plain (F)-facies

712 (characterized by high microspores, MS; marked by red in Fig. 15a) are also removed. The resulting

713 PCA (Fig. 17) show two new floodplain (F, green)-facies outliers (marked by red) also

714 characterized by high microspores (MS), but at a lower level.

715

716 All these six, successively identified outliers were removed from the flood-plain (F)-facies in the

717 next iteration of the data analysis (Figs. 18-20).

718

719 The score plot of PC1 vs. PC2 (Fig. 18) shows that in spite of substantial overlapping of nearly all

720 facies, the lagoonal (L, purple)- and the washover-fan flat (W, orange)- facies are completely

721 discriminated from each other along the PC1 axis. PC1 may be interpreted as a "buoyancy

722 component". Other possible interpretations are outlined in the Discussion (Washover-fan flat

723 Facies Association). The offshore transition (O, dark blue)-facies and the shoreface (SF, yellow)-

724 facies discriminates, albeit not completely, along the PC2 axis. PC2 is interpreted as a land-sea

725 discriminating component reflecting terrestrial (microspores, MS and non-saccate pollen, NSP) vs.

726 marine (dinocysts, DI) origins.

727

728 The score plot of PC1 vs. PC3 (Fig. 19) discriminates the washover-fan flat (W, orange)-facies

729 completely from the shoreface (SF, yellow)-facies. This discrimination appears to be controlled by

25

730   very high abundances of bisaccate pollen (BP) in the washover-fan flat (W)-facies vs. microspores

731   (MS), dinocysts (DI) and non-saccate pollen (NSP) in the shoreface (SF)-facies. The extensive

732   overlap between prodelta (P, brown)- and shelf (S, light blue)-facies indicates high similarity

733   between these two environments, which is to be expected.

734

735   The three compositionally most varying facies in the score plot of PC2 vs. PC3 (Fig. 20) are offshore

736   transition (O, dark blue)-, lagoonal (L, purple)- and shoreface (SF, yellow)-facies. The plot (Fig. 20)

737   discriminate between these three facies associations much more effectively than the PC1 vs. PC2

738   plot (Fig. 18) , because the dominating PC1 facies extensions have been projected away. Bisaccate

739   pollen (BP) is not correlated with freshwater algae (FA) and fungal hyphae and spores (FU) as it

740   may seem from Figure 20b; the association seen in this plot is only a reflection of bisaccate pollen

741   (BP) having a very high loading on PC1 (Figs. 18, 19).

742

743   The PC2 vs. PC3 plot (Fig. 20) reveals a distinct three-fold variable grouping (ellipses). There is a

744   large overlap between facies associations in the center of this plot, prodelta (P, brown), shelf (S,

745   light blue), flood-plain (F, green), washover-fan flat (W, orange), – only more distinctive samples

746   from the offshore transition (O, dark blue), lagoonal (L, purple) and the shoreface (SF, yellow)

747   facies show extensions away from this average cluster, "driven by" higher relative abundances of

748   dinocysts (DI), freshwater algae and fungal hyphae and spores (FA, FU) and non-saccate pollen

749   (NSP), respectively. The PC2 vs. PC3 plot (Fig. 20) shows evidence that even the compositionally

750   most varying facies associations are overlapping in the center of the plot when their relative

751   abundances are at average levels.

752
753   6.3 P/D index

754

755   The relative amount of terrestrial palynomorphs have often been used as an indicator of the

756   relative distance to the coast (e.g. McCarthy et al. 2003; Donders et al. 2009). In order to test this

757   approach we calculated the P/D index (P/(D+P)*100), see Appendix 1b. The terrestrial

758   palynomorphs (P) include the non-saccate pollen (NSP), the microspores (MS), the freshwater

759   algae (FA) and the fungal hyphae and –spores (FU). The marine palynomorphs (D) only comprise of

760   the dinocysts (DI). The bisaccate pollen have been excluded due to the "Neves effect" which can

761 result in a disturbed proximal-distal trend. *Botryococcus* and acritarchs have also been excluded as

762 our study shows that these two sub-categories thrive best in brackish water environments in the

763 study area. (see chapter 7.2).Therefore, they would probably not be useful in order to gain a clear

764 terrestrial/marine index.

765 **7 DISCUSSION**

766

767 **7.1 PALYNOFACIES CHARACTERISTICS OF THE SEVEN FACIES ASSOCIATIONS**

768

769 *7.1.1 Flood-plain Facies Association (F) (Green)*

770

771 **Characteristics.---** This facies is characterized by high variability of terrestrially and fluvially derived

772 organic particles, while marine derived particles (dinocysts, DI) are almost absent (not above 1%,

773 Fig. 9; Appendix 1b). The samples show very highly variable relative abundances of e.g. cuticles

774 (CU) (0-12%), microspores (MS) (0-88%), *Botryococcus* (BO) (0-40%), freshwater algae (FA) (0-17%)

775 and fungal hyphae and spores (FU) (0-12%).

776

777 In contrast to other environments microspores (MS) may be very abundant, i.e. seven out of 17

778 samples yielded between 3% and 88% of microspores (MS) (Appendix 1b). In all other

779 environments (except for two samples from the shoreface (SF)-facies with 9% and 5%,

780 respectively) the relative abundance of microspores (MS) is at or below 3%.

781

782 Some samples are characterized by elevated values of freshwater algae (FA) and fungal hyphae

783 and spores (FU). However, this is also seen in samples from the lagoonal (L)-facies. The floodplain

784 (F)-facies can be discriminated from the lagoonal (L)-facies by the higher amounts of amorphous

785 organic matter (AOM) and the lower bisaccate/non-saccate pollen ratio in the latter (Figs. 9; 10).

786

787 In addition, the floodplain (F)-facies is characterized by slightly elevated values of cuticle (CU) in

788 some samples (up to 12%) (Appendix 1a).

789

790 The P/D-index has an average value of 97.1 for the floodplain environment (Appendix 1b),

791 indicating a strong dominance of terrestrial palynomorphs.

792

793

794 **Interpretation.---** As expected, the floodplain (F)-facies discriminates from the other facies as

795 being the most proximal (Fig. 15a). This facies is characterized by maximum abundances of

796 terrestrially and fluvially derived organic particles such as fungal hyphae and spores (FU),

797 freshwater algae (FA), microspores (MS) and cuticle (CU) (Figs. 8A, 9, 11A,B). These particles origin

798 from the floodplain environment itself and are often not transported very far from the source. The

799 very high abundances of microspores (MS) in some samples indicate that spore-producing plants,

800 e.g. ferns, were an important part of the vegetation on the floodplain.

801

802 The high variability in the palynofacies associations probably reflects that a floodplain is a very

803 dynamic setting with frequent avulsion of the channel systems and variable discharge of water,

804 resulting in some periods with flooding of the floodplain areas. The samples further possibly

805 represents different parts of this setting; some may represent river-channel deposits, others minor

806 ponds (e.g. oxbow lakes) etc. During storms, eventually combined with high tide, marine water

807 may reach far into the fluvial system, transporting e.g. dinocysts into the floodplain setting.

808

809 **Comments.---** Due to its high variability, either all of the floodplain (F)-facies (Figs. 12-14) or only

810 six floodplain (F)-outlier samples (Figs. 18, 19) were removed from some of the analysis, improving

811 the discrimination of the other facies.

812

813

814 *7.1.2 Lagoonal Facies Association (L) (Purple)*

815

816 **Characteristics.---** Like the floodplain (F)-facies, the palynofacies association of the lagoonal (L)-

817 facies is markedly variable. Similarly to the flood-plain (F)-facies, freshwater algae (FA) and fungal

818 hyphae and spores (FU) are common (up to 10%) (Figs. 9; 12, 16, 18), but high amounts of

819 amorphous organic matter (AOM) (up to 94%), common dinocysts (DI) (2-18%) and rare

820 microspores (MS) (0-2%) discriminates the lagoonal (L)-facies from the flood-plain (F)-facies (Figs.

821 9; 10).

822

823 In contrast to all other environments the relative abundances of amorphous organic matter (AOM)

824 are extremely variable (2-94%), especially due to very high abundances (86% and 94%) in two end-

825 member samples (Figs. 9; 10; Appendix 1b), while non-saccate pollen (NSP) generally show high

826 relative abundances (22-67%) (Figs. 9; 18; Appendix 1b).

827

828 The higher relative abundances of freshwater algae (FA), fungal hyphae and spores (FU) and non-

829 saccate pollen (NSP) differentiate the lagoonal (L)-facies from the prodelta (P)-facies (Fig. 12) and

830 the washover-fan flat (W)-facies (Fig. 18). The last two facies further carry high loads of bisaccate

831 pollen (BP); in the prodelta (P)-facies it varies between 27% and 76% and in the washover-fan flat

832 (W)-facies bisaccate pollen (BP) varies from 66% to 92% , while the abundances of bisaccate pollen

833 (BP) in the lagoonal (L)-facies yields maximum 47% (except for 1 sample at 61%) (Fig. 10; Appendix

834 1b). Additionally, the lagoonal (L)-facies discriminates from the prodelta (P)-facies by higher

835 abundances of *Botryococcus* (BO) (0-16%) (Fig. 9).

836

837 The P/D-index has an average value of 84.3 (Appendix 1b), indicating a strong dominance of

838 terrestrial palynomorphs – however, slightly lower than in the floodplain environment.

839

840

841 **Interpretation.---** <u>Lagoonal (</u>L)-facies plot in between the proximal (floodplain, F-) and distal

842 (offshore transition, O-and shelf, S-) facies (Fig.16). It overlaps with the most distal part of the

843 floodplain (F)-facies and with the most proximal parts of the offshore transition (O)- and shelf (S)-

844 facies. This position may reflect the mixed terrestrially/fluvially and marine influence on the

845 lagoonal (L)-facies.

846

847 The high abundances of non-saccate pollen probably reflect that the lagoonal areas were

848 surrounded by swamp forests (Larsson et al. 2010; 2011). The very high abundances of AOM

849 (degraded wood-particles) in some samples probably reflect the short distance from the source

29

850 (decaying trunks from the swamp forest surrounding the lagoon), combined with the more quiet

851 environment allowing bacterial degradation. This contrasts the high-energy shoreface (SF)-facies

852 with high abundances of wood and almost no AOM (Figs. 9; 10; Appendix 1a).

853

854 The low relative abundance of microspores (MS) in the lagoonal (L)-facies have also been observed

855 in previous studies – compare Rasmussen and Dybkjær (2005) and Larsson et al. (2010). It can be

856 speculated that either (i) the microspore-producing plants, e.g. ferns, were not that common in

857 the swamp forests - perhaps not enough light could penetrate the canopy to allow ferns to thrive

858 in the understory? However, ferns are common constituents of modern swamp forests; (ii) the

859 clay-rich samples from the L-facies represent locations some distance away from the shoreline. As

860 microspores are generally produced by plants (e.g. ferns) forming part of the undergrowth, they

861 are not transported far away from their mother plants. Therefore, they may not have reached the

862 middle to outer parts of the lagoonal setting. In contrast, spreading of pollen from trees forming

863 the upper canopy are more effectively transported and spread by wind and water. As the deepest

864 parts of lagoons have the highest preservation potential, the samples representing lagoonal

865 depositional environments in the present study may in fact only be representative for the deeper

866 parts of a lagoon. Alternatively (iii) the amount of bisaccate and non-saccate pollen produced by

867 the trees in the swamp forest simply were so large that they diluted the input of microspores.

868

869 The inner parts of the lagoon were probably a fresh- to brackish-water environment, as suggested

870 by the presence of freshwater algae (FA) and *Botryococcus* (BO). However, some of the freshwater

871 algae (FA) and *Botryococcus* (BO) could also have been transported into the lagoon by rivers and

872 streams.

873

874 The higher abundances of dinocysts in this environment compared with the floodplain reflect

875 some connection to the marine environment. Some low-saline tolerant dinocyst taxa probably

876 thrived within the lagoon, while others were transported into the lagoon from the normal marine

877 settings by tidal currents.

878

879

880   *7.1.3 Washover-fan flat Facies Association (W) (Orange)*

881

882   **Characteristics.--- The assemblage is most** similar to the floodplain (F)-facies. Hovewer, in contrast

883   to the floodplain (F)-facies, in which the relative abundances of bisaccate pollen (BP) varies

884   between 3% and 88%, all of the samples from the washover-fan flat (W)-facies are characterized

885   by constantly very high abundances of bisaccate pollen (66-92%) (Figs. 9; 17; Appendix 1b). The

886   washover-fan flat (W)-facies, in contrast to all other five facies, shows a near absence of dinocysts

887   (DI) (maximum 2%) (Fig. 9; Appendix 1b).

888

889   The washover-fan flat (W)-facies to a high degree overlap the shoreface (SF)-facies (Figs. 10, 12, 14

890   and 18), however this is only true for samples with high palynomorph/wood (PM/WO) ratios (Fig.

891   13). The relative abundance of wood is highly varying in the washover-fan flat (W)-facies (Figs. 9

892   and 10).

893

894   The washover-fan flat (W)-facies (like the shoreface, SF,-facies) differentiate from all other

895   environments by high bisaccate pollen (BP) abundances (Fig. 12). When analyzing only

896   palynomorphs (MVDA-III), the washover-fan flat (W)-facies discriminates completely from the

897   shoreface (SF)-facies by distinctly high relative abundances of bisaccate pollen (BP) (66-92%) and

898   low values of dinocysts (DI), non-saccate pollen (NSP) and microspores (MS) (Figs. 9; 19).

899

900   The washover-fan flat (W)- and lagoonal (L)-facies discriminates completely from each other along

901   the PC1 axis in Figure 18 where the bisaccate pollen (BP) is negatively correlated with the

902   freshwater algae (FA), fungal hyphae and spores (FU) and non-saccate pollen (NSP). Cuticle (CU) is

903   slightly more common than in the lagoonal (L), prodelta (P)-, offshore transition (O)- and shelf (S)-

904   facies (Fig. 9; Appendix 1b).

905

906   The P/D-index has an average value of 88.9 (Appendix 1b), indicating a strong dominance of

907   terrestrial palynomorphs also for this environment.

908

909

31

910

911

912 **Interpretation.---** The generally low abundances of wood (WO) compared with parts of the

913 shoreface (SF)-facies probably reflect that the washover-fan flat (W)-facies represents a protected

914 depositional environment on the backside of the barrier islands, while the shoreface (SF)-facies is

915 prone to waves (high energy) (see further the part concerning the shoreface (SF)-facies).

916

917 The high relative abundances of bisaccate pollen (BP) in the washover-fan flat (W)-facies can be

918 explained by either – or a combination of the following hypothesis;

919　　1) The "Neves-effect" with bisaccate pollen floating further away from the vegetated

920　　　　coastline along the innerside of the lagoon.

921　　2) The washover-fan flat facies are located on the landward side of barrier islands (Fig. 1). The

922　　　　barrier islands typically consist of sand and on such soils, which periodically may dry out

923　　　　and which are poor in nutrients, conifers (producing bisaccate pollen) thrive better than

924　　　　most non-saccate- and microspore- producing plants.

925

926

927　　　　　　　　　*7.1.4 Shoreface Facies Association (SF) (Yellow)*

928

929 **Characteristics.---** The shoreface facies association is characterized by varying, but generally much

930 higher relative abundances of wood (WO) than in any other environment (Figs. 9; 10). The

931 abundance of wood varies between 3% and 94% (Fig. 9), but in 17 of the 23 samples the

932 abundance is above 40% (Appendix 1a). Furthermore the shoreface (SF)-facies is characterized by

933 generally high non-saccate pollen (NSP) (15-71%) and bisaccate pollen (BP) (16-78%) abundances

934 and rather low dinocyst (DI) abundances (0-16%) (Figs. 9; 12; 13; 18).

935

936 A nearly complete differentiation between the shoreface (SF)- and offshore transition (O)-facies

937 (Fig. 13) is due to high abundances of wood (WO), non-saccate pollen (NSP) and bisaccate pollen

938 (BP) and to a minor degree microspores (MS), controlling the shoreface (SF)-facies in contrast to

939 the high abundances of dinocysts (DI) controlling the offshore transition (O)-facies.

940

941 The shoreface (SF)-facies is seen to be located between the proximal and distal facies (Fig. 16). The

942 location on the plot seems to be controlled mainly by high amounts of non-saccate pollen (NSP)

943 and low amounts of dinocysts (DI).

944

945 The shoreface (SF)-facies and the washover-fan flat (W)-facies are completely discriminated (Fig.

946 19) by the anti-correlation of higher abundances of non-saccate pollen (NSP), dinocysts (DI) and

947 microspores (MS) in the shoreface (SF)-facies versus higher relative abundances of bisaccate

948 pollen (BP) in the washover-fan flat (W)-facies.

949

950 An average P/D-index value of 87 (Appendix 1b) indicates that the shoreface environment is

951 characterized by a dominance of terrestrial palynomorphs, in the same order as the washover-fan

952 flat and lagoonal environments.

