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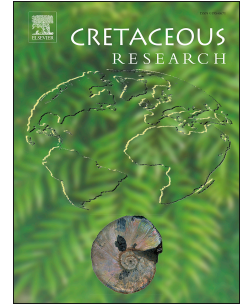
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1 **Dinocyst stratigraphy and palaeoenvironmental interpretation of**
2 **the Cretaceous/Paleogene boundary at Stevns Klint, Denmark**

3

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14

15 **ABSTRACT**

16 A re-examination of the uppermost Maastrichtian chalks and an expanded section of
17 the Fish Clay (Fiskeler Member) undertaken at Stevns Klint, Denmark, one of the
18 classic outcrops of the Cretaceous/Palaeogene boundary, has identified diverse and
19 abundant dinoflagellate cyst assemblages, which are compared with earlier
20 dinoflagellate cyst (dinocyst) studies. The uppermost part of the white coccolith chalk
21 (Sigerslev Member) of the uppermost Maastrichtian is placed in the *Palynodinium*
22 *grallator* Zone. The overlying 'Grey Chalk' (Højerup Member) represents a shallower-
23 water marine succession that is characterised by a series of dune-like structures.
24 The last common occurrence of *P. grillator* is within the Højerup Member, confirming
25 the Danian age for the Fish Clay (Fiskeler Member) and a latest Maastrichtian age
26 for the *P. grillator* Zone. Within the Fiskeler Member, *Damassadinium californicum*
27 (previously known as *Danea californica*), a key biostratigraphical marker, is only
28 intermittently present, while the distributions of *Senoniasphaera inornata* and

29 *Xenicodinium reticulatum* provide useful biostratigraphic control. The well-preserved
30 dinocysts of the Fiskeler Member are replaced by reduced assemblages in the
31 Cerithium Limestone Member with only pollen grains recorded.

32

33 *Keywords:* K/Pg boundary, dinoflagellate cysts, biostratigraphy, Fiskeler Member

34

35 **1. Introduction**

36 In an investigation of the Stevns Klint, Maastrichtian–Paleogene succession, Hart et
37 al. (2005) identify an expanded section of the boundary clay at Kulstirenden. As
38 earlier studies of the dinocyst assemblages had been undertaken on much thinner
39 successions of the boundary clay, this research aims to record the dinocyst changes
40 in more detail across the K/Pg boundary.

41 While the basal Paleocene ‘Global Stratigraphic Section and Point’ (GSSP) is
42 located in Tunisia (Molina et al., 2006), the Cretaceous/Paleogene (K/Pg) boundary
43 at Stevns Klint, Denmark, remains an important reference point (Damholt and Surlyk,
44 2012). Stevns Klint includes the original site where the K/Pg boundary was first
45 described by Desor (1847), lying between the coccolith chinks of the Maastrichtian
46 and the bryozoan-rich chinks of the lower Danian. Desor (1847) also included the
47 Faxe (Fakse) Quarry in his original definition of the Danian. While this working quarry
48 is located only 17 km to the west of Rødving, and has exceptionally interesting
49 occurrences of bryozoan mounds and cool-water corals (Bernecker and Weidlich,
50 1990, 2005; Willumsen, 1995; Surlyk and Håkansson, 1999), other invertebrate
51 fossils (Graversen, 2001), gastroliths (Noe-Nygaard, 1975) and evidence of
52 coprolites (Milàn, 2010), the K/Pg boundary was not exposed there during our
53 fieldwork. The old quarries at Holtug and Boesdal contain similar features and were
54 also un-sampled.