953

954

955 **Interpretation.---** The very high relative abundances of wood (WO) in most of the samples from

956 the shoreface (SF)-facies likely reflect the high energy in this environment (above the fair-weather

957 wave-base). Palynomorphs (PM) have a buoyancy comparable with clay and silt particles, and are,

958 like clay and silt, only deposited in quiet periods (fair weather conditions). In contrast, wood

959 particles are generally the only organic particles found in sandy deposits.

960 The overlap of the shoreface (SF)-facies and the washover-fan flat (W)-facies in the leftmost side

961 on Figure 14 may be interpreted as representing samples deposited in a low-energy environment,

962 while the extreme right part of the shoreface (SF)-facies is reflecting the high-energy environment.

963

964 The high relative abundances of non-saccate pollen (NSP) among the palynomorphs probably

965 reflect the presence of a Taxodium swamp forest growing along the coastline (Koch 1989; Larsson

966 et al. 2006; 2010; 2011) which produced very high amounts of pollen. The few samples with

967 relative abundances of microspores (MS) slightly higher than normal (5% and 9%, respectively)

968 seem to have influenced the PCA of this facies. The spore producing plants possibly formed the

969 understorey of the swamp-forests, see further the discussion in the lagoonal (L)-facies.

970

971 The complete discrimination between the shoreface (SF)-facies and the washover-fan flat (W)-

972 facies (Fig. 19) may reflect the nutrient-poor, sandy soils on the barrier-islands in contrast to the

973 better soils along the coast (see discussion for the washover-fan flat facies in the previous section).

974 The palynomorphs delivered to the washover-fan flat -facies possibly mainly came from the sandy

975 barrier-islands on which only conifers (producing bisaccate pollen) could grow, while nutrient-rich,

976 continuously wet peaty soils along the coastline formed the basis for a rich and diverse Taxodium

977 swamp forest, delivering huge amounts of both non-saccate and bisaccate pollen to the shoreface

978 environment.

979

980 The rather low relatively abundances of dinocysts (DI) (compared with the offshore facies) are

981 probably the result of dilution due to the high influx of non-saccate pollen (NSP) and bisaccate

982 pollen (BP). Dilution may also explain the surprisingly lower relative abundances of *Botryococcus*

983 (BO) in the shoreface (SF)- facies compared with the offshore transition (O)- facies (Fig. 9;

984 Appendix 1b).

985

986 **Comments.---** As mentioned above, the samples from the shoreface (SF)-facies were taken so that

987 they consisted of both the dominating sandy deposits, but also minor clay-layers in order to assure

988 the presence of enough palynomorphs for the statistical analysis.

989

990 *7.1.5 Prodelta Facies Association (P) (Brown)*

991

992 **Characteristics.---** The prodelta (P)-facies is characterized by well-mixed homogene assemblages

993 of organic particles with no categories or subcategories becoming distinctly abundant (Fig. 9). The

994 prodelta (P)-facies overlaps extensively with the shelf (S)-facies (Figs. 10; 12; 16; 19).

995

996 When compared with the washover-fan flat (W)- and shoreface (SF)-facies, the prodelta (P)-facies

997 show lower abundances of wood (WO) and constantly high abundances of amorphous organic

998 matter (AOM) (Fig. 10). It shows extremely low abundances of microspores (MS), fungal hyphae

999 and spores (FU), *Botryococcus* (BO) and acritarchs (AC) (max 2%), while freshwater algae (FA) show

1000 slightly increased abundances in some samples, up to 8% (Fig. 9; Appendix 1b).

1001

1002 In contrast to the lagoonal (L)- and shoreface (SF)-facies, the relative abundances of bisaccate

1003 pollen (BP) are generally higher (27-76%) than the abundances of non-saccate pollen (NSP) (7-

1004 52%) (Fig. 9). The prodelta (P)-facies also shows higher abundances of dinocysts (DI). However, the

1005 relative abundances of dinocysts are highly variable, from 2-47% (Fig. 9).

1006

1007 Compared with the offshore transition (O)-facies, the prodelta (P)-facies generally has lower

1008 abundances of dinocysts (DI) and *Botryococcus* (BO) and higher abundances of bisaccate pollen

1009 (BP) (Figs. 9; 17; 18).

1010

1011 The average P/D-index value of 60.8 (Appendix 1b) show a less strong dominance of terrestrial

1012 palynomorphs, compared with the shoreface, washover-fan flat, lagoonal and floodplain

1013 environments.

1014

1015

1016

1017 **Interpretation.---** The prodelta (P)-facies is characterized by generally well-mixed assemblages of

1018 organic particles. This probably reflects a high degree of re-deposition of the sediments,

1019 homogenizing the varying influx of fluvially and terrestrially derived particles via rivers and deltas,

1020 into the marine environment. The variations seen in the relative abundances of dinocysts (DI) may

1021 reflect delta-lobal shifts, resulting in variations in the influx of fluvial- and terrestrially derived

1022 particles, diluting the dinocyst-assemblages. The high amounts of partly degraded wood (AOM)

1023 are probably transported into the prodelta (P)-facies from floodplain areas via rivers.

1024

1025 The constantly high relative abundances of bisaccate pollen (BP) related to non-saccate pollen

1026 (NSP), which contrast what is seen in the lagoonal (L)- and shoreface (SF)-facies, probably reflect

1027 the "Neves-effect".

1028

35

1029   The extensively overlap with the shelf (S)-facies, probably reflects that both environments are

1030   well-mixed, being located in fully marine settings but also receiving large amounts of fluvial and

1031   terrestrially derived organic particles. Furthermore, coast-parallel currents probably eroded the

1032   pro-delta deposits and transported these sediments along the coast and deposited them on the

1033   shelf. Much of the shelf deposits thus probably originate from pro-delta settings.

1034

1035   **Comments.---** For these reasons the compositional 'spread' of a facies in the score plot may be

1036   extensive, or may be strongly coherent – and may in fact sometimes appear uncorrelated to the

1037   number of samples included. Thus, despite a high total sample number, distinct discriminability

1038   between the shelf (S)- and the prodelta (P)-facies remains elusive.

1039

1040   *7.1.6 Offshore Transition Facies Association (O) (Dark blue)*

1041

1042   **Characteristics.---** The offshore transition (O)-facies discriminates from all other facies except the

1043   shelf (S)-facies, by showing very high relative abundances of dinocysts (DI), even extremely high

1044   abundances (83% and 92%) in a few samples (Figs. 9; 12; 13). However, the abundances of

1045   dinocysts (DI) are very variable, ranging from 2% to 92%, and below 20% in most samples

1046   (Appendix 1b).

1047

1048   The relative abundances of non-saccate pollen (NSP) and bisaccate pollen (BP) are approximately

1049   equal (Fig. 9).

1050

1051   The abundances of microspores (MS) are extremely low (max 2%), while freshwater algae (FA),

1052   fungal hyphae and spores (FU) and acritarchs (AC) show slightly increased abundances in some

1053   samples, up to 7%.

1054

1055   The abundances of *Botryococcus* (BO) are remarkably high, up to 35% and above 10% in

1056   approximately half of the analyzed samples.

1057

1058   Figures 12, 13 and 16 show nearly completely discriminations of the offshore transition (O)- and

1059   the shoreface (SF)-facies, mainly driven by a negative correlation of dinocysts (DI) and

1060   Botryococcus (BO) versus wood (WO), non-saccate pollen (NSP), microspores (MS) and cuticle

1061   (CU).

1062

1063   The P/D-index has an average value of 60.0 (Appendix 1b), indicating an influx of terrestrial

1064   palynomorphs in the same order as for the prodelta environment.

1065

1066

1067

1068

1069   **Interpretation.---** The generally high relative abundances of dinocysts (DI) probably reflect optimal

1070   salinity and nutrient supply in which dinoflagellates thrive.

1071   The clear discrimination between the offshore transition (O)- and the shoreface (SF)-facies may

1072   further reflect that the offshore transition (O)-facies is less influenced by fluvial- and terrestrially

1073   derived particles (non-saccate pollen, NSP, microspores, MS, wood, WO, cuticle, CU) due to the

1074   more distal location. The lower relative abundances of wood (WO) probably also reflects the

1075   increased water-depths of the offshore transition (O)-facies (below fair-weather wave-base),

1076   allowing palynomorphs to settle.

1077

1078   The high relative abundances of *Botryococcus* (BO) probably reflect that these freshwater algae

1079   are tolerant to brackish water and probably thrived in the shallow marine areas.

1080

1081

1082   *7.1.7 Shelf Facies Association (S) (Light blue)*

1083

1084   **Characteristics.---** The shelf (S)-facies is characterized by well-mixed assemblages of organic

1085   particles (Figs. 9; 10; 18) with no categories or subcategories becoming distinctly abundant. This

1086   feature was characteristic also for the prodelta (P)-facies. As was seen in the prodelta (P)-facies,

1087 the relative abundances of bisaccate pollen (BP) are constantly high and distinctly higher than non-

1088 saccate pollen (NSP) (Fig. 9). The shelf (S)-facies, like the offshore transition (O)-facies, is further

1089 characterized by high relative abundances of dinocysts (DI) and low abundances of freshwater

1090 algae (FA), fungal hyphae and spores (FU), and microspores (MS) (max 2% of the two former and

1091 max 3% of the latter). The relative abundance of *Botryococcus* (BO) is not as high as in the

1092 offshore transition (O)-facies, but reaches up to 14%. In Figure 16 the shelf (S)-facies plots within

1093 the rightmost part of the offshore transition (O)-facies polygon.

1094

1095 The shelf facies are characterized by the lowest average value of the P/D index in the study area.

1096 The index has an average value of 45.5 (Appendix 1b), indicating a clearly lower influx of terrestrial

1097 palynomorphs than that of the other six studied environments.

1098

1099

1100

1101

1102 **Interpretation:---** The overlap pattern of the offshore transition (O)- and the shelf (S)-facies

1103 polygons (Fig. 16) probably reflects the more constantly high abundances of dinocysts (DI) in the

1104 shelf (S)-facies in contrast to the offshore transition (O)-facies where the dinocyst (DI) abundances

1105 vary extensively, with a few samples with extremely high dinocyst (DI) abundances pulling the

1106 offshore transiton (O)-facies polygon towards the left, see also Appendix 1b. The apparent reverse

1107 locations of the offshore transition (O)- and shelf (S)-facies polygons, as seen in Figures 13 and 16,

1108 with parts of the offshore transition (O)-facies polygon reaching further "distally" than the shelf

1109 (S)-facies polygon, is an artifact due to these extremely high dinocyst (DI) abundances.

1110

1111 The constantly high relative abundances of bisaccate pollen (BP) related to non-saccate pollen

1112 (NSP), as also seen in the prodelta (P)-facies but contrasting the lagoonal (L)- and shoreface (SF)-

1113 facies, probably reflect the "Neves-effect" (Fig. 9).

1114

1115 As seen in e.g. Figures 10 and 19, there is an extensive overlap between the prodelta (P)- and shelf

1116 (S)-facies. It must be assumed that the pro-delta environment received more fluvially and

1117 terrestrially derived organic particles (from the rivers forming the deltas). The overlap may

1118 indicate that currents associated with submarine gyres redistributed the prodeltaic deposits along

1119 the shelf (Hansen et al. 2004; Hansen and Rasmussen 2008).

1120

1121

1122 **7.2 DISTRIBUTION PATTERNS OF SELECTED PARTICLES**

1123

1124 a) Traditionally, in studies of marine depositional environments, high amounts of amorphous

1125 organic matter have been interpreted as an indicator of anoxic/dysoxic bottom waters and

1126 the origin of this organic matter have often been found to be mainly marine algae (e.g.

1127 Tyson 1995; Pacton et al. 2011). However, in the present study, dealing with a fluvio-deltaic

1128 setting, the degraded organic matter found in the samples comprises degraded vitrinite,

1129 probably coming from the Taxodium swamp areas along the coast. Transitional stages from

1130 structured wood-particles and to totally structureless particles are shown in Figure 8J

1131 (photos). It is difficult to know to which degree abundance of this degraded vitrinite can be

1132 used to indicate oxygen deficiency in the bottom waters, or rather indicate proximity to the

1133 swamp areas

1134

1135 b) In the PCA-plots (Figs. 10-20), freshwater algae (FA) and fungal hyphae and spores (FU)

1136 consistently plot closely together. This coupling probably reflects the mutual origin (fluvial

1137 environments and from the swamp forests) and riverine transport mode. *Botryococcus* (BO)

1138 and acritarchs (AC) also seem to be coupled, plotting in between the freshwater/fungal

1139 hyphae and spores (FA/FU) and the dinocysts (DI). Acritarchs (AC) originate from/live in

1140 shallow marine environments, which is in good agreement with its location in Figure 20,

1141 indicating a relationship with dinocysts (DI). Freshwater algae (FA) and *Botryococcus* (BO)

1142 most often plot with some distance (e.g. Figs. 16; 17; 18; 20). The results thus show the

1143 importance of not including *Botryococcus* (BO) in the freshwater algae (FA)-subcategory.

1144 The positioning of *Botryococcus* (BO) on Figure 20 probably reflects that this algae thrive in

1145 brackish water as well as freshwater and therefore can be found in both shallow marine and

1146 fluvial environments.

1147   The distance between the freshwater algae (FA) and *Botryococcus* (BO) in the plots, and the

1148   coupling between *Botryococcus* (BO) and acritarchs (AC) probably reflect that the

1149   euryhaline algae *Botryococcus* in the present studyis more related to brackish water than

1150   freshwater environments. If *Botryococcus* only thrived in freshwater settings, it would be

1151   expected to be distributed together with the other freshwater algae (*Pediastrum* and

1152   *Pseudokomewuia*) rather than with the shallow marine acritarchs. The semi-enclosed

1153   situation for the North Sea Basin during the early Miocene in combination with a humid

1154   climate (ca. 1500 mm annual precipitation, Larsson et al. 2011; Rasmussen et al. 2013) may

1155   have resulted in a general lowered salinity – corresponding to the situation for the Baltic

1156   Sea today. It can be speculated if such an overall lowered salinity may have resulted in the

1157   possibility for *Botryococcus* to expand the area where it thrived from floodplain, lagoonal

1158   and deltaic settings to include shallow marine (low-salinity) settings.

1159

1160   c)   Extremely high abundances of microspores (MS) (17-88%) are in the present study only

1161   found in samples from the floodplain (F) environment and are therefore a very good

1162   indicator for this environment. Relatively high abundances of freshwater algae (FA) (12-

1163   17%) and fungal hyphae and spores (FU) (11-12%) are also characteristic for the floodplain

1164   (F) facies, although a few samples from the lagoonal (L) facies also reaches 10%. The

1165   samples from the lagoonal facies differ however, in their distinctly higher abundances of

1166   dinocysts (DI). Extremely high abundances of AOM (degraded vitrinite) have only been

1167   recorded from the lagoonal (L) depositional environment and are thus a very good indicator

1168   for this environment, when observed.

1169   d)   The dominance of bisaccate pollen (BP) in most of the floodplain (F) samples (and of

1170   microspores (MS) in a few samples) rather than non-saccate pollen (NSP), may be

1171   interpreted as reflecting a floodplain mainly consisting of sandy deposits with frequent

1172   avulsions of channels, not offering good, stable conditions for development of a rich and

1173   variable vegetation. This may suggest a relatively high relief of the floodplain, which is also

1174   supported by the fact that the gravel front reached the delta outlet (Rasmussen et al. 2010;

1175   Helland-Hansen et al. 2016).

1176   e)   The P/D-index show a clear trend in the distribution of palynomorphs with a decreasing

1177   ratio of terrestrial palynomorphs in a proximal-distal direction. The index show values

1178   ranges from close to 100 (97.1) in the floodplain environment to 45.5 in the shelf

1179   environment. The most variable ratios are observed in the offshore environment and to a

1180   lesser degree in the shelf and prodelta environments. The remaining environments are

1181   characterized by high and relatively stable ratios.

1182

1183

1184   **7.3 EVALUATION OF STATISTICAL METHODS;**

1185   a)   Univariate Box-plots are very efficient in outlining the general distribution of sedimentary

1186   organic particles for each depositional environment. Furthermore, they clearly show the

1187   overall trends across depositional environments, however, only as expressed by one

1188   parameter at the time.

1189

1190   In contrast, the multivariate PCA plots effectively present the characteristics and the

1191   variability of each depositional environment as expressed simultaneously by up to 12

1192   palynofacies variables. The major PCA plots show both the degree of overlap and the

1193   resolvable distinctions between the seven environments. One issue that must be borne in

1194   mind during the multivariate data analysis interpretations is that depending on the degree,

1195   sometimes bimodal distributions may have a marked influence on the data disposition in

1196   certain score cross-plots, even when the relative abundances all are low (e.g. microspores

1197   (MS) in the shoreface (SF)-facies), see comments regarding outliers below. More constant

1198   high abundances does not bias much towards a specific PCA component direction (e.g.

1199   dinocysts (DI) in the shelf (S)-facies). It is the effective *combination* of both PCA-plots and

1200   Box-plots that reveal both general trends and outliers in the presented palynofacies data-

1201   set.

1202   b)   The recognized and deleted outlier samples (<u>two</u> samples from the lagoonal (L)- facies

1203   showing extremely high relative abundances of AOM, two samples from the floodplain (F)-

1204   facies showing relatively high abundances of freshwater algae (FA) and fungal hyphae and

1205   spores (FU), and <u>four</u> samples from the floodplain (F)- facies showing high abundances of

41

1206   microspores (MS), should not be forgotten although these samples (at some point) were

1207   removed from the dataset in the latter part of the statistical analyses. <u>None</u> of these

1208   samples were interpreted as representing erroneous identification of environments, faults

1209   in processing etc. They simply represent extreme end-members of the natural variations of

1210   the environment they come from. Bimodal distributions and end-member dispositions are

1211   always to be expected to the degree that the data sets are able, or not fully able, to

1212   represent complete depositional facies variabilities. It is to be expected that such lacunae

1213   will be filled-in when more samples are analyzed in future studies.

1214

1215

1216   **8 CONCLUSIONS**

1217

1218 A palynofacies reference dataset for seven different depositional environments from the upper

1219 Oligocene - lower Miocene of the North Sea Basin has been established. The dataset have been

1220 treated statistically using univariate Box Plots and multivariate Principal Component Analysis

1221 (PCA).

1222

1223 Three depositional environments can be fully differentiated using the palynofacies dataset:

1224   -   The floodplain environment is characterized by the near absence of dinocysts. Some

1225   samples from this environment are further characterized by relatively high abundances

1226   (compared with the other environments) of freshwater algae, fungal hyphae and spores

1227   and *Botryococcus* and (in other samples) very high relative abundances of microspores.

1228   -   The washover-fan flat environment is characterized by high relative abundances of

1229   bisaccate pollen.

1230   -   The shoreface environment is characterized by high relative abundances of wood particles.

1231

1232 The data from the other four environments reveal various degrees of overlaps, but also depicts

1233 clear overall trends. The proximal-distal trend expressed as increased relative abundances of

1234 dinocysts and decreased non-saccate pollen, are valuable and useful information, e.g. for

1235 differentiating lagoonal mud from shelfal mud. Lithologically these two environments are difficult

1236 to distinguish. The median for dinocysts in the lagoonal facies is 10% and never higher than 18%.

1237 The median for the shelf facies is 26%. In most samples from the lagoonal facies the relative

1238 abundance of non-saccate pollen are higher than the abundance of bisaccate pollen. In most

1239 samples from the shelf facies a clear dominance of bisaccate pollen in relation to non-saccate

1240 pollen is found.

1241

1242 The increase in relative abundances of bisaccate pollen from offshore transition to shelf, possibly

1243 reflecting the "Neves-effect", can, possibly in combination with increase in dinocysts, be used to

1244 indicate a deepening/flooding trend.

1245

1246 The present reference dataset can be used for identifying the overall depositional setting, e.g.

1247 floodplain, lagoon, shoreface etc. at a specific time. Such reconstruction of the palaeogeography is

1248 important for the understanding of basin development.

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FIGURES

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1470   FIG. 1.- Schematic figure showing the seven depositional environments. FWWB: Fair weather

1471   wave-base.

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1473   FIG. 2A-C.- Detailed paleogeographic maps for the study area in the uppermost Oligocene –

1474   lower Miocene, Jylland, showing rivers, deltas, estauries, barrier islands, etc. Modified from

1475   Rasmussen et al. (2010).

1476

1477   FIG. 3.- Lithostratigraphic scheme, chronostratigraphy and dinocyst zonation. Modified from

1478   Rasmussen et al. (2010). The time intervals represented by the palaeogeographical maps shown in

1479   Figure 2 are indicated. *D.p.*: *Deflandrea phosphoritica*; *C.g.*: *Chiropteridium galea*; *H.* spp:

1480   *Homotryblium* spp.; *C.am.*: *Caligidinium amiculum*; *T.p.*: *Thalassiphora pelagica*; *S.h.*:

1481   *Sumatradinium hamulatum*; *C.c.*: *Cordosphaeridium cantharellus*; *E.i.*: *Exochosphaeridium insigne*;

1482   *C. au.*: *Cousteaudinium aubryae*; *L.t.*: *Labyrinthodinium truncatum*.

1483

1484   FIG. 4.-Location of studied boreholes and outcrops and location of seismic line shown in Figure

1485   6.

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1487   FIG. 5.- Log-correlation panel showing sample locations in boreholes and outcrops (compare

1488   with "Samples" in Appendices 1a and 1b) and illustrating the depositional environments. In order

1489   to show a simplified geological model of a NNW-SSE striking correlation of the studied boreholes

1490   and outcrops, it was necessary to exclude the two outcrops Hvidbjerg and Dykær. All samples from

1491   the Hvidbjerg outcrop (samples SFH 1-11) represent shoreface deposits and were sampled within

1492   the Hvidbjerg Member, see further Rasmussen et al. (2010; their Figs. 31, 33). The position of the

1493   two lagoonal samples from the Dykær outcrop (LD 1-2) are shown in Rasmussen and Dybkjær

1494   (2005; their Figs. 5-7). Inserted principal sketch shows the lateral distribution of the different

1495   facies defined in this study.

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1497   FIG. 6.-Example of combined seismic data and borehole data (logs and lithology), the St.

1498   Vorslunde borehole, prodelta and shelf environments.

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1500   FIG. 7A-H.-Examples from outcrops showing sedimentary structures and trace fossils, based on

1501   which the depositional environments were interpreted. No photos of prodelta and shelf

1502   environments are shown, as they were only represented in boreholes and identified based on a

1503   combination of seismic data and borehole data (see Figure 6). A) Floodplain, Salten profile, notice

1504   wood in orange. B) Floodplain, Salten profile, rootlets indicated by arrows. C) Lagoon deposits

1505   (dark layer in lower third part of the photo) overlain by washover-fan flat deposits. Hagenør

1506   profile. D) Washover-fan flat. *Macaronichnus* trace-fossils indicated (M), Hagenør profile. E)

1507   Shoreface, Hvidbjerg profile. F) Shoreface, Børup profile. Example of a storm sand layer capped by

1508   a ripple laminated sand. The samples for the palynofacies study were taken from the thin clay-

1509   layers. *Ophiomorpha* trace-fossils indicated (O). G) Offshore, Fænø profile, Hommocky Cross

1510   Stratification alternating with heterolithic deposits. H) Offshore, Hostrup profile. Example of

1511   *Chondrites* trace-fossils.

1512

1513 FIG. 8A-J.- Palynofacies from the seven depositional environments. A) Floodplain, Salten profile,

1514 overview, 40 cm over sandlayer, sl. 5, N38. Non-saccate pollen (NSP), bisaccate pollen (BP) and

1515 cuticle (CU) indicated. B) Floodplain, Salten profile, sample dominated by monolete spores, 60 cm

1516 over sandlayer, sl. 5, J31. *Botryococcus* (BO), non-saccate pollen (NSP), bisaccate pollen (BP),

1517 microspores (MS) and fungal spores (FU) indicated. C) Lagoon, Hagenør profile, overview, Lab nr.

1518 21535,sl.4, E30. Amorphous organic matter (AOM), bisaccate pollen (BP), acritarchs (AC), wood

1519 (WO) and *Botryococcus* (BO) indicated. D) Lagoon, Dykær profile, close-up of sample dominated by

1520 AOM (=partly degraded vitrinite), Lab. Nr. 17877, 14.70 m, sl.4, W40-4. Amorphous organic matter

1521 (AOM), dinocysts (DI) and non-saccate pollen (NSP) indicated. E) Washover-fan flat, Hagenør

1522 profile. 4.0 m over base profile, sl. 5, L30-3. Bisaccate pollen (BP) and wood (WO) indicated. F)

1523 Shoreface, Hvidbjerg profile, lab nr. 26953, sl. 4, O35-2. Wood (WO), non-saccate pollen (NSP) and

1524 bisaccate pollen (BP) indicated. G) Prodelta. St. Vorslunde, 108m, sl. 5, K35. Freshwater algae (FA),

1525 non-saccate pollen (NSP), wood (WO) and bisaccate pollen (BP) indicated. H) Offshore. Fænø,

1526 5.01m, sl.4, L37-2. Dinocysts (DI), bisaccate pollen (BP), non-saccate pollen (NSP) and wood (WO)

1527 indicated. I) Shelf, Klosterhede, overview, 267-268m, sl.3, J34-3. Dinocysts (DI), acritarchs (AC) and

1528 wood (WO) indicated. J) Shelf, Harre-1,close-up, transition from structured wood to amorphous

1529 organic matter (AOM) (from 1 to 3) 48,25m, sl. 4, N54-1. Dinocysts (DI), non-saccate pollen (NSP)

1530 and bisaccate pollen (BP) indicated.

1531 FIG. 9.- Box Plot. A) The four main categories. B) The eight palynomorph-subcategories. Note

1532 that the data from the lagoonal facies and the floodplain facies are shown inclusive outliers and

1533 exclusive outliers, respectively. The data are presented as relative abundances with a minimum

1534 and a maximum value, 25% and 75% values and a median value of each category/subcategory.

1535

1536 FIG. 10.- A) MVDA-I score plot (PC1 vs. PC2). All facies except (O) and (F) are delineated as

1537 convex polygons. O and F are not delineated in this plot, but are treated below. Note the two end-

1538 members of the (L)-facies (orange). W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O:

1539 Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) MVDA-I loading plot. The disposition of

1540 depositional facies in Fig. 10A is overwhelmingly due to variations in the three main variables

1541 (categories) wood (WO), amorphous organic matter (AOM) and palynomorphs (PM), while the

1542 fourth category, cuticle (CU) does not seem to have any influence.

1543

1544   FIG. 11.- A) MVDA-II score plot (PC1 vs. PC2), based on 12 variables. This PCA plot is collectively

1545   accounting for 44% of the total data variance. Note two end-members of the L-facies (marked

1546   orange) and three end-members of the F-facies (marked red). W: Washover-fan flat, F: Flood-

1547   plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) MVDA-II loading

1548   plot (PC1 vs. PC2). The black ellipse highlights the most influencing variables controlling the

1549   distribution of the three end-members of the F-facies (red). The stippled ellipse highlights the

1550   AOM, which is driving the two end-members of the L-facies (orange). Wood (WO), amorphous

1551   organic matter (AOM), palynomorphs (PM), cuticle (CU), bisaccate pollen (BP), non-saccate pollen

1552   (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA),

1553   fungal hyphae and spores (FU).

1554

1555   FIG. 12.- A) MVDA-II score plot (PC1 vs. PC3) is collectively accounting for 39% of the total data

1556   variance. After removal of the F-facies, discrimination between the L-, O-, P-, SF- and W-facies is

1557   more distinct, but the data points of the S-facies do not show a clear pattern in this plot. W:

1558   Washover-fan flat, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B)

1559   Corresponding loading plot for PC1 vs. PC3 (Fig. 12A). Wood (WO), amorphous organic matter

1560   (AOM), palynomorphs (PM), cuticle (CU), bisaccate pollen (BP), non-saccate pollen (NSP),

1561   microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal

1562   hyphae and spores (FU).

1563

1564   FIG. 13.- A) MVDA-II score plot (PC3 vs. PC4). While collectively accounting for only 27% of the

1565   total data set variance, this plot gives a nearly complete separation of the SF-facies and the O-

1566   facies. Note how the S-facies is fully embedded in the O-facies. W: Washover-fan flat, SF:

1567   Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B). Corresponding loading plot

1568   to the PC3-PC4 score plot in Figure 13A. A clear grouping of categories can be observed: the

1569   distinctly marine DI influence (rightmost) contrast markedly with fluvial and terrestrially derived

1570   particle types (NSP, MS, CU, BP, WO) (leftmost). (BO, AC) also contribute to the positive PC3 but

1571   with significantly lower loadings than DI. Wood (WO), amorphous organic matter (AOM),

1572   palynomorphs (PM), cuticle (CU), bisaccate pollen (BP), non-saccate pollen (NSP), microspores

1573 (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and

1574 spores (FU).

1575

1576   FIG. 14.- A) MVDA-II score plot (PC2 vs. PC3), collectively accounting for 31% of the total data

1577 set variance. W: Washover-fan flat, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta,

1578 S: Shelf. B) Corresponding loading plot to Figure 14A, showing a negative correlation between PM

1579 and W. The variable MS has an extreme bimodal distribution; only the two rightmost SF samples in

1580 Figure 14A have very high MS abundances. Wood (WO), amorphous organic matter (AOM),

1581 palynomorphs (PM), cuticle (CU), bisaccate pollen (BP), non-saccate pollen (NSP), microspores

1582 (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and

1583 spores (FU).

1584

1585   FIG. 15.- A) MVDA-III score plot (PC1 vs. PC2), collectively accounting for 52% of the total data

1586 set variance. Overview of the seven facies, as characterized by the eight individual palynomorph

1587 subcategories only. Two marginal F-samples (outliers), high in FA and FU, are marked green, while

1588 two other marginal F samples (marked red) display the highest PC2 scores reflecting a high

1589 proportion of MS (cfr. Fig. 15B). W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore

1590 transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading to Figure 15A explaining the

1591 marginal behavior of the four marked samples in Figure 15A. Bisaccate pollen (BP), non-saccate

1592 pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater

1593 algae (FA), fungal hyphae and spores (FU).

1594

1595

1596   FIG. 16.- A) MVDA-III score plot (PC1 vs. PC4), with two marginal F-samples excluded,

1597 collectively accounting for 32% of the total data set variance. This visualization shows a gradation

1598 from the F-facies (green) → SF-facies (yellow) → S- and O-facies (light blue and dark blue,

1599 respectively) (black arrow) described as a proximal-distal palynomorph spatial framework in the

1600 text. W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P:

1601 Prodelta, S: Shelf. B) Corresponding loading plot to Figure 16A. Bisaccate pollen (BP), non-saccate

1602   pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater

1603   algae (FA), fungal hyphae and spores (FU).

1604

1605   FIG. 17.- A) MVDA-III score plot (PC1 vs. PC2), collectively accounting for 53% of the total data

1606   set variance. PCA with the previously found four F-facies samples excluded. Two more outlying F-

1607   samples (marked red) are identified here, along the positive PC2. W: Washover-fan flat, F: Flood-

1608   plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding

1609   loading plot to Figure 17A. Bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS),

1610   dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores

1611   (FU).

1612

1613   FIG. 18.- A) MVDA-III score plot (PC 1 vs. -PC2), collectively accounting for 54% of the total data

1614   set variance. PCA with six extreme F-facies samples excluded. This visualization illustrates well the

1615   relationships between the L-, O-, SF- and W-facies. In spite of substantial overlapping, the L and W

1616   facies are completely discriminated from each other; see Figure 18B for the determining category

1617   characteristics. W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore transition, L:

1618   Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading plot to Figure 18A. Bisaccate pollen (BP),

1619   non-saccate pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO),

1620   freshwater algae (FA), fungal hyphae and spores (FU).

1621

1622

1623   FIG. 19.- A) MVDA-III score plot of (PC1 vs. PC3) collectively accounting for 48% of total data

1624   variance. In this plot the SF-facies discriminates completely from the W-facies, while P and S are

1625   extensively overlapping. W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore

1626   transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading plot to Figure 19A.

1627

1628   FIG. 20.- A) MVDA-III score plot (PC2 vs. PC3), collectively accounting for 34% of total data

1629   variance. The three compositionally most varying facies are O, L, SF. W: Washover-fan flat, F:

1630   Flood-plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B)

1631   Corresponding loading plot to Figure 20A. This figure shows that DI is the main varying category in

1632   O; NSP plays a similar role for SF. The lagoonal facies (L) is more complex, also involving BP, FA and

1633   FU. The variable MS has an extreme bimodal distribution; only the two rightmost SF samples have

1634   high MS abundances. Bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS), dinocysts

1635   (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores (FU).

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Appendices
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1641   Appendix 1a: Results of the counts of sedimentary organic particles, main categories. The numbers

1642   shown are relative abundances within the main categories.

1643

1644   Appendix 1b: Results of the counts of sedimentary organic particles, subcategories

1645   (palynomorphs). The numbers shown are relative abundances within the subcategories (the

1646   palynomorphs).

1647

1648   Appendix 2a: Major palynofacies categories counted in the present study ('variables' in the

1649   multivariate data analysis), their origin and comments on factors influencing the occurrence of the

1650   organic particles. The abbreviations used in the PCA loading plots are indicated in parentheses.

1651

1652   Appendix 2b: Palynomorph subcategories counted in the present study ('variables' in the

1653   multivariate data analysis), their origin and comments on factors influencing the occurrence of the

1654   palynomorphs. The abbreviations used in the PCA loading plots are indicated in parentheses.

1655

FIGURES

F<small>IG</small>. 1.- Schematic figure showing the seven depositional environments. FWWB: Fair weather wave-base.

F<small>IG</small>. 2A-C.- Detailed paleogeographic maps for the study area in the uppermost Oligocene – lower Miocene, Jylland, showing rivers, deltas, estauries, barrier islands, etc. Modified from Rasmussen et al. (2010).