55 The K/Pg transition is exposed almost continuously along the ~14 km-long cliff
56 from Rødvig in the south to Bøgeskov in the north (Fig. 1). As reported by Hart et al.
57 (2004, 2005), the Fish Clay, now renamed the Fiskeler Member by Surlyk et al.
58 (2006), has been found to display considerable variation along the length of the cliffs
59 at the eastern end of the Stevns Peninsula. At Kulstirenden the Fiskeler Member
60 attains its maximum thickness (~50 cm). It is worth noting that in the definition of the
61 GSSP the greater thickness of the boundary clay at El Kef, as compared to Stevns
62 Klint, was used (Molina et al., 2006, p. 265) as evidence of the greater continuity of
63 sedimentation in the Tunisian section. While this is certainly true at Rødvig and
64 Højerup, the Kulstirenden exposure is quite comparable in thickness to that at El Kef.
65 In their definition of the basal-Paleogene GSSP at El Kef, Molina et al. (2006, p. 265)
66 recorded that there was no 'mass extinction' of dinocysts across the boundary and
67 *Damassadinium californicum* – while at the base of the boundary clay in Scandinavia
68 – appears 10 cm above the base of the boundary clay in the El Kef succession
69 (Brinkhuis and Leereveld, 1988; Brinkhuis and Zachariasse, 1988; Donze and Méon,
70 1997). Despite the relatively low numbers of *D. californicum* three of the voting
71 members of the Paleocene Working Group supported the FO of *D. californicum* as
72 marking the boundary while 11 voted for the base of the boundary clay and,
73 therefore, the impact event as the marker for the GSSP.

74 In recent years there have been a number of papers on the Stevns Klint K/Pg
75 boundary succession, including a revision of the lithostratigraphy (Surlyk et al.,
76 2006). The micropalaeontology and stable isotope stratigraphy have been described,
77 in some detail, by Schmitz et al. (1992), Hart et al. (2004, 2005) and Rasmussen et
78 al. (2005). Missing from all these recent investigations is any re-assessment of the

79 organic-walled dinocyst stratigraphy which has, in the past, been somewhat
80 problematic.

81 There have been a number of dinocyst investigations at Stevns Klint, dating
82 back to the 1960s. These include the works of Morgenroth (1968), Wilson (1974),
83 J.M. Hansen (1977) and H.J. Hansen et al. (1986). Unfortunately, these
84 investigations all used samples collected from the thinner sections of the Fiskeler
85 Member. Hultberg (1985, 1986, 1987) did sample from slightly thicker parts of the
86 Fiskeler Member, but the representativeness of some of his results has been
87 questioned (Brinkhuis et al., 1998). In particular, two of Hultberg's (1986) Fiskeler
88 Member samples contained a monospecific or near-monospecific assemblage of
89 *Manumiella druggii*, which Hultberg interpreted as indicative of a lagoonal or
90 brackish-water environment. J.M. Hansen (1977), H.J. Hansen et al. (1986) and
91 Brinkhuis et al. (1998) all found more diverse assemblages at these locations.
92 Furthermore, despite sampling from the slightly thicker parts of the Fiskeler Member,
93 Hultberg only had eight samples within that member that actually contained
94 dinocysts. Isotopic data from Stevns Klint presented by Hart et al. (2005) indicate
95 potential environmental changes on a scale that Hultberg's sampling resolution
96 would not be expected to achieve.

97 The primary objectives of our research are, therefore: 1) to increase the
98 sampling resolution through the Fiskeler Member, which will provide a more detailed
99 analysis of the dinocyst assemblages and species distributions across the K/Pg
100 boundary at Stevns Klint; and 2) to use this new information on dinocyst stratigraphy
101 to make comparisons with the distribution of these taxa from a number of other K/Pg
102 boundary sites.

103

104 2. Geological setting

105 Forming the edge of the Stevns Peninsula in eastern Sjaelland, Stevns Klint is
106 located ~40 km south of Copenhagen (Fig. 1). The cliff, which varies in height
107 between 20 and 41 m, hosts several quarries along its 14 km length (Surlyk, 1979;
108 Hart et al., 2004, 2005; Surlyk et al., 2006; Damholt and Surlyk, 2012). One of the
109 first descriptions of Stevns Klint and the classic Cretaceous–Paleogene boundary
110 sections, dates back to the eighteenth century (Abildgaard, 1759), but it was not until
111 a century later that the complicated stratigraphy of the boundary was appreciated.
112 Desor (1847) was the first to recognise the K/Pg boundary, while Rosenkrantz
113 (1924) later described the palaeontology of the Maastrichtian and Danian strata.
114 Together with Faxe (Fakse) Quarry, Stevns Klint constitutes the classic type area of
115 the Danian Stage in Europe (Surlyk, 1979), but has been passed over as the Global
116 Stratotype Section and Point for the base of the Danian because of its rather
117 complex stratigraphy and lack of many key species of planktic foraminifera (Hart et
118 al., 2004, 2005). The two localities used in this investigation are at Højerup, where
119 most previous field studies have taken place (Schmitz et al., 1992; Hart et al., 2004,
120 2005) and Kulstirenden, which is located approximately 8 km to the north of Højerup.