F<small>IG</small>. 3.- Lithostratigraphic scheme, chronostratigraphy and dinocyst zonation. Modified from Rasmussen et al. (2010). The time intervals represented by the palaeogeographical maps shown in Figure 2 are indicated. *D.p.*: *Deflandrea phosphoritica*; *C.g.*: *Chiropteridium galea*; *H.* spp: *Homotryblium* spp.; *C.am.*: *Caligidinium amiculum*; *T.p.*: *Thalassiphora pelagica*; *S.h.*: *Sumatradinium hamulatum*; *C.c.*: *Cordosphaeridium cantharellus*; *E.i.*: *Exochosphaeridium insigne*; *C. au.*: *Cousteaudinium aubryae*; *L.t.*: *Labyrinthodinium truncatum*.

F<small>IG</small>. 4.-Location of studied boreholes and outcrops and location of seismic line shown in Figure 6.

F<small>IG</small>. 5.- Log-correlation panel showing sample locations in boreholes and outcrops (compare with "Samples" in Appendices 1a and 1b) and illustrating the depositional environments. In order to show a simplified geological model of a NNW-SSE striking correlation of the studied boreholes and outcrops, it was necessary to exclude the two outcrops Hvidbjerg and Dykær. All samples from the Hvidbjerg outcrop (samples SFH 1-11) represent shoreface deposits and were sampled within the Hvidbjerg Member, see further Rasmussen et al. (2010; their Figs. 31, 33). The position of the two lagoonal samples from the Dykær outcrop (LD 1-2) are shown in Rasmussen and Dybkjær (2005; their Figs. 5-7). Inserted principal sketch shows the lateral distribution of the different facies defined in this study.

F<small>IG</small>. 6.-Example of combined seismic data and borehole data (logs and lithology), the St. Vorslunde borehole, prodelta and shelf environments.

F<small>IG</small>. 7A-H.-Examples from outcrops showing sedimentary structures and trace fossils, based on which the depositional environments were interpreted. No photos of prodelta and shelf environments are shown, as they were only represented in boreholes and identified based on a combination of seismic data and borehole data (see Figure 6). A) Floodplain, Salten profile, notice wood in orange. B) Floodplain, Salten profile, rootlets indicated by arrows. C) Lagoon deposits (dark layer in lower third part of the photo) overlain by washover-fan flat deposits. Hagenør profile. D) Washover-fan flat. *Macaronichnus* trace-fossils indicated (M), Hagenør profile. E) Shoreface, Hvidbjerg profile. F) Shoreface, Børup profile. Example of a storm sand layer capped by a ripple laminated sand. The samples for the palynofacies study were taken from the thin clay-layers. *Ophiomorpha* trace-fossils indicated (O). G) Offshore, Fænø profile, Hommocky Cross Stratification alternating with heterolithic deposits. H) Offshore, Hostrup profile. Example of *Chondrites* trace-fossils.

FIG. 8A-J.- Palynofacies from the seven depositional environments. A) Floodplain, Salten profile, overview, 40 cm over sandlayer, sl. 5, N38. Non-saccate pollen (NSP), bisaccate pollen (BP) and cuticle (CU) indicated. B) Floodplain, Salten profile, sample dominated by monolete spores, 60 cm over sandlayer, sl. 5, J31. *Botryococcus* (BO), non-saccate pollen (NSP), bisaccate pollen (BP), microspores (MS) and fungal spores (FU) indicated. C) Lagoon, Hagenør profile, overview, Lab nr. 21535,sl.4, E30. Amorphous organic matter (AOM), bisaccate pollen (BP), acritarchs (AC), wood (WO) and *Botryococcus* (BO) indicated. D) Lagoon, Dykær profile, close-up of sample dominated by AOM (=partly degraded vitrinite), Lab. Nr. 17877, 14.70 m, sl.4, W40-4. Amorphous organic matter (AOM), dinocysts (DI) and non-saccate pollen (NSP) indicated. E) Washover fan flat, Hagenør profile. 4.0 m over base profile, sl. 5, L30-3. Bisaccate pollen (BP) and wood (WO) indicated. F) Shoreface, Hvidbjerg profile, lab nr. 26953, sl. 4, O35-2. Wood (WO), non-saccate pollen (NSP) and bisaccate pollen (BP) indicated. G) Prodelta. St. Vorslunde, 108m, sl. 5, K35. Freshwater algae (FA), non-saccate pollen (NSP), wood (WO) and bisaccate pollen (BP) indicated. H) Offshore. Fænø, 5.01m, sl.4, L37-2. Dinocysts (DI), bisaccate pollen (BP), non-saccate pollen (NSP) and wood (WO) indicated. I) Shelf, Klosterhede, overview, 267-268m, sl.3, J34-3. Dinocysts (DI), acritarchs (AC) and wood (WO) indicated. J) Shelf, Harre-1,close-up, transition from structured wood to amorphous organic matter (AOM) (from 1 to 3) 48,25m, sl. 4, N54-1. Dinocysts (DI), non-saccate pollen (NSP) and bisaccate pollen (BP) indicated.

FIG. 9.- Box Plot. A) The four main categories. B) The eight palynomorph-subcategories. Note that the data from the lagoonal facies and the floodplain facies are shown inclusive outliers and exclusive outliers, respectively. The data are presented as relative abundances with a minimum and a maximum value, 25% and 75% values and a median value of each category/subcategory.

FIG. 10.- A) MVDA-I score plot (PC1 vs. PC2). All facies except (O) and (F) are delineated with convex polygons. O and F are not delineated in this plot, but are treated below. Note the two end-members of the (L)-facies (orange). W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) MVDA-I loading plot. The disposition of depositional facies in Fig. 10A is overwhelmingly due to variations in the three main variables (categories) wood (WO), amorphous organic matter (AOM) and palynomorphs (PM), while the fourth category, cuticle (CU) does not seem to have any influence.

FIG. 11.- A) MVDA-II score plot (PC1 vs. PC2), based on 12 variables. This PCA plot is collectively accounting for 44% of the total data variance. Note two end-members of the L-facies (marked orange) and three end-members of the F-facies (marked red). W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) MVDA-II loading plot (PC1 vs. PC2). The black ellipse highlights the most influencing variables controlling the distribution of the three end-members of the F-facies (red). The stippled ellipse highlights the AOM, which is driving the two end-members of the L-facies (orange). Wood (WO), amorphous organic matter (AOM), palynomorphs (PM), cuticle (CU), bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores (FU).

FIG. 12.- A) MVDA-II score plot (PC1 vs. PC3) is collectively accounting for 39% of the total data variance. After removal of the F-facies, discrimination between the L-, O-, P-, SF- and W-facies is more distinct, but the data points of the S-facies do not show a clear pattern in this plot. W: Washover-fan flat, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading plot for PC1 vs. PC3 (Fig. 12A). Wood (WO), amorphous organic matter (AOM), palynomorphs (PM), cuticle (CU), bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores (FU).

FIG. 13.- A) MVDA-II score plot (PC3 vs. PC4). While collectively accounting for only 27% of the total data set variance, this plot gives a nearly complete separation of the SF-facies and the O-facies. Note how the S-facies is fully embedded in the O-facies. W: Washover-fan flat, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S:

Shelf. B). Corresponding loading plot to the PC3-PC4 score plot in Figure 13A. A clear grouping of categories can be observed: the distinctly marine DI influence (rightmost) contrast markedly with fluvial and terrestrially derived particle types (NSP, MS, CU, BP, WO) (leftmost). (BO, AC) also contribute to the positive PC3 but with significantly lower loadings than DI. Wood (WO), amorphous organic matter (AOM), palynomorphs (PM), cuticle (CU), bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores (FU).

FIG. 14.- A) MVDA-II score plot (PC2 vs. PC3), collectively accounting for 31% of the total data set variance. W: Washover-fan flat, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading plot to Figure 14A, showing a negative correlation between PM and W. The variable MS has an extreme bimodal distribution; only the two rightmost SF samples in Figure 14A have very high MS abundances. Wood (WO), amorphous organic matter (AOM), palynomorphs (PM), cuticle (CU), bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores (FU).

FIG. 15.- A) MVDA-III score plot (PC1 vs. PC2), collectively accounting for 52% of the total data set variance. Overview of the seven facies, as characterized by the eight individual palynomorph subcategories only. Two marginal F-samples (outliers), high in FA and FU, are marked green, while two other marginal F samples (marked red) display the highest PC2 scores reflecting a high proportion of MS (cfr. Fig. 15B). W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading to Figure 15A explaining the marginal behavior of the four marked samples in Figure 15A. Bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores (FU).

FIG. 16.- A) MVDA-III score plot (PC1 vs. PC4), with two marginal F-samples excluded, collectively accounting for 32% of the total data set variance. This visualization shows a gradation from the F-facies (green) → SF-facies (yellow) → S- and O-facies (light blue and dark blue, respectively) (black arrow) described as a proximal-distal palynomorph spatial framework in the text. W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading plot to Figure 16A. Bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores (FU).

FIG. 17.- A) MVDA-III score plot (PC1 vs. PC2), collectively accounting for 53% of the total data set variance. PCA with the previously found four F-facies samples excluded. Two more outlying F-samples (marked red) are identified here, along the positive PC2. W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading plot to Figure 17A. Bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores (FU).

FIG. 18.- A) MVDA-III score plot (PC 1 vs. -PC2), collectively accounting for 54% of the total data set variance. PCA with six extreme F-facies samples excluded. This visualization illustrates well the relationships between the L-, O-, SF- and W-facies. In spite of substantial overlapping, the L and W facies are completely discriminated from each other; see Figure 18B for the determining category characteristics. W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading plot to Figure 18A. Bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores (FU).

FIG. 19.- A) MVDA-III score plot of (PC1 vs. PC3) collectively accounting for 48% of total data variance. In this plot the SF-facies discriminates completely from the W-facies, while P and S are extensively overlapping. W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading plot to Figure 19A.

FIG. 20.- A) MVDA-III score plot (PC2 vs. PC3), collectively accounting for 34% of total data variance. The three compositionally most varying facies are O, L, SF. W: Washover-fan flat, F: Flood-plain, SF: Shoreface, O: Offshore transition, L: Lagoonal, P: Prodelta, S: Shelf. B) Corresponding loading plot to Figure 20A. This figure shows that DI is the main varying category in O; NSP plays a similar role for SF. The lagoonal facies (L) is more complex, also involving BP, FA and FU. The variable MS has an extreme bimodal distribution; only the two rightmost SF samples have high MS abundances. Bisaccate pollen (BP), non-saccate pollen (NSP), microspores (MS), dinocysts (DI), acritarchs (AC), *Botryococcus* (BO), freshwater algae (FA), fungal hyphae and spores (FU).

Appendix 1a: Palynofacies data, main categories, relative abundances (100% = total)

Position of samples are shown in Fig. 5

Palaeoenvironment: Shelf

	Samples		Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-particles	Total %
St. Vorslunde	SSV1		0	61	25	14	100
	SSV2		0	63	23	14	100
	SSV3		0	60	29	11	100
	SSV4		1	23	52	24	100
	SSV5		0	32	46	22	100
	SSV6		0	50	40	10	100
	SSV7		0	20	54	26	100
Vandel Mark	SVM1		0	36	49	15	100
Andkær	SA1		0	81	11	8	100
Resen	SR1		1	59	18	22	100
	SR2		0	69	13	18	100
	SR3		1	77	8	14	100
	SR4		1	90	2	7	100
	SR5		1	87	4	8	100
	SR6		0	78	3	19	100
	SR7		1	87	2	10	100
Harre	SH1		0	64	29	7	100
	SH2		0	57	34	9	100
	SH3		0	64	30	6	100
	SH4		0	79	18	3	100
	SH5		0	83	14	3	100
	SH6		0	77	17	6	100
Number of samples:	22	MIN	0	20	2	3	
		25%	0	57.5	11.5	7.25	
		Median:	0	64	20.5	10.5	
		75%	0.75	78.75	33	17.25	
		MAX	1	90	54	26	

Palaeoenvironment: Offshore

	Samples	Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-	Total %

						particles	
Hostrup	OH1		0	90	8	2	100
	OH2		0	98	1	1	100
	OH3		2	89	7	2	100
	OH4		3	84	5	8	100
	OH5		3	72	5	20	100
	OH6		1	76	6	17	100
	OH7		1	94	2	3	100
	OH8		1	97	0	2	100
	OH9		1	97	1	1	100
Fænø	OF1		1	89	1	9	100
	OF2		1	89	3	7	100
	OF3		0	90	2	8	100
	OF4		1	71	6	22	100
	OF5		1	96	1	2	100
	OF6		1	95	0	4	100
	OF7		1	51	6	42	100
	OF8		4	66	2	28	100
	OF9		3	38	2	57	100
	OF10		1	65	1	33	100
	OF11		0	86	1	13	100
Klosterhede	OK1		1	68	4	27	100
	OK2		0	50	10	40	100
	OK3		1	59	14	26	100
Number of samples:	23	MIN	0	38	0	1	
		25%	1	67	1	2.5	
		Median:	1	86	2	9	
		75%	1	92	6	26.5	
		MAX	4	98	14	57	

Palaeoenvironment: Prodeltaic

	Samples	Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-particles	Total %
St. Vorslunde	PSV1	1	19	43	37	100
	PSV2	1	78	12	9	100
	PSV3	0	43	26	31	100

PSV4	1	52	31	16	100
PSV5	0	43	25	32	100
PSV6	0	40	46	14	100
PSV7	0	47	46	7	100
PSV8	0	65	28	7	100
PSV9	0	53	30	17	100
PSV10	0	84	10	6	100
PSV11	0	60	26	14	100
PSV12	0	50	35	15	100
PSV13	0	49	31	20	100
PSV14	0	41	35	24	100
PSV15	0	40	44	16	100
PSV16	0	62	25	13	100
PSV17	0	62	30	8	100
PSV18	0	65	29	6	100
PSV19	0	59	27	14	100
PSV20	0	41	41	18	100
PSV21	0	43	35	22	100
PSV22	0	58	30	12	100
PSV23	0	43	45	12	100
PSV24	0	58	27	15	100
PSV25	0	48	36	16	100
PSV26	0	67	22	11	100
PSV27	0	62	24	14	100
Vandel Mark PVM1	0	22	35	43	100
PVM2	0	24	35	41	100
PVM3	1	31	51	17	100
PVM4	0	28	45	27	100
PVM5	0	50	21	29	100
PVM6	0	50	33	17	100
PVM7	0	40	45	15	100
PVM8	0	41	41	18	100
PVM9	0	30	59	11	100
PVM10	0	43	38	19	100
PVM11	0	56	28	16	100
PVM12	0	33	50	17	100
PVM13	0	30	58	12	100
PVM14	0	48	24	29	101
PVM15	0	44	40	16	100
Andkær PA1	0	65	28	7	100

Samples	Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-particles	Total %
PA2	0	58	38	4	100
PA3	0	66	23	11	100
PA4	0	60	31	9	100
PA5	0	54	28	18	100
PA6	0	58	25	17	100
PA7	0	63	22	15	100
PA8	0	48	22	30	100
PA9	0	25	35	40	100
PA10	0	75	20	5	100
PA11	0	77	13	10	100

Number of samples:	53					
		MIN	0	19	10	4
		25%	0	41	25	11
		Median:	0	50	31	16
		75%	0	60	40	19
		MAX	1	84	59	43

Palaeoenvironment: Shoreface

	Samples	Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-particles	Total %
Andkær	SFA1	0	46	8	46	100
	SFA2	1	28	12	59	100
	SFA3	0	42	12	46	100
	SFA4	0	29	14	57	100
Børup	SFB1	0	14	2	84	100
	SFB2	0	63	1	36	100
	SFB3	0	10	1	89	100
	SFB4	1	29	1	69	100
Hvidbjerg	SFH1	3	77	3	17	100
	SFH2	6	86	2	6	100
	SFH3	4	54	2	40	100
	SFH4	0	14	2	84	100
	SFH5	0	4	2	94	100
	SFH6	0	59	0	41	100
	SFH7	0	10	1	89	100
	SFH8	1	33	0	66	100
	SFH9	1	16	1	82	100
	SFH10	1	35	1	63	100
	SFH11	1	21	0	78	100

Rønshoved	SFR1		1	93	1	5	100
	SFR2		1	91	1	7	100
	SFR3		1	94	2	3	100
	SFR4		1	90	1	8	100
Number of samples:	23	MIN	0	4	0	3	
		25%	0	18.5	1	26.5	
		Median:	1	35	1	57	
		75%	1	70	2	80	
		MAX	6	94	14	94	

Palaeoenvironment: Washover fan flat	Samples		Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-particles	Total %
Hagenør	WH1		3	91	0	6	100
	WH2		4	59	3	34	100
	WH3		2	32	3	63	100
	WH4		3	41	2	54	100
Skansebakke	WS1		4	88	1	7	100
	WS2		0	86	1	13	100
	WS3		1	97	1	1	100
	WS4		1	92	0	7	100
	WS5		0	82	1	17	100
Number of samples:	9	MIN	0	32	0	1	
		25%	1	59	1	7	
		Median:	2	86	1	13	
		75%	3	91	2	34	
		MAX	4	97	3	63	

Palaeoenvironment: Lagoonal	Samples		Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-particles	Total %
			CU	PM	AOM	WO	
Dykær, data from Dybkjær and Rasmussen (2005)	LD1		0	4	94	2	100
	LD2		0	7	86	7	100
Hagenør	LH1		1	77	4	18	100

	Samples	CU	PM	AOM	WO	Total %
	LH2	2	62	8	28	100
	LH3	2	75	5	18	100
	LH4	2	35	12	51	100
	LH5	0	86	4	10	100
	LH6	1	88	2	9	100
	LH7	1	32	9	58	100
	LH8	1	62	20	17	100
	LH9	2	37	7	54	100
	LH10	1	59	31	9	100
	LH11	0	55	33	12	100
	LH12	0	42	45	13	100
	LH13	0	47	42	11	100
	LH14	0	36	54	10	100
Fakkegrav	LF1	1	83	3	13	100
	LF2	1	91	3	5	100
Skansebakke	LS1	2	89	2	7	100
	LS2	1	94	1	4	100
	LS3	1	93	1	5	100
	LS4	0	95	1	4	100

Number of samples:	22	MIN	0	4	1	2	
		25%	0	38.25	3	7	
		Median:	1	62	7.5	10.5	
		75%	1	87.5	32.5	17.75	
		MAX	2	95	94	58	

Palaeoenvironment: Lagoonal
Note: dataset is excl. outliers

	Samples	Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-particles	Total %
		CU	PM	AOM	WO	
Hagenør	LH1	1	77	4	18	100
	LH2	2	62	8	28	100
	LH3	2	75	5	18	100
	LH4	2	35	12	51	100
	LH5	0	86	4	10	100
	LH6	1	88	2	9	100
	LH7	1	32	9	58	100
	LH8	1	62	20	17	100

	Samples	Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-particles	Total %
	LH9	2	37	7	54	100
	LH10	1	59	31	9	100
	LH11	0	55	33	12	100
	LH12	0	42	45	13	100
	LH13	0	47	42	11	100
	LH14	0	36	54	10	100
Fakkegrav	LF1	1	83	3	13	100
	LF2	1	91	3	5	100
Skansebakke	LS1	2	89	2	7	100
	LS2	1	94	1	4	100
	LS3	1	93	1	5	100
	LS4	0	95	1	4	100
Number of samples:	20	MIN	0	32	1	4
		25%	0	45.75	2.75	8.5
		Median:	1	68.5	6	11.5
		75%	1.25	88.25	22.75	18
		MAX	2	95	54	58

Palaeoenvironment: Fluvial/floodplain

	Samples	Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-particles	Total %
Voervadsbro	FVB1	1	86	1	12	100
	FVB2	1	94	1	4	100
Salten	FS1	1	64	10	25	100
	FS2	1	82	1	16	100
	FS3	0	66	8	26	100
	FS4	12	71	4	13	100
	FS5	3	97	0	1	101
	FS6	8	92	0	0	100
	FS7	2	97	1	0	100
	FS8	4	86	4	6	100
	FS9	9	79	4	8	100
	FS10	1	89	1	9	100
	FS11	1	97	0	2	100
	FS12	7	86	4	3	100
	FS13	1	98	0	1	100
	FS14	1	97	1	1	100

Number of samples:	16	MIN	0	64	0	0	
		25%	1	81.25	0.75	1	
		Median:	1	87.5	1	5	
		75%	4.75	97	4	12.25	
		MAX	12	98	10	26	

Palaeoenvironment: Fluvial/floodplain
Note: dataset is excl. outliers

	Samples	Cuticle	Palynomorphs	AOM/degraded vitrinite	Wood-particles	Total %
Voervadsbro	FVB1	1	86	1	12	100
	FVB2	1	94	1	4	100
Salten	FS1	1	64	10	25	100
	FS2	1	82	1	16	100
	FS3	0	66	8	26	100
	FS7	2	97	1	0	100
	FS11	1	97	0	2	100
	FS12	7	86	4	3	100
	FS13	1	98	0	1	100
	FS14	1	97	1	1	100

Number of samples:	10	MIN	0	64	0	0
		25%	1	83	1	1.25
		Median:	1	90	1	3.5
		75%	1	97	3.25	15
		MAX	7	98	10	26

Appendix 1b: Palynofacies data, subcategories, relative abundances (100% = total)

Position of samples are shown in Fig. 5

Palaeoenvironment: Shelf	Samples		Dinocysts	Acritarchs	Botryococcus	Bisaccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
			DI	AC	BO	BP	NSP	MS	FA	FU		
St. Vorslunde	SSV1		30	1	2	54	12	1	0	0	100	30.2
	SSV2		13	1	1	64	18	1	1	1	100	61.8
	SSV3		31	1	1	50	16	1	0	0	100	35.4
	SSV4		24	1	0	59	13	2	1	0	100	40.0
	SSV5		26	0	1	59	13	1	0	0	100	35.0
	SSV6		21	1	2	53	22	1	0	0	100	52.3
	SSV7		28	1	1	51	17	1	1	0	100	40.4
Vandel Mark	SVM1		14	0	1	70	13	1	1	0	100	51.7
Andkær	SA1		24	1	1	50	23	1	0	0	100	50.0
Resen	SR1		21	1	10	31	33	1	2	1	100	63.8
	SR2		33	1	11	30	19	3	2	1	100	43.1
	SR3		29	4	14	26	24	0	2	1	100	48.2
	SR4		6	1	4	41	45	1	1	1	100	88.9
	SR5		14	2	1	43	37	1	1	1	100	74.1
	SR6		26	1	2	42	28	0	1	0	100	52.7
	SR7		29	2	1	39	27	1	0	1	100	50.0
Harre	SH1		12	0	0	69	18	1	0	0	100	61.3
	SH2		19	0	0	65	15	1	0	0	100	45.7
	SH3		32	0	0	60	7	1	0	0	100	20.0
	SH4		44	0	1	48	6	1	0	0	100	13.7
	SH5		34	0	1	53	11	0	0	1	100	26.1
	SH6		42	0	0	50	6	1	0	1	100	16.0
											Avg-ratio	45.5
Number of samples:	22	MIN	6	0	0	26	6	0	0	0		
		25%	19.5	0	1	42.25	13	1	0	0		
		Median:	26	1	1	50.5	17.5	1	0	0		
		75%	30.75	1	2	59	23.75	1	1	1		
		MAX	44	4	14	70	45	3	2	1		

Palaeoenvironment: Offshore	Samples		Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
Hostrup	OH1		12	2	2	43	39	1	1	0	100	77.4
	OH2		6	1	1	53	39	0	0	0	100	86.7
	OH3		5	1	2	40	50	1	1	0	100	91.2
	OH4		16	2	4	30	44	0	3	1	100	75.0
	OH5		36	4	10	13	28	1	6	2	100	50.7

	Samples	Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
	OH6	11	1	5	32	42	0	2	7	100	**82.3**
	OH7	6	2	2	31	54	1	2	2	100	**90.8**
	OH8	7	1	2	35	53	1	1	0	100	**88.7**
	OH9	6	1	3	49	40	0	1	0	100	**87.2**
Fænø	OF1	4	0	8	79	8	0	1	0	100	**69.2**
	OF2	6	1	3	40	47	1	1	1	100	**89.3**
	OF3	19	1	12	31	28	2	7	0	100	**66.1**
	OF4	19	1	12	44	21	2	1	0	100	**55.8**
	OF5	2	0	24	64	7	1	2	0	100	**83.3**
	OF6	4	1	8	69	16	1	1	0	100	**81.8**
	OF7	43	7	35	5	4	1	4	1	100	**18.9**
	OF8	31	3	32	17	13	0	2	2	100	**35.4**
	OF9	53	2	30	4	9	0	2	0	100	**17.2**
	OF10	28	2	14	41	12	1	2	0	100	**34.9**
	OF11	30	1	22	20	25	1	1	0	100	**47.4**
Klosterhede	OK1	41	1	6	26	23	1	1	1	100	**38.8**
	OK2	83	1	8	1	5	0	1	1	100	**7.8**
	OK3	92	1	3	0	2	1	1	0	100	**4.2**
										Avg-ratio	**60.0**
Number of samples:	23	MIN	2	0	1	0	2	0	0	0	
		25%	6	1	3	18.5	10.5	0	1	0	
		Median:	16	1	8	32	25	1	1	0	
		75%	33.5	2	13	43.5	41	1	2	1	
		MAX	92	7	35	79	54	2	7	7	

Palaeoenvironment: Prodeltaic	Samples	Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
St. Vorslunde	PSV1	12	1	2	59	16	2	8	0	100	**68.4**
	PSV2	9	1	1	70	16	1	2	0	100	**67.9**
	PSV3	10	1	0	58	26	1	4	0	100	**75.6**
	PSV4	12	0	1	68	13	1	4	1	100	**61.3**
	PSV5	12	0	1	65	18	1	3	0	100	**64.7**
	PSV6	12	1	1	65	16	1	3	1	100	**63.6**
	PSV7	15	2	2	63	15	1	1	1	100	**54.5**
	PSV8	25	1	1	57	14	1	0	1	100	**39.0**
	PSV9	5	0	1	76	16	1	0	1	100	**78.3**
	PSV10	11	1	1	69	17	1	0	0	100	**62.1**
	PSV11	18	1	1	43	35	1	1	0	100	**67.3**
	PSV12	17	1	0	47	32	1	1	1	100	**67.3**
	PSV13	21	1	0	53	23	1	1	0	100	**54.3**
	PSV14	24	1	1	47	24	1	1	1	100	**52.9**
	PSV15	21	1	1	51	23	1	1	1	100	**55.3**
	PSV16	30	0	1	54	13	1	1	0	100	**33.3**
	PSV17	27	1	1	58	13	0	0	0	100	**32.5**
	PSV18	47	1	1	42	7	1	1	0	100	**16.1**

	Samples	Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
	PSV19	35	1	1	47	15	1	0	0	100	**31.4**
	PSV20	39	1	1	37	20	1	0	1	100	**36.1**
	PSV21	21	1	1	53	22	1	1	0	100	**53.3**
	PSV22	22	0	1	58	17	1	1	0	100	**46.3**
	PSV23	21	1	1	45	31	1	0	0	100	**60.4**
	PSV24	12	1	1	59	26	1	0	0	100	**69.2**
	PSV25	24	1	1	50	23	1	0	0	100	**50.0**
	PSV26	23	1	1	63	10	1	1	0	100	**34.3**
	PSV27	40	2	1	40	16	1	0	0	100	**29.8**
Vandel Mark	PVM1	2	1	1	56	33	2	4	1	100	**95.2**
	PVM2	4	1	1	59	32	1	1	1	100	**89.7**
	PVM3	19	0	1	58	20	1	1	0	100	**53.7**
	PVM4	4	2	0	61	30	1	2	0	100	**89.2**
	PVM5	12	1	1	65	17	1	2	1	100	**63.6**
	PVM6	13	1	1	56	26	1	1	1	100	**69.0**
	PVM7	16	2	2	60	16	1	2	1	100	**55.6**
	PVM8	19	1	2	58	19	1	0	0	100	**51.3**
	PVM9	25	1	1	56	14	1	1	1	100	**40.5**
	PVM10	14	1	0	69	16	0	0	0	100	**53.3**
	PVM11	30	2	2	50	14	1	1	0	100	**34.8**
	PVM12	13	1	1	70	13	2	0	0	100	**53.6**
	PVM13	17	1	1	63	17	1	0	0	100	**51.4**
	PVM14	10	1	3	60	21	2	2	1	100	**72.2**
	PVM15	23	1	1	65	9	0	1	0	100	**30.3**
Andkær	PA1	6	2	1	44	44	1	1	1	100	**88.7**
	PA2	6	1	0	41	50	1	1	0	100	**89.7**
	PA3	8	1	0	41	48	1	1	0	100	**86.2**
	PA4	8	0	0	43	46	1	1	1	100	**86.0**
	PA5	13	1	0	38	46	1	1	0	100	**78.7**
	PA6	7	1	1	38	50	1	1	1	100	**88.3**
	PA7	13	1	1	33	50	0	2	0	100	**80.0**
	PA8	14	1	1	28	52	1	3	0	100	**80.0**
	PA9	15	1	1	27	51	1	4	0	100	**78.9**
	PA10	14	1	2	43	39	1	0	0	100	**74.1**
	PA11	21	1	1	38	37	1	1	0	100	**65.0**
										Avg-ratio	**60.8**
Number of samples:	53	MIN	2	0	0	27	7	0	0	0	
		25%	12	1	1	43	16	1	0	0	
		Median:	15	1	1	56	20	1	1	0	
		75%	22	1	1	61	32	1	2	1	
		MAX	47	2	3	76	52	2	8	1	

Note: MIN/25%/Median/75%/MAX values are displayed across the Dinocysts through Fungal hyphae and -spores columns.

Palaeoenvironment: Shoreface

	Samples	Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
Andkær	SFA1	16	2	1	53	27	1	0	0	100	**63.6**

	Samples	Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
	SFA2	15	1	1	49	33	1	0	0	100	69.4
	SFA3	9	2	1	47	38	2	0	1	100	82.0
	SFA4	11	1	1	48	38	1	0	0	100	78.0
Børup	SFB1	3	1	9	49	36	1	1	0	100	92.7
	SFB2	4	0	9	54	32	1	0	0	100	89.2
	SFB3	4	1	19	41	34	1	0	0	100	89.7
	SFB4	3	0	20	48	28	0	1	0	100	90.6
Hvidbjerg	SFH1	4	1	3	66	23	2	0	1	100	86.7
	SFH2	7	1	3	57	30	2	0	0	100	82.1
	SFH3	1	1	3	56	36	2	0	1	100	97.5
	SFH4	1	0	10	32	47	9	0	1	100	98.3
	SFH5	0	2	4	16	71	5	1	1	100	100.0
	SFH6	4	1	3	72	20	0	0	0	100	83.3
	SFH7	2	1	3	72	19	1	1	1	100	91.7
	SFH8	1	0	4	38	52	1	3	1	100	98.3
	SFH9	2	1	4	61	29	1	1	1	100	94.1
	SFH10	3	0	6	62	28	0	1	0	100	90.6
	SFH11	2	0	4	69	22	2	0	1	100	92.6
Rønshoved	SFR1	7	0	1	68	23	1	0	0	100	77.4
	SFR2	5	0	2	78	15	0	0	0	100	75.0
	SFR3	5	0	2	32	60	1	0	0	100	92.4
	SFR4	6	1	2	54	36	0	0	1	100	86.0
										Avg-ratio	87.0
Number of samples:	23 MIN	0	0	1	16	15	0	0	0		
	25%	2	0	2	47.5	25	1	0	0		
	Median:	4	1	3	54	32	1	0	0		
	75%	6.5	1	5	64	37	2	1	1		
	MAX	16	2	20	78	71	9	3	1		

Palaeoenvironment: Washover fan flat

	Samples	Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
Hagenør	WH1	0	1	1	92	4	0	2	0	100	100.0
	WH2	1	1	4	66	23	1	4	0	100	96.6
	WH3	2	1	5	71	17	1	2	1	100	91.3
	WH4	1	1	3	75	16	1	2	1	100	95.2
Skansebakke	WS1	0	0	2	92	6	0	0	0	100	100.0
	WS2	1	1	7	88	3	0	0	0	100	75.0
	WS3	2	0	2	92	3	1	0	0	100	66.7
	WS4	1	1	2	91	4	1	0	0	100	83.3
	WS5	1	0	5	83	9	1	1	0	100	91.7
										Avg-ratio	88.9
Number of samples:	9 MIN	0	0	1	66	3	0	0	0		
	25%	1	0	2	75	4	0	0	0		
	Median:	1	1	3	88	6	1	1	0		

		Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
75%		1	1	5	92	16	1	2	0		
MAX		2	1	7	92	23	1	4	1		

Palaeoenvironment: Lagoonal

	Samples	Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
Dykær, data from Dybkjær and Rasmussen (2005)	LD1	18	2	1	21	55	1	1	1	100	**76.3**
	LD2	18	1	2	33	43	1	1	1	100	**71.9**
Hagenør	LH1	6	1	2	61	27	1	1	1	100	**83.3**
	LH2	16	3	5	43	23	1	6	3	100	**67.3**
	LH3	7	1	1	47	37	2	3	2	100	**86.3**
	LH4	18	1	7	36	22	1	9	6	100	**67.9**
	LH5	7	1	1	29	57	2	2	1	100	**89.9**
	LH6	4	2	1	31	57	0	3	2	100	**93.9**
	LH7	12	2	15	9	44	1	10	7	100	**83.8**
	LH8	11	5	2	19	54	1	4	4	100	**85.1**
	LH9	11	5	16	9	40	1	8	10	100	**84.3**
	LH10	12	1	2	32	51	1	1	0	100	**81.5**
	LH11	10	0	1	32	54	1	2	0	100	**85.1**
	LH12	12	1	0	37	46	2	1	1	100	**80.6**
	LH13	7	1	1	35	54	0	1	1	100	**88.9**
	LH14	10	1	1	30	54	2	1	1	100	**85.3**
Fakkegrav	LF1	2	3	1	26	64	2	1	1	100	**97.1**
	LF2	5	3	1	19	67	2	2	1	100	**93.5**
Skansebakke	LS1	9	2	3	35	48	2	0	1	100	**85.0**
	LS2	10	1	2	32	53	1	1	0	100	**84.6**
	LS3	5	2	1	39	51	1	0	1	100	**91.4**
	LS4	5	2	4	41	44	1	2	1	100	**90.6**
										Avg-ratio	**84.3**
Number of samples:	22	MIN 2	0	0	9	22	0	0	0		
		25% 6.25	1	1	26.75	43.25	1	1	1		
		Median: 10	1.5	1.5	32	51	1	1.5	1		
		75% 12	2	2.75	36.75	54	2	3	2		
		MAX 18	5	16	61	67	2	10	10		