121 Although laterally variable over the ~14-km long cliff, the composite
122 stratigraphical sequence at Stevns Klint can be divided into five major lithological
123 units (Hart et al., 2005; see Fig. 2 here) all of which have now been re-named by
124 Surlyk et al. (2006). Except where stated otherwise, the following lithological details
125 are derived from Hart et al. (2004, 2005) and Surlyk et al. (2006).

126 Low, rounded chalk mounds constitute the lowermost 5–10 m of the visible white
127 coccolith chalk which is now known as the Sigerslev Member of the Tor Formation.
128 The mounds grade upwards into ~20 m of *Zoophycos*-rich, horizontally-bedded

129 chalks, which host gently undulating lines of (generally) small black flints. Two
130 features are present near the top of this member. There is a prominent, laterally-
131 continuous nodular flint layer approximately 3–4 m below the Fiskeler Member (Fig.
132 3) at Højerup. At Harvig there are two phosphatised ‘hardgrounds’, approximately
133 100 mm apart, that are located ~ 30 cm above this flint horizon. Along the section
134 northwards, towards Højerup, these merge into a single horizon. This line of flints
135 (and the overlying hardground) can be followed along almost all of Stevns Klint and
136 appear to be a reliable datum level (Surlyk et al. 2006, plates 7,10). At Rødvig this
137 line of flints is just below beach level and rarely visible. On the coast to the south-
138 east of Kulstirenden it is visible in the cliff just below the Fiskeler Member as the
139 overlying Højerup Member is locally absent.

140 The Højerup Member is <4 m thick at Højerup and consists of grey-coloured,
141 bryozoan- and *Thalassinoides*-rich chalk that was deposited in low, elongate,
142 asymmetric mounds (3.5 to 4 m in height and with a basal dimension of ~25 m). Flint
143 bands populate parts of the more gently-dipping northern slopes (~5° compared to
144 ~15° for the southern slopes). At Kulstirenden, the Højerup Member is very thin or
145 completely absent where the Fiskeler Member is at its thickest (Hart et al., 2005, fig.
146 7). At this location, the hardground at the boundary between the Sigerslev and
147 Højerup members is immediately below the Fiskeler Member, almost giving the
148 impression of a phosphatised sub-K/Pg boundary hiatus.

149 The Fiskeler Member lies within the troughs formed by the mounds in the
150 underlying chalk. At some locations along Stevns Klint it can be missing as a result
151 of the erosion at the top of the Cerithium Limestone Member. At Højerup, the
152 maximum thickness of the clay is 7 cm (Christensen et al., 1973). At Kulstirenden the
153 clay attains a maximum thickness of 45–50 cm in the centre of a large trough but

154 thins away from this centre so that at some locations it is absent from the succession
155 (Hart et al., 2005). Where the clay is thickest, at Kulstirenden, the Højerup Member
156 is absent and the clay lies just above the hardground that marks the boundary
157 between the Sigerslev and Højerup members.

158 Christensen et al. (1973) divided the Fiskeler Member into four units: 1) the
159 lowermost grey, laminated marl; 2) black marl, with pyrite concretions, that is often
160 stained reddish-yellow in weathered outcrops; 3) black, laminated marl; 4) light grey
161 marl also containing pyrite concretions. Figure 4 shows the Fiskeler Member at
162 Kulstirenden where most of the samples for this study were collected.

163 The Fiskeler Member is observed to grade into the overlying Cerithium
164 Limestone Member, with small lenses of chalk near the transition (making the
165 boundary imprecise). Schmitz et al. (1992) reported the presence of a hiatus marked
166 by an erosion surface but this has not been confirmed, especially in the expanded
167 succession at Kulstirenden. The Cerithium Limestone Member is formed of <1 m of
168 yellowish-white hard chalk with two hardgrounds at its uppermost boundary at
169 Kulstirenden, which converge into a single hardground at other locations, including
170 Højerup and Rødvig. This surface is regionally important as a sequence boundary
171 (Rasmussen et al., 2005; Hart et al., 2011) and can be seen cross-cutting parts of
172 the succession along the length of Stevns Klint. The overlying, bryozoan-rich chinks
173 (Korsnæb Member) are cream-coloured, bryozoan-rich packstones and wackestones
174 that occur as large asymmetric mounds. These mounds are on a much larger scale
175 than those recorded from the Højerup Member and are best seen east of Rødvig, in
176 the old quarries of Boesdal and immediately north of the old church at Højerup
177 (where they were previously quarried).