Palaeoenvironment: Lagoonal
Note: dataset is excl. outliers

	Samples	Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
Hagenør	LH1	6	1	2	61	27	1	1	1	100	**83.3**
	LH2	16	3	5	43	23	1	6	3	100	**67.3**
	LH3	7	1	1	47	37	2	3	2	100	**86.3**
	LH4	18	1	7	36	22	1	9	6	100	**67.9**
	LH5	7	1	1	29	57	2	2	1	100	**89.9**
	LH6	4	2	1	31	57	0	3	2	100	**93.9**
	LH7	12	2	15	9	44	1	10	7	100	**83.8**

	Samples	Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
	LH8	11	5	2	19	54	1	4	4	100	**85.1**
	LH9	11	5	16	9	40	1	8	10	100	**84.3**
	LH10	12	1	2	32	51	1	1	0	100	**81.5**
	LH11	10	0	1	32	54	1	2	0	100	**85.1**
	LH12	12	1	0	37	46	2	1	1	100	**80.6**
	LH13	7	1	1	35	54	0	1	1	100	**88.9**
	LH14	10	1	1	30	54	2	1	1	100	**85.3**
Fakkegrav	LF1	2	3	1	26	64	2	1	1	100	**97.1**
	LF2	5	3	1	19	67	2	2	1	100	**93.5**
Skansebakke	LS1	9	2	3	35	48	2	0	1	100	**85.0**
	LS2	10	1	2	32	53	1	1	0	100	**84.6**
	LS3	5	2	1	39	51	1	0	1	100	**91.4**
	LS4	5	2	4	41	44	1	2	1	100	**90.6**
										Avg-ratio	**85.3**

Number of samples:	20										
	MIN	2	0	0	9	22	0	0	0		
	25%	5.75	1	1	28.25	43	1	1	1		
	Median:	9.5	1.5	1.5	32	51	1	2	1		
	75%	11.25	2.25	3.25	37.5	54	2	3.25	2.25		
	MAX	18	5	16	61	67	2	10	10		

Palaeoenvironment: Fluvial/floodplain

	Samples	Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
Voervadsbro	FVB1	0	0	10	85	4	1	0	0	100	**100.0**
	FVB2	1	1	8	85	5	0	0	0	100	**83.3**
Salten	FS1	1	0	4	88	4	3	0	0	100	**87.5**
	FS2	1	0	2	76	19	1	1	0	100	**95.5**
	FS3	1	0	2	80	14	1	1	1	100	**94.4**
	FS4	0	0	30	26	37	1	2	4	100	**100.0**
	FS5	0	0	5	55	39	1	0	0	100	**100.0**
	FS6	0	0	3	34	57	3	2	1	100	**100.0**
	FS7	1	0	1	5	33	60	0	0	100	**98.9**
	FS8	1	1	23	15	35	1	12	12	100	**98.4**
	FS9	1	1	40	8	21	1	17	11	100	**98.0**
	FS10	0	1	3	77	16	2	1	0	100	**100.0**
	FS11	1	1	2	50	25	17	1	3	100	**97.9**
	FS12	0	0	1	42	16	36	2	3	100	**100.0**
	FS13	0	0	0	3	8	88	0	1	100	**100.0**
	FS14	0	0	2	83	11	1	2	1	100	**100.0**
										Avg-ratio	**97.1**

Number of samples:	16										
	MIN	0	0	0	3	4	0	0	0		
	25%	0	0	2	23.25	10.25	1	0	0		
	Median:	0.5	0	3	52.5	17.5	1	1	1		
	75%	1	1	8.5	80.75	33.5	6.5	2	3		
	MAX	1	1	40	88	57	88	17	12		

Palaeoenvironment: Fluvial/floodplain
Note: dataset is excl. outliers

	Samples		Dinocysts	Acritarchs	Botryococcus	Saccate pollen	Non-saccate pollen	Microspores	Freshwater algae	Fungal hyphae and -spores	Total %	P/D index
Voervadsbro	FVB1		0	0	10	85	4	1	0	0	100	**100.0**
	FVB2		1	1	8	85	5	0	0	0	100	**83.3**
Salten	FS1		1	0	4	88	4	3	0	0	100	**87.5**
	FS2		1	0	2	76	19	1	1	0	100	**95.5**
	FS3		1	0	2	80	14	1	1	1	100	**94.4**
	FS7		1	0	1	5	33	60	0	0	100	**98.9**
	FS11		1	1	2	50	25	17	1	3	100	**97.9**
	FS12		0	0	1	42	16	36	2	3	100	**100.0**
	FS13		0	0	0	3	8	88	0	1	100	**100.0**
	FS14		0	0	2	83	11	1	2	1	100	**100.0**
											Avg-ratio	**95.8**
Number of samples:	10	MIN	0	0	0	3	4	0	0	0		
		25%	0	0	1.25	44	5.75	1	0	0		
		Median:	1	0	2	78	12.5	2	0.5	0.5		
		75%	1	0	3.5	84.5	18.25	31.25	1	1		
		MAX	1	1	10	88	33	88	2	3		

Appendix 2a

Wood particles (WO)

Description: Sharply edges wood particles or degraded wood particles with fluffy edges, but with recognizable internal structures. Varies from totally brown through mixed brown and black to totally black. Angular to rounded, some lath-shaped (see examples on Figs. 8 f,g,h,j).

Origin and distribution: Terrestrial. During the Early Miocene swamp forests grew along large parts of the palaeo-coastline surrounding the North Sea Basin (Larsson et al. 2010; 2011). Therefore a major part of the recorded wood particles probably originate from trees that grew along the coast, some of them as mangrove, with submerged roots. When these trees died, the trunk ended up directly in the shallow water of the mangrove/swamp and slowly degraded. In a more traditional approach wood particles are seen as being mainly transported by streams and rivers from the inland vegetation (refs) to the sea. That also occurred during the Early Miocene in the Danish area, but have possible been a minor contribution to the total wood content.

Environmental significance: Wood-particles are generally more resistant to oxidation and decay than palynomorphs and are therefore generally concentrated in well-oxygenated, high-energy environments. In high-energy environments, there is also a sorting effect resulting in relatively higher abundances of wood in coarse grained deposits.

Non-structured, partly degraded vitrinite (AOM)

Description: This group comprises all forms from totally amorphous particles to strongly degraded vitrinite, with fluffy edges but without recognizable internal structures. The colors may range from lighter yellowish-grey to dark brown. See examples on figs. 8 d, j.

Origin and distribution: The major part of particles referred to this category in the present study is of dark brown color and are probably of terrestrial origin, representing degraded vitrinite (see photos showing the entire spectrum of degradation from well-preserved structured wood to

strongly degraded vitrinite, Fig.8 j). The degraded vitrinite may have a similar origin and distribution pattern in our study area as the wood particles.

Very little (less than 1%) of the recorded amorphous organic matter consists of the yellowish-grey granular amorphous matter normally found in marine environments. These particles were mainly recorded from the shelf-environment. The origin of these particles is more difficult to determine, but they could be remnants from marine algae (e.g. *Tasmanites*, dinoflagellates) as well as freshwater algae or pollen/spores. They may have been deposited as pellets, or formed on or in the sea-bed by bacterial activity and/or by aquatic invertebrates.

Environmental significance: The particles presumed to represent degraded vitrinite have the same overall environmental significance as the wood particles. Traditionally high amounts of amorphous organic matter have been interpreted as an indicator of anoxic/dysoxic bottom waters (Tyson 1995). However, it is not clear to which degree abundance of this degraded vitrinite can be used to indicate oxygen deficiency in the bottom waters, or rather indicate proximity to the swamp areas.

Cuticle and membranes (CU)

Description: Light, thin-walled (some transparent), small to large particles. Some (cuticle) show cellular structures, seldom stomata. Others (membranes) are unstructured, or show weak striation (see example on fig. 8a).

Origin and distribution: Terrestrial, comprising leaf-cuticle and plant membranes. The majority of studies on the distribution of cuticle are from deltaic settings (See refs in Tyson p. 238). In the present study, the major source of terrestrially derived organic matter, including leaf cuticle and plant membranes, must be assumed to be the mangrove forest.

Environmental significance: Cuticle fragments are easily damaged by physical degradation and therefore cannot withstand longer periods of high-energy transportation. The size and shape of

cuticles suggests that they are less resistant to degradation than wood (Fisher 1980). In the modern sediments of the Orinoco Delta, studied by Muller (1959), the cuticle fragments were concentrated near the large delta estuaries and both size and abundance decreased rapidly offshore.

Palynomorphs (PM)

This group comprises microspores, non-saccate pollen, bisaccate pollen, fungal hyphae and – spores, *Botryococcus*, other freshwater algae, dinocysts and acritarchs.

APPENDIX 2B: PALYNOMORPH SUBCATEGORIES

Palynomorph subcategories counted in the present study ('variables' in the multivariate data analysis), their origin and comments on factors influencing the occurrence of the palynomorphs. The abbreviations used in the PCA loading plots are indicated in parentheses.

Microspores (MS)

Description: Spores are microscopic grains produced during the life cycle of plants. Spores from the Cenozoic and Mesozoic eras rarely exceed 50 μm in diameter. Their wall (like in pollen grains) is made of sporopollenin and is remarkably resistant to microbial, thermal or mechanical degradation. Morphologically, spores are divided into two types: trilete and monolete, see Figure 8b.

Origin and distribution: Terrestrial. Spores are produced by ferns, scrubs, mosses and other 'lower' land plants. Spores are often deposited close to their parent plants. If transported, then primarily by water, mainly by streams and rivers and therefore deposited relatively close to river-mouths and coastal areas.

Environmental significance: High abundances of microspores indicate a terrestrial or nearshore marine environment (lake, floodplain, lagoon, estuary, delta) (Tyson 1995). Because of the riverine transport and the low buoyancy of spores and pollen, they can be used for recognizing proximal-distal trends (Muller 1959; Mudie 1982).

Non-saccate pollen (NSP)

Description: Non-saccate pollen are microscopic grains produced during the lifecycle of ('higher') land plants. In contrast to saccate pollen they don´t have saccae (airbags). The three important morphological features of non-saccate pollen are: (1) character (number, type, position, shape) of the aperture; (2) type and complexity of ornamentation; as well as (3) general shape/outline (e.g. round, oblate, prolate, lenticular), see examples in Figures 8 a, f, h.

Origin and distribution: Terrestrial. Produced by higher land plants (e.g. Taxodiaceae-Cupresseae, Alnus, Betula, Salix). Some of the pollen found in the marine deposits originates from the hinterland vegetation (transported by wind and rivers) and some were deposited very close to their parent plants which grew along the coastline.

Environmental significance: Similar to microspores the relative abundance decrease offshore and therefore can be used for a proximal-distal trend recognition (Muller 1959; Mudie 1982).

Bisaccate pollen (BP)

Description: Saccate pollen are microscopic grains produced during the lifecycle of coniferous trees. Saccate pollen contains one, two or (rarely) three air-filled sacs (saccai, bladders) attached to the central body (colpus) (see Armstrong and Brasier, 2005). In the studied material, only pollen grains with two sacci (i.e. bisaccate) were found. See examples in Figures 8 a,c,e.

Origin and distribution: Terrestrial. They can be distributed (mainly by water and wind) long distances from the parent plant. Their air-filled sacci, functioning as "swimming-belts", allow them to float on the sea-surface for some time before they sink to the bottom (the "Neves-effect") (Tyson 1995 and references therein, Armstrong and Brasier, 2005).

Environmental significance: Not a good environmental indicator as they are widely distributed in both marine and terrestrial environments. Due to the higher buoyancy of the bisaccate pollen the bisaccate/non-saccate ratio increases in a proximal-distal trend (Tyson 1995 and references therein).

***Botryococcus* spp. (BO)**

Description: Colonial Botryococcaceaen algae with an orange-brown to lustrous yellow color. The colonies show a pseudo-radial appearance and a characteristic globular outline, resembling a cauliflower (Tyson 1995) (Fig. 8c). Colonies of *Botryococcus braunii* are about 30 µm in diameter, but can grow to larger sizes up to 2000 µm in diameter (Tyson 1995 and references therein).

Origin and distribution: Aquatic organisms, found in freshwater lacustrine, fluvial, lagoonal and deltaic areas (Tyson 1995 and refs therein). They can be distributed by streams and rivers to nearshore marine depositional environments.

Environmental significance: *Botryococcus* are freshwater algae but also tolerant to brackish water conditions. *Botryococcus* spp. thrives in inland water-bodies (including lagoons) with salinities between 5 and 13‰ (Tyson 1995 and references therein).

Other freshwater algae (FA)

Description: In the present study this group comprises *Pediastrum* spp., *Mougeotia laetevirans* and *Pseudokomewuia* aff. *granulata*.

Pediastrum is a genus of green algae, in the family Hydrodictyaceae. It is a colonial algae with a flat discoidal shape and a "cog wheel shaped" outline. The coenobia (colonies of *Pediastrum*) varies in diameter between 30 and 200 µm.

Mougeotia laetevirans (A. Braun) Wittrock 1877 is a species within the family of Zygnemataceaen algae. Zygospores form as conjugating tubes. In the palynological slides of the present study they appear as cylindrical tubes in combination with circular discs (Fig. 8g).

Pseudokomewuia aff. *granulata* He Chengquan 1980 is a minute fresh water dinocyst. It is an ovoidal to spindle-shaped cyst with an apical archaeopyle, a minute antapical horn and a characteristic granulate/baculate ornamentation. The length is between 42-65 µm (Batten et al. 1999).

Origin and distribution: All these algae are aquatic organisms, living in fresh water bodies, like ponds, lakes and rivers. They may be relocated into near-coastal areas by fluvial transport.

Environmental significance: These algae do not tolerate brackish or saline waters. High abundances indicate either a fluvial depositional environment or a near-coastal setting, close to a larger river mouth.

Fungal hyphae and –spores (FU)

Description: The fungal hyphae are thin, branching tubular structures 1-30 μm wide. They may be internally divided by septae. The fungal spores are typically rounded to elongate grains, small (10-20 μm in diameter; 20-30 μm in length) with a smooth surface. Some of the spores show a "bottleneck-shaped" opening. Both hyphae and -spores have a characteristic dark brownish color (Fig. 8b). In the present study, in contrast to the approach by Tyson (1995, p. 162), both hyphae and spores are considered as palynomorphs.

Origin and distribution: The fungi included in the present study are terrestrial organisms thriving mainly in humid environments as peats and bogs. Comparable to other terrestrial palynomorphs with low buoyancy they are most abundant near their place of origin and tend to sink in still water. However, they can be transported by streams and rivers to near-coastal areas (Ingold 1971; Rees 1980, Tyson 1995 and references therein).

Environmental significance: Fungal hyphae and spores generally do not occur in high abundances in Danish Miocene successions, and rarely exceed a few percentages of the total palynomorph counts. The presence of fungal tissues indicates either a fluvial depositional environment or a near-coastal setting, close to a river mouth (Elsik 1976). Fungal spores were found to be most abundant in delta top facies compared to prodelta and outer shelf deposits (Muller 1959, Tyson 1995 and references therein). Lagoonal facies are generally characterized by a higher fungal spore content than adjacent marine shelf facies (Oboh 1992).

Acritarchs (AC)

Description: Acritarchs are hollow, organic-walled cysts. Their size (5-240 μm), shape (e.g. round, fusiform), ornamentation (from smooth to a variety of spinose, granulate or reticulate) and other morphological features (e.g. presence, length and termination of processes) are highly variable

and important for defining species or genera. Acritarchs differ from dinocysts in the absence of reflected tabulation and pre-formed excystment openings of definitive form, see example in Figure 8c.

Origin and distribution: Eukaryotic unicells of unknown biological affinity (Armstrong and Brasier, 2005). However, they are considered to be resting cysts of (marine) phytoplanktonic algae (Strother 1996).

Environmental significance: Acritarchs have mostly been found in marine deposits and probably indicate proximity to the shoreline as they often occur together with known terrestrially derived palynomorphs, (Tyson 1995).

Organic-walled dinoflagellate cysts (dinocysts) (DI)

Description: The most important defining features for dinocysts are their tabulation pattern and the type of archaeopyle. On top of that, secondary characteristics like their size (20-150 μm), shape, ornamentation and other morphological features (e.g. presence, positioning, length and termination form of processes), are highly variable and important for defining species or genera, see further Fensome et al. (1996). See examples in Figures 8 h,i,j.

Origin and distribution: Dinoflagellates are organic-walled, eukaryotic unicells, both auto- and heterotrophic. Some of them produce a resting cyst (dinocyst) as part of their lifecycle, which are preserved in the geological record. The absolute majority of dinoflagellates are marine algae and their cysts are thus indicators for marine settings. Dinocysts can be found in an array of marine environments, ranging from inner neritic to oceanic settings. Occasionally dinocysts are found far up in river systems, probably as a result of transport by high tides and storm-waves.

Environmental significance: Dinocysts are most abundant and diverse in outer neritic settings. Some dinoflagellates are tolerant to lower salinities and thrive in back-barrier environments, while others, at the contrary, prefer oceanic settings (Brinkhuis 1994). Blooms of specific autotrophic dinoflagellate taxa occur in high nutrient environments Armstrong and Brasier (2005). However,

the environmental preferences of extinct dinoflagellates are not fully understood, sometimes even contradicting (see discussion about the genus *Homotryblium* spp. in Sliwinska et al. 2014). Therefore, in the present study, dinocysts are treated as a uniform group indicating an overall marine depositional environment.

A. 21.8 Ma
B. 21.3 Ma
C. 20,7 Ma

100 km
100 km
100 km
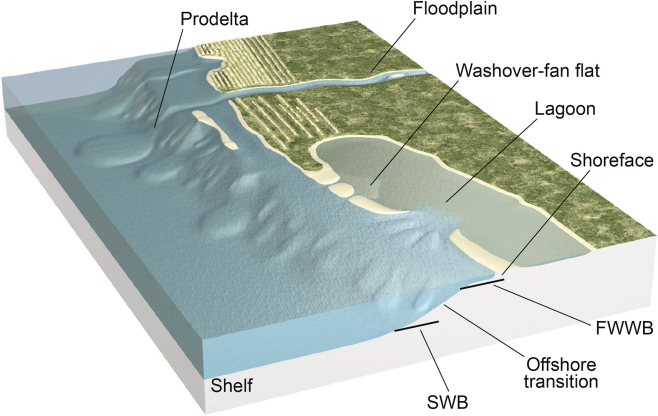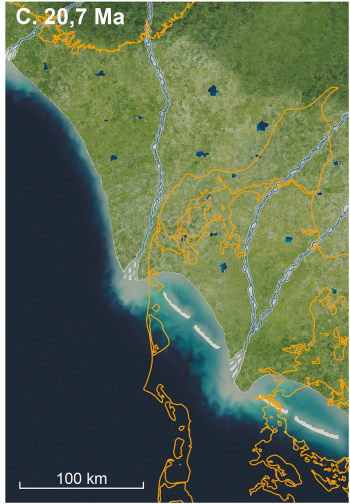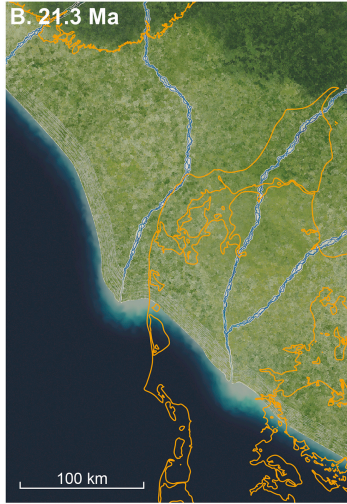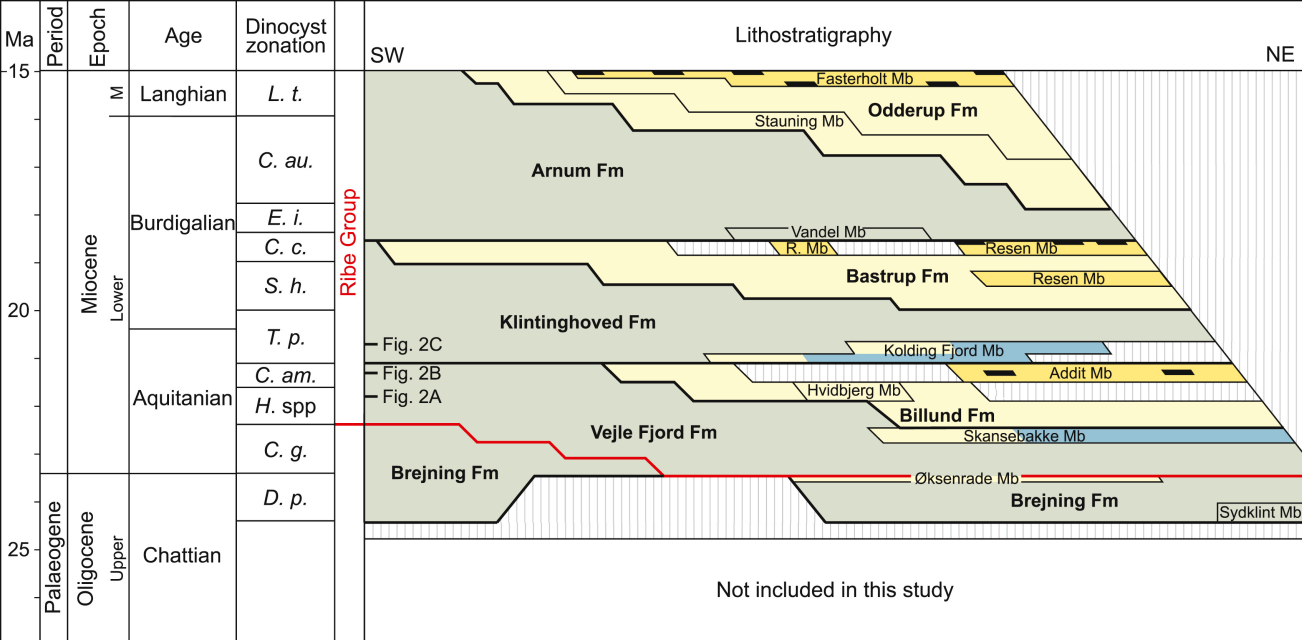
NNW Shoreface | Delta lobe

Hostrup — OH 1-9

Klosterhede DGU no. 53.617 — OK 1-3

Resen DGU no. 65.1643 — SR 1-7

Salten — FS 1-11

Voervadsbro outcrop — FVB 1-2

Harre — SH 1-6

Shoreface

SSE

Store Vorslunde
DGU no. 104.2325

Vandel Mark
DGU no. 115.1371

Fakkegrav
Skansebakke

Andkær
DGU no. 125.2017

Børup
Hagenør
Fænø
Rønshoved (east)
outcrop

PA 1-9

SFR 3-4

SFR 1-2

SFA 1-4

SFB 1-3

OF 1-11

PSV 1-27

PVM 1-15

LF 1-2

WS 1-5

LS 1-4

PA 10-11

SA 1

*WH 1-4
**LH 1-14

SVM 1

SSV 1-7

10 m

50 m

	Fluvial sand og gravel
	Flodplain
	Lagoon
	Washover-fan flat
	Delta plain
	Prodelta sand
	Prodelta mud
	Shoreface
	Offshore
	Shelf
	Borehole
	Outcrop
	Sample interval
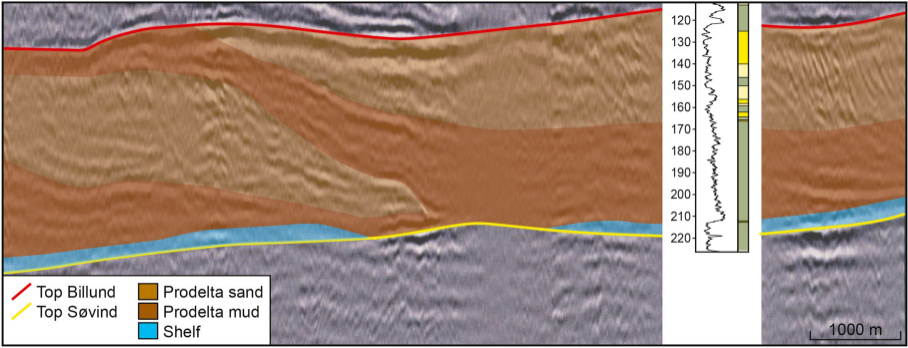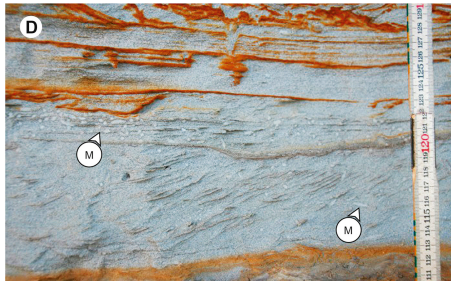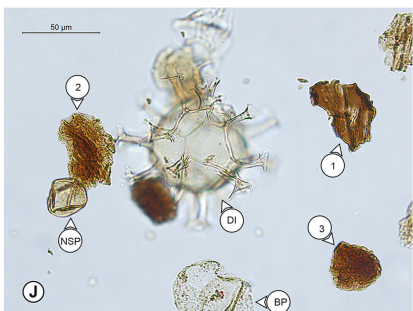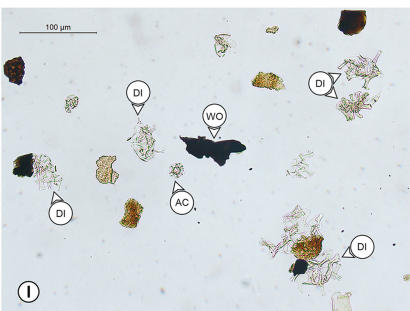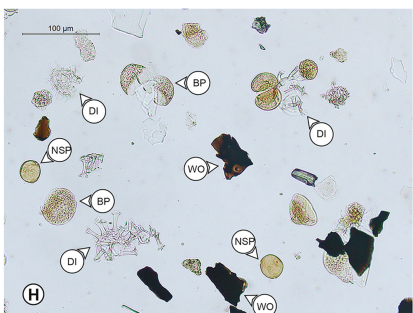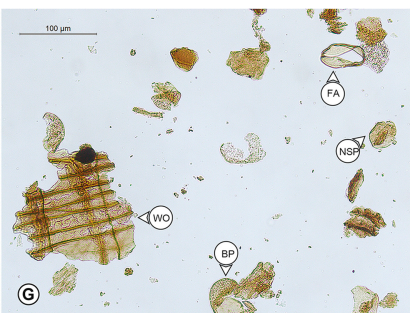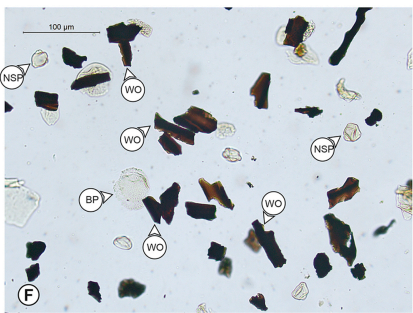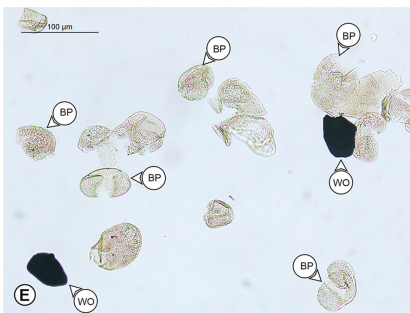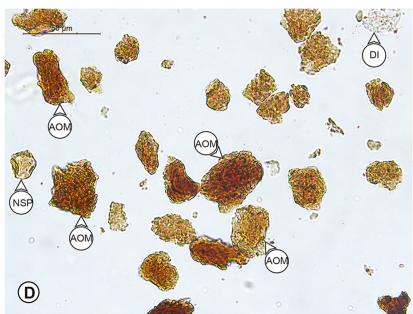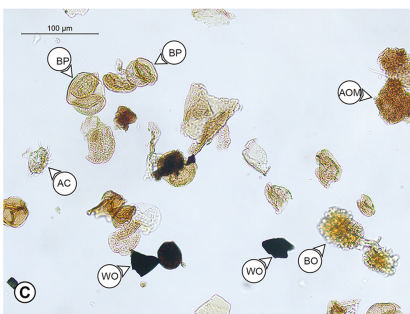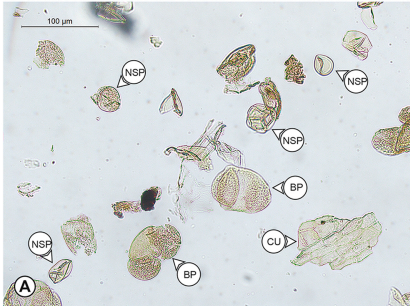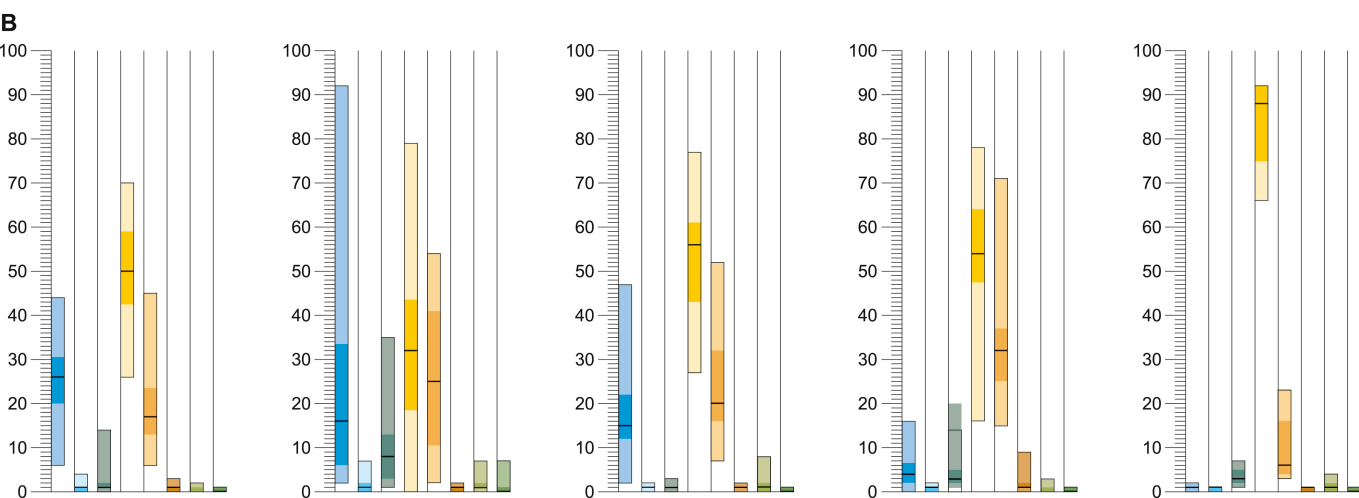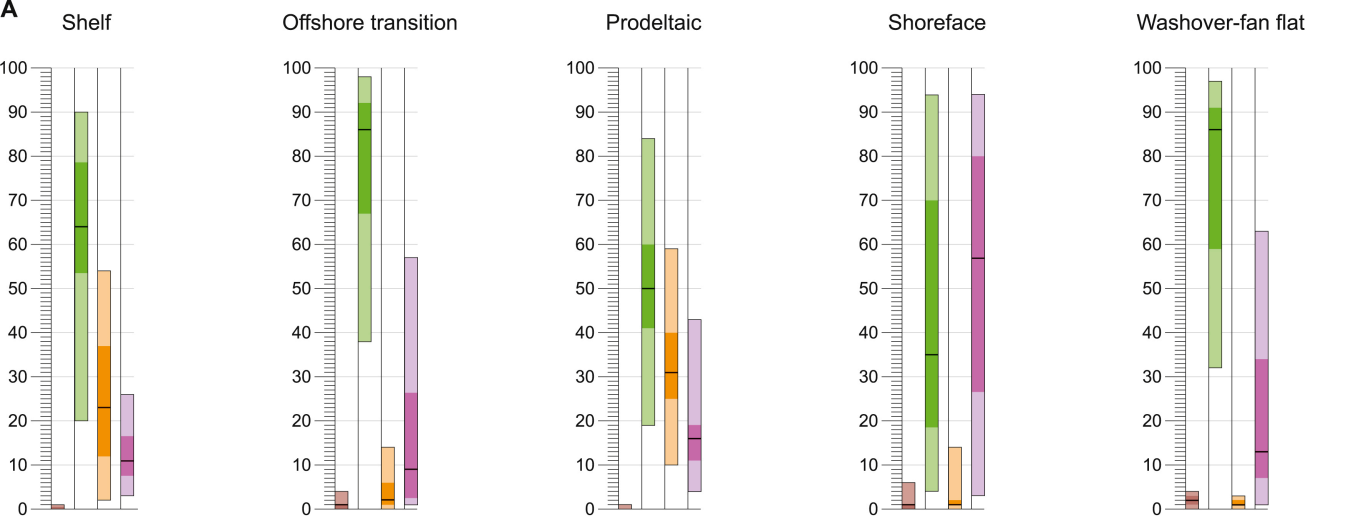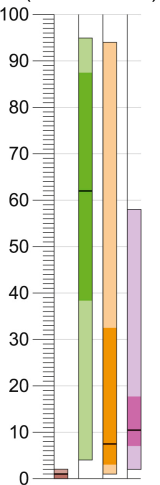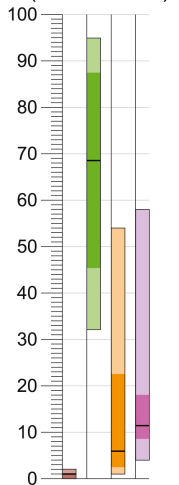
25 km

Top Billund
Top Søvind
Prodelta sand
Prodelta mud
Shelf

1000 m

Figure A — Scores: PC2 (vertical, -4 to 4) versus PC1 (horizontal, -2 to 12).