178

179 3. Material and methods

180 Over the last few years several suites of samples have been collected from various
181 locations along Stevns Klint by Malcolm Hart, Sean Feist, Eckhart Håkansson and
182 Claus Heinberg. Of these, thirty-one were selected for palynological processing and
183 analysis, with two slides prepared for each sample. For each slide 300 dinocyst
184 specimens were counted; bisaccate pollen, spores and foraminiferal test linings were
185 noted but did not form part of this count. The Gonyaulacoid/Peridinioid (G/P) and
186 Protoperidinioid /Gonyaulacoid (P/G) ratios were calculated.

187 The G/P ratio calculated here follows Harland (1973), whereby $G/P = nG/nP$;
188 n =number of species (identified as G/P^{species}). The G/P ratio was also calculated
189 using $G/P = nG/nP$; n =number of specimens (identified as G/P^{specimens}) in order to
190 allow comparison with some other authors. The P/G ratio follows Versteegh (1994),
191 whereby $P/G = nP/(nP+nG)$; n = number of specimens.

192 Twenty-seven of the thirty-one samples selected for our investigation were
193 collected from Kulstirenden. The K8 samples came from the white coccolith chalk of
194 the Sigerslev Member immediately below the prominent flint horizon, only two of
195 which were sent for processing (K8/7 and K8/5). The KUL/I and KUL/K samples
196 were collected between the prominent flint horizon and the hardground(s) that
197 usually mark the boundary between the Sigerslev and Højerup members. To
198 complete the Maastrichtian succession, four samples (L5 series) were selected from
199 the Højerup Member at Højerup, because this member is missing in the accessible
200 section at Kulstirenden. Sixteen, mostly contiguous samples (KU14–29), represent
201 the Fiskeler Member at Kulstirenden. Samples KU45–50 (excluding KU48, which
202 was not sent for processing) were collected from the Cerithium Limestone Member.
203 By using this selection of samples there has been a complete coverage of the K/Pg

204 transition (Fig. 5). The sampling of the Fiskeler Member is particularly detailed and
205 this has allowed a more complete analysis of the dinocyst stratigraphy than has
206 previously been the case.

207

208 **4. Palynological processing**

209 The full processing procedure is, perhaps unusually, described here as it was the
210 sample preparation methods adopted by Hultberg (1985, 1986, 1987) that concerned
211 Brinkhuis et al. (1998). All samples were processed in the Palynology Laboratory of
212 the Natural History Museum (London) in February 2005 by Jonah Chitolie. Samples
213 were processed using standard (see Batten, 1999) palynological techniques
214 (hydrochloric acid followed by hydrofluoric acid for demineralisation). Oxidation was
215 not deemed necessary, however, because of the well-preserved nature of the
216 palynomorphs.

217 The chalk samples all weighed between 119 and 166 g, while the clay
218 samples weighed 9–13 g. All the samples were cleaned of surface contamination
219 either by scraping the outer layer of the sediment with a stainless steel scalpel (for
220 hard chalks), or by brushing with a dry nylon toothbrush (for clays, marls and soft
221 chalks). The clean samples were oven-dried at 100°C for approximately ten hours.
222 After drying and weighing (chalk samples weighed 50–118 g; clay samples weighed
223 5–8 g), the samples were placed in glass beakers: 2-litre beakers for the chalk and 1
224 litre for the clay. 100 ml of distilled water was added to each sample, subsequently
225 followed by a small amount of 50% hydrochloric acid, with any reaction being
226 allowed to subside before the addition of more acid. The chalk samples foamed due
227 to their high reactivity.

228 After being washed through a 15 µm sieve with filtered tap water, the residues
229 were returned to the glass beakers where concentrated hydrochloric acid was added
230 to eliminate un-dissolved carbonates. After further washing, the samples were
231 placed in 250 ml polypropylene beakers where 50% hydrofluoric acid was added and
232 left overnight. Samples were then washed through a 15 µm polyester sieve.

233 The recovered residues, in almost all of the samples, contained well-
234 preserved palynomorphs, some of which were transparent. All residues were
235 examined before mounting and any that were found to contain calcium fluoride
236 precipitate were treated with 50% hydrochloric acid and heated at 80°C for
237 approximately one hour. The residues were divided in two, with one part stained
238 using Bismark brown R.

239 For each sample two glass coverslips were cleaned and placed on a warm
240 plate. A small amount of residue was placed in a vial and mixed with polyvinyl
241 acetate. The residue was pipetted onto the coverslip and left to dry. A small amount
242 of Elvacite was used as the mounting medium and was placed on each slide and
243 then inverted onto the coverslip. Elvacite is made by dissolving 20 g of Elvacite 2044
244 resin (a trade name for methacrylate resin) in 35 ml of xylene. The slides were kept
245 in a fume hood over night and then placed in a drying oven at 80°C for two hours.

246

247 **5. Dinocyst distribution**

248 A range of well-known taxa have been identified in this study, all of which are listed
249 and counts given in Appendix 1, while the ranges of selected taxa are shown in
250 Table 1 and images of selected taxa are shown in Figure 6. Taxonomic classification
251 follows Fensome et al. (2008), although, it is accepted that some aspects of the
252 taxonomy may be in need of further investigation and revision.

253

254 5.1. *Kulstirenden – Sigerslev Member (K8 samples)*

255 Sample K8/7 was dominated by *P. grallator*, which recorded ~30% (112 specimens)
256 of the count. The *Achomosphaera-Spiniferites* complex of dinocysts, together
257 accounted for 80 specimens or ~ 25%, with *A. ramulifera*, *S. ramosus multibrevis*
258 and *S. ramosus reticulates* being particularly common. The *Achomosphaera-*
259 *Spiniferites* complex of dinocysts is here defined as a grouping of all species and
260 subspecies belonging to these two genera. *Palaeoperidinium pyrophorum* showed its
261 highest abundance at this level with 15 specimens counted. This produces a G/P
262 $\frac{\text{species}}{\text{specimens}}$ ratio of 25; G/P $\frac{\text{specimens}}{\text{specimens}}$ ratio of 293 and a P/G ratio of 0.05 (see Fig. 7).

263 Sample K8/5 was similar to K8/7 with *P. grallator* comprising 180 specimens or 30%
264 of the cysts counted, and the *Achomosphaera-Spiniferites* complex of dinocysts
265 accounting for 79 specimens, c. 25% of the count, *S. ramosus multibrevis*, however,
266 was not quite as abundant as in K8/5, while *P. pyrophorum* was only observed once.
267 Species diversity was 25 and 21 for K8/7 and K8/5, respectively, similar to the L5
268 series of samples from Højerup. This produces the following ratios: G/P $\frac{\text{species}}{\text{specimens}}$ =21;
269 G/P $\frac{\text{specimens}}{\text{specimens}}$ = 305 and P/G = 0.

270

271 5.2. *Kulstirenden – Højerup Member (KUL samples)*

272 KUL/K produced a near-monospecific assemblage of *P. grallator* (235 specimens;
273 87.7%). Of the other taxa only *Oligosphaeridium complex* and *S. ramosus gracilis*,
274 were found in abundances greater than one. *Impagidinium cristatum* was relatively
275 common (32 specimens). There were no peridiniacean cysts resulting in a G/P $\frac{\text{species}}{\text{specimens}}$
276 ratio of 0. Only 17 species and sub-species were observed in this sample, the lowest

277 diversity of dinocysts encountered (see Fig.7). KUL/I was barren and did not contain
278 any dinocysts.

279

280 5.3. Højerup – Højerup Member (L5 samples)

281 These four samples showed a dinocyst assemblage almost completely dominated by
282 gonyaulacacean cysts. Species diversity varied between 27–30 (Fig. 7). The only
283 peridiniacean cyst observed in these samples was *Palaeoperidinium pyrophorum*,
284 which was found in samples L5/60-65 and L5/290-295, but was absent from the
285 other two. Where it did occur, abundance was low: 3 specimens in the former
286 sample and 8 specimens in the latter. Consequently, the G/P^{species} ratio increases
287 and decreases from 26 to 0 and from 29 to 0 from the lowest to uppermost samples
288 (see Fig. 7). Similarly the $G/P^{\text{specimens}}$ ratio varied between 0–103. The P/G ratio
289 varied from 0.01 to 0 and 0.03 to 0 from the lowest to the uppermost samples (see
290 Fig. 7). Collectively, the *Achomosphaera-Spiniferites* complex cysts are the most
291 abundant species (78–143 specimens) in the Højerup Member samples, comprising
292 between 24.6–45 % of the count. Within this complex, *A. ramulifera*, *A. sagena*
293 *sagena*, and several subspecies of *Spiniferites ramosus* were identified (see Fig. 6).

294 *Tanyosphaeridium xanthiopyxides* is a common species throughout all of the
295 samples (14–37 specimens). *Impagidinium cristatum*, is also common; its
296 abundance is consistently higher in the older samples (16/12 specimens in L5/60-65
297 and L5/125-130 respectively). Of the other taxa, only *P. grillator*, *Spiniferites*
298 *ramosus ramosus*, *Spiniferites ramosus gracilis* and *Hystrichosphaeridium tubiferum*
299 appear in any significant numbers. In addition, abundant algae and foraminiferal
300 linings were noted in all of the samples, particularly L5/125–130.

301

302 5.4. *Kulstirenden – Fiskeler Member (KU samples)*

303 Of the species that were recorded below the boundary, *I. cristatum* was absent and
304 *P. grallator* disappears above KU15. The *Achomosphaera–Spiniferites* complex
305 cysts were still present in large numbers (between 60–114 specimens in samples
306 KU14-22). *Tanyosphaeridium xanthiopyxides* continued its predominance from the
307 L5 samples (20–81 specimens) forming between 5 and 26% of the total species
308 count. Species that were not present below the K/Pg boundary but were present in
309 samples KU14–KU29 include *Fibrocysta capitata*, *Senoniasphaera inornata* as well
310 as *Criboperidinium* spp. and *Thalassiphora pelagica*. These species were present in
311 low numbers (1–8 specimens) and not seen in every KU sample. A criboperidinioid
312 cyst attributed here to *Criboperidinium* sp. A of Brinkhuis and Schiøler (1996), has
313 been recorded by Brinkhuis et al. (1998), Slimani et al. (2010) and Vellekoop et al.
314 (2014). *Criboperidinium* sp. A of Brinkhuis and Schiøler (1996) is considered a
315 transitional form with *Carpatella cornuta* sensu stricto (Damassa, 1988). It has a
316 short apical horn and spongy appearance but lacks the definite antapical protrusion
317 of *C. cornuta* s.s. This taxon only occurs at Stevns Klint above the K/Pg boundary in
318 the Fiskeler Member. This is consistent with other studies (Brinkhuis et al., 1998;
319 Schiøler et al., 1997; Vellekoop et al., 2014) which have described transitional forms
320 such as this occurring in the lowermost Danian, below the first appearance of
321 *C. cornuta* s.s., however, Vellekoop et al. (2015) and Slimani et al. (2010) record its
322 first appearance just below the boundary. The acritarch *Raphidodinium* sp. cf.
323 *armatum* was always present in these samples and occurred in significant numbers
324 (23–59 specimens) from samples KU19 to KU23 and KU27–29. *Xenicodinium*
325 *reticulatum* was observed in low numbers (2–5 specimens) in two of the uppermost

326 samples (KU23 and KU29). In addition, *Damassadinium californicum* was only
327 observed intermittently and as single to rare occurrences.

328 Peridinioid cysts were found to be more common and diverse than below the
329 boundary, increasing in number up through the succession. There were more
330 peridiniacean specimens recorded in the higher, more productive KU samples
331 (KU24-29). *Palaeoperidinium pyrophorum* continued to be intermittently present and
332 *Cerodinium diebelii* was often common (8–47 specimens) with rare *Deflandrea* spp.
333 and *Palaeocystodinium australinum*. *Manumiella seelandica* (formerly, *M. druggii*)
334 was only observed intermittently and in variable numbers (1–14 specimens).
335 *Trithyrodinium evittii* was very common, becoming abundant (163 and 214
336 specimens) in the highest samples (KU28 and KU29, respectively), where it
337 accounted for 50–65% of the assemblages. Species diversity (31–41) remained high
338 in the KU samples, similar to the L5 and K8 samples throughout the clay, with an
339 overall increase through the upper samples (see Fig. 7).

340 No dinocysts were observed in samples KU48–KU50 (Cerithium Limestone
341 Member), although bisaccate pollen grains were recorded.

342

343 6. Biostratigraphy

344 Wilson (1974), using a relatively limited number of samples, was the first to propose
345 a dinocyst zonation for Denmark. Subsequently, J.M. Hansen and co-workers (J.M.
346 Hansen, 1977, 1979, Kjellström and Hansen, 1981) and Hultberg (1986), working
347 across a range of sites in southern Scandinavia (including Stevns Klint), generated a
348 zonation for the uppermost Maastrichtian and lowermost Danian. More recently,
349 Schiøler and Wilson (1993) refined Wilson's (1974) dinocyst zonation for the whole
350 of the Maastrichtian. The problem with many of these zonations is a lack of precise

351 information on how the sampling of the variable lithostratigraphical units was
352 accomplished, especially in Denmark.

353 In the discussion of the K/Pg boundary at El Kef (Molina et al., 2006) the
354 stratigraphical value of *Danea californica* (= *Damassadinium californicum*) was
355 regarded as important: it was one of the potential criteria for the definition of the
356 GSSP.

357 Sample KUL/I contained no dinocysts but was collected immediately below
358 the hardground surface at the top of the Sigerslev Member. This suggests that
359 hardground formation (which also characterises the upper levels of the Cerithium
360 Limestone Formation) inhibits the preservation of dinocysts. This has previously
361 been noted by FitzPatrick (1992) in the Turonian chalk succession of the United
362 Kingdom.

363 *Palynodinium grillator* occurs, often in large numbers (e.g., 110–235
364 specimens) in the upper parts of the Sigerslev Member, aside from sample KUL/I
365 adjacent to the hardground and continues in reduced numbers (0–38) throughout the
366 Højerup Member to the very top of the Maastrichtian. In the Højerup Member, *P.*
367 *grillator* occurs in reduced numbers while *Achomosphaera ramulifera* and
368 *Impagidinium cristatum* are present in reasonable numbers (6–20 and 2–16,
369 respectively) before the latter species disappears at the K/Pg boundary. Records of
370 rare *P. grillator* (1–5 specimens) within the Fiskeler Member are possibly the result
371 of inclusion of minute clasts of chalk within the samples processed. Vellekoop et al.
372 (2015) record the first appearance of *P.grillator* above the K/Pg boundary in Tunisia
373 and Slimani et al. (2010) describe a similar occurrence from Morocco. This
374 occurrence of *P.grillator* was, in both cases, interpreted as the southward migration
375 of a cooler water species in response to cooling during the early Danian.

376 *Palynodinium minus* occurs throughout the Fiskeler Member, from KU15–KU28, but
377 in low numbers (1–5 specimens). This species has reduced lateroventral protrusions
378 similar to that described as *P. cf. grallator* by Machalski et al. (2016) which was
379 noted from the Maastrichtian of Lechówka, south east Poland. The sporadic
380 occurrence of *P.grallator* and *P.minus* above the K/Pg boundary is, therefore, not
381 unusual.

382 *Damassadinium californicum* does occur in the Stevns Klint material (see
383 Table 1), but is very rare. It is present only in the Fiskeler Member, although the
384 environmental changes recorded higher in the succession probably were a limiting
385 control on its reported range.

386 The occurrence of *Cribopteridinium* sp. A of Brinkhuis and Schiøler (1996),
387 although rare within the Fiskeler Member is quite characteristic, appearing in the
388 sample below *D. californicum* which is only millimetres above the K/Pg boundary as
389 defined by Molina et al. (2006). A number of other taxa (e.g., *Fibrocysta capitata*,
390 *Cribopteridinium* spp.) also occur throughout the Fiskeler Member, which contains a
391 diverse dinocyst assemblage throughout (31–41 species per sample). This result is
392 different to the near-monospecific association described by Hultberg (1985, 1986,
393 1987).

394 Appearing in KU23 is *Xenicodinium reticulatum*, another marker species to
395 have a first appearance within the Fiskeler Member, including *Trithyrodinium evitii*,
396 *Senoniasphaera inornata* and *Manumiella seelandica*. We suggest, therefore, that
397 the upper *X. reticulatum* Sub-zone of the *D. californicum* Zone, of the lowermost
398 Danian can be recognised here.

399

400 *6.1 Comparison with biostratigraphic zonations of Scandinavia*

401 In the following paragraphs the results from this study are discussed in relation to
402 previously published distributions of stratigraphically significant dinocysts from
403 southern Scandanavia.

404

405 6.1.1 *Palynodinium grillator* Zone (new definition)

406 The uppermost part of the upper Maastrichtian is characterised by the *P.*
407 *grillator* Zone (Wilson, 1974; Schiøler and Wilson, 1993). This zone, is here defined
408 by the first and last common occurrences of *P. grillator*, (K8/7–KUL-K) respectively
409 and is different to Wilson's (1974) Zone Vb, as the top of this zone was defined by
410 the last occurrence of *P.grillator*. The uppermost part of this zone has been divided
411 into the *Tanyosphaeridium magdaliium* (= *T. xanthiopyxides*) and *Thalassiphora*
412 *pelagica* Subzones by Schiøler and Wilson (1993). In previous studies at Stevns
413 Klint, and throughout the Danish region (e.g., Hultberg, 1986; Schiøler and Wilson,
414 1993), *T. xanthiopyxides* has always been referred to as *T. magdaliium*. Lentin &
415 Williams (1993), however, noted that *T. magdaliium* was almost certainly a junior
416 synonym of *T. xanthiopyxides*.

417 Kjellström and Hansen (1981) also included the *Chiropteridium inornatum*–
418 *Palynodinium grillator* Concurrent Range Zone in their zonation, with its upper
419 boundary corresponding to the Maastrichtian–Danian (K/Pg boundary). This
420 Concurrent Range Zone was later renamed the *Senoniasphaera inornata*–
421 *Palynodinium grillator* Concurrent Range Zone by Hultberg (1985). The common
422 occurrence of *T.xanthiopyxides*, and the consistent occurrence of *Thalassiphora*
423 *pelagica*, in this study, through the Højerup Member and into the Fiskeler Member,
424 prevents the recognition of these subzones as defined by Hansen (1977) and
425 Kjellström and Hansen (1981).

426

427 6.1.2 *Damassadinium californicum* (*Danea californica*) Zone428 Originally named after its taxonomic junior synonym *Danea mutabilis* (Hansen, 1977)429 this zone begins with the first occurrence of *D. californicum* (Kjellström and Hansen,

430 1981; Hultberg, 1985). The zone extends over much of the lower Danian and has

431 previously been divided into two subzones (*Chiropteridium inornatum* and432 *Hafniasphaera cyrptovesiculata* Subzones), of which only the lower one (the433 *Senoniasphaera inornata* Subzone, formerly the *Chiropteridium inornatum* Subzone)

434 has been observed at Stevns Klint (e.g., J.M. Hansen, 1977). Hultberg (1985, 1986)

435 did not record *D. californicum* at Stevns Klint but this is unsurprising as it is relatively

436 rare in our samples (1–3 specimens in some, but not all samples of the Fiskeler

437 Member). The rare but consistent occurrence of *S.inornata* here, with its first438 appearance just below that of *D. californicum*, within the Fiskeler Member, supports439 this zonation. The *Senoniasphaera inornata* Subzone was divided into three zonules:440 *Carpatella cornuta*, *Xenicodinium rugulatum*, *Xenicodinium reticulatum* Zonules, by

441 Hansen (1977) and Kjellström and Hansen (1981), but Hultberg (1986) added a

442 fourth: the *Fibrocyta axialis* Zonule. These zonules, as defined by Hansen (1977)

443 and Kjellström and Hansen (1981), were not all recognised here in the samples from

444 Stevns Klint.

445

446 6.1.3 *Carpatella cornuta* Sub-zone (new definition)447 This subzone should contain *C. cornuta* (Kjellström and Hansen, 1981), however, it448 is not recognised here. The transitional form, *Cribroperidinium* sp. A of Brinkhuis and

449 Schiøler (1996) present here, is known to occur in lowermost Danian samples

450 (Brinkhuis et al. 1998; Slimani et al., 2010; Schiøler et al., 1997; Vellekoop et al.,

451 2015). *Xenicodinium reticulatum* is not present. Kjellström and Hansen (1981)
452 indicated that *Cordosphaeridium inodes longipes* was not found at this level and this
453 is consistent with our results. *Cribroperidinium* sp. A of Brinkhuis and Schiøler