Legend:
- W (red +)
- F (light blue +)
- SF (orange +)
- O (magenta +)
- L (yellow-green ●)
- P (blue ●)
- S (yellow ●)

Figure B — X-loadings: PC2 (vertical, -0.4 to 0.6) versus PC1 (horizontal, -0.4 to 0.5).

Labels: PM, MS, BP, CU, BO, FU, FA, NSP, AOM, DI, WO, AC

PC3 Scores

A

W   L
SF P
O   S

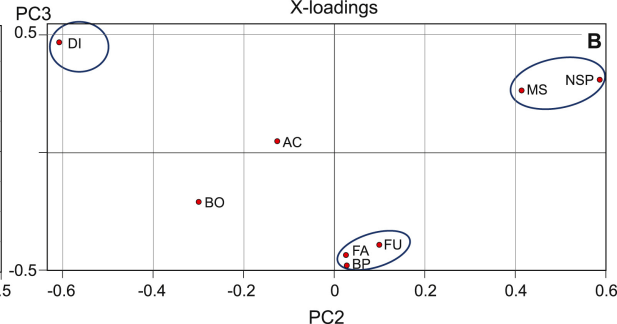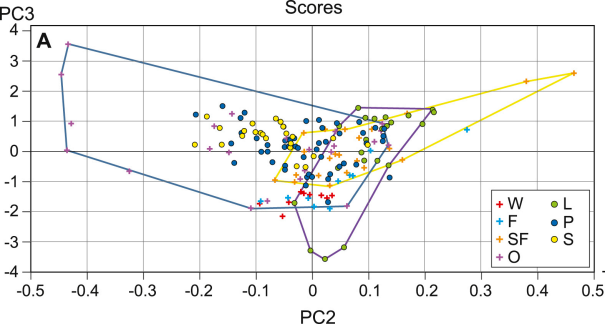PC3 X-loadings

B

DI

AC
AOM
BO

PM

FA
FU

CU

BP

NSP
WO
MS
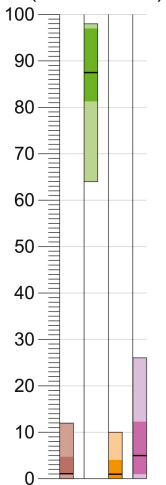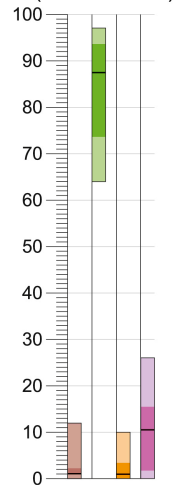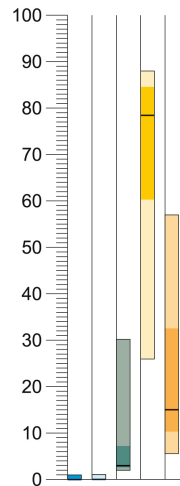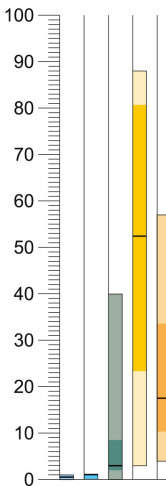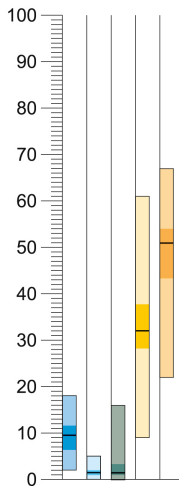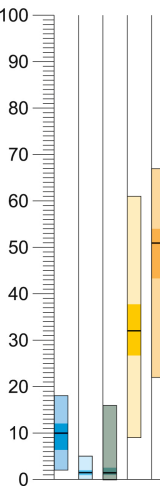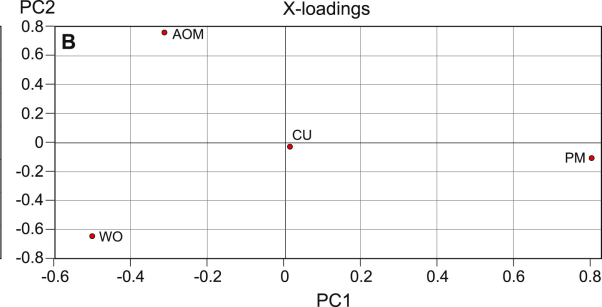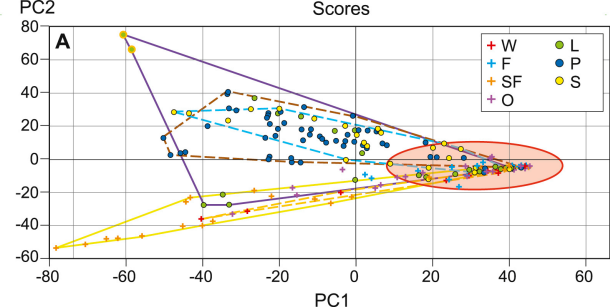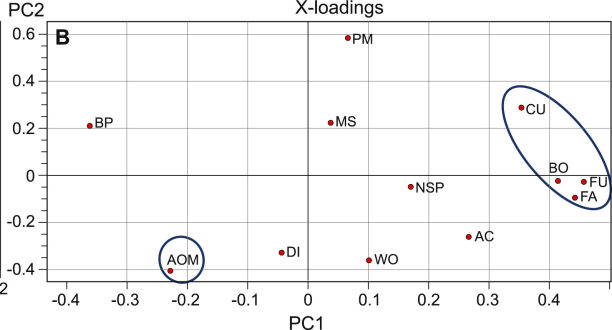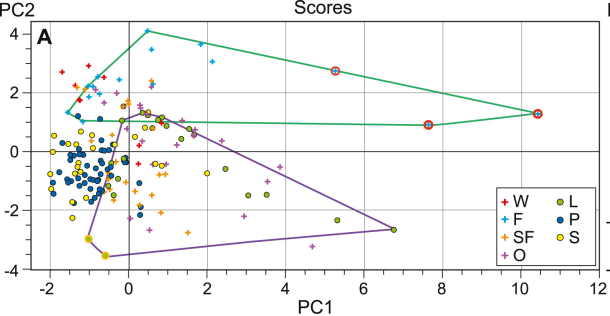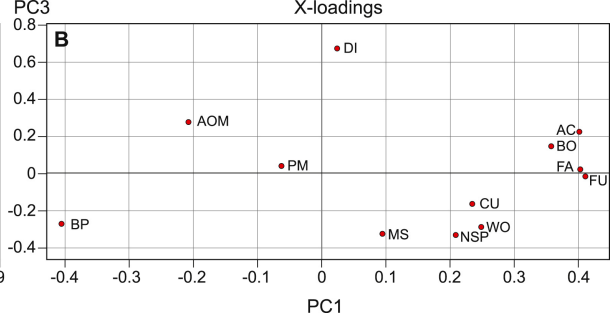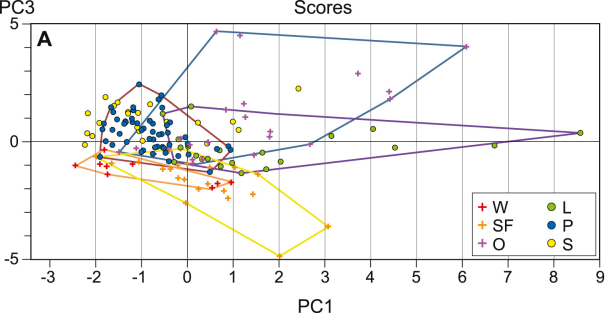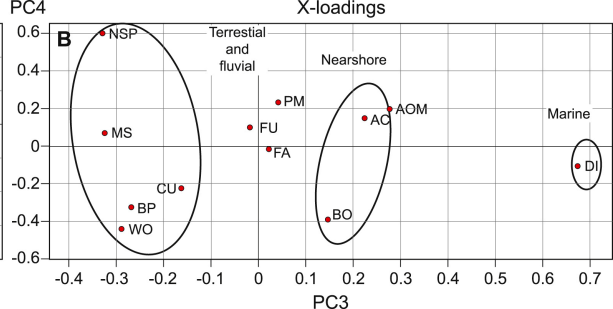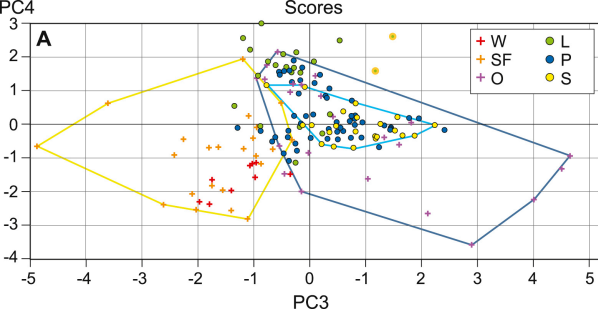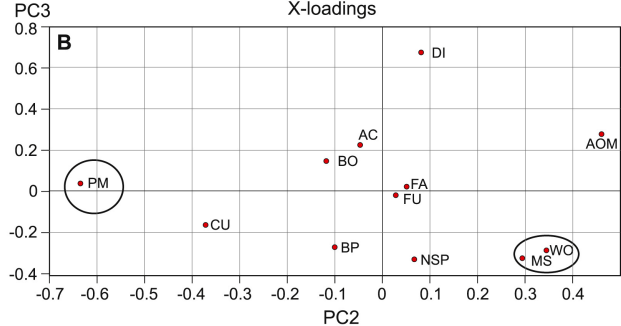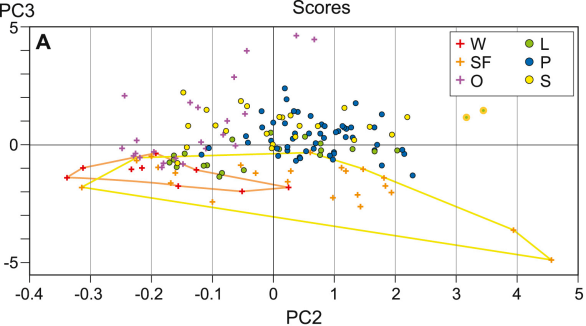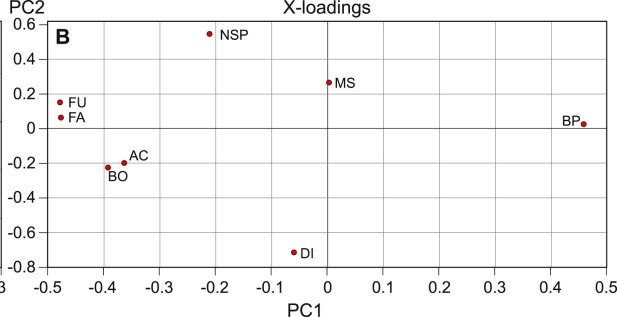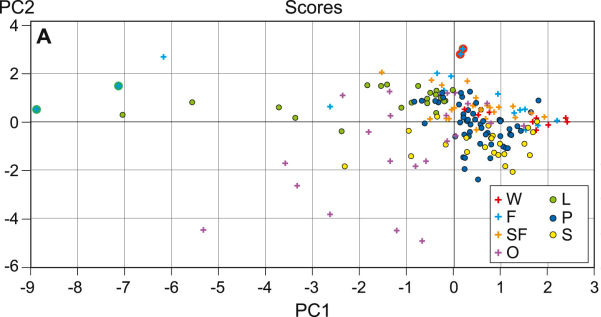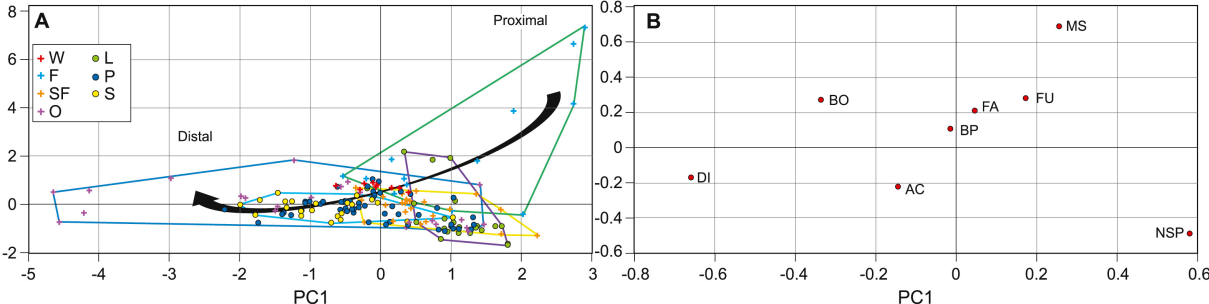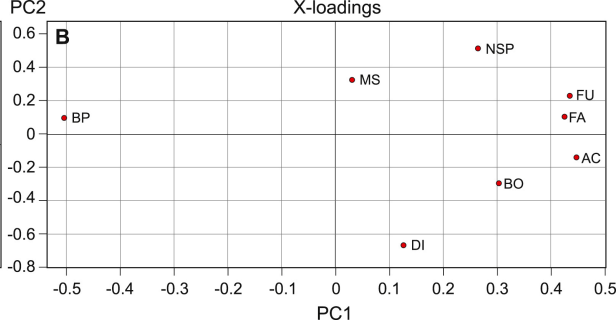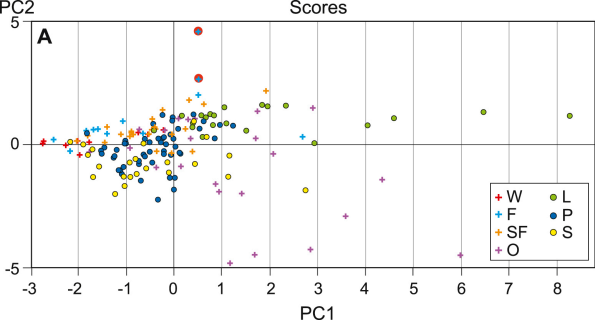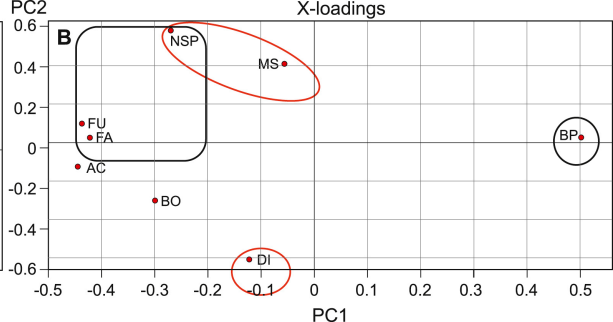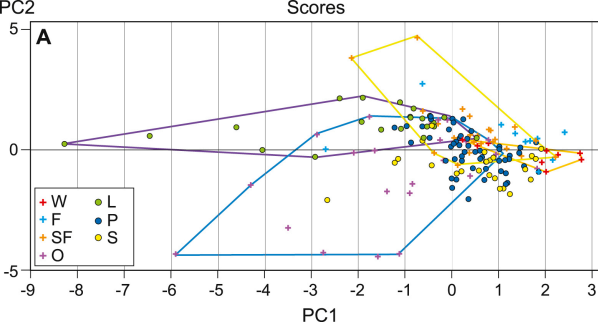
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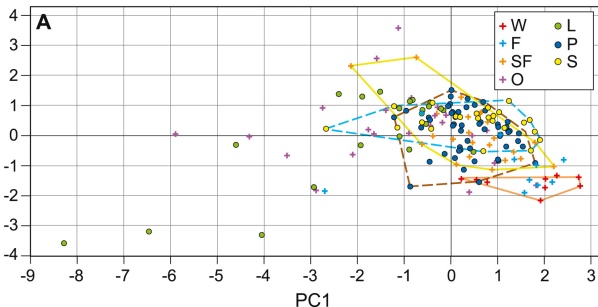
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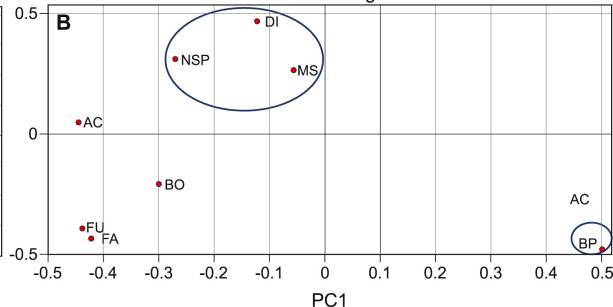
Highlights:

Palynofacies analysis of 7 Lower Miocene fluvio-deltaic and shelf environments are provided.

The shoreface environment is characterized by a strong dominance of wood particles.

The washover-fan flat environment showed a strong dominance of bisaccate pollen.

The results show how to distinguish floodplain from lagoonal mud with use of palynofacies.

Lagoonal mud and shelf mud can be distinguished based on the abundance of dinocysts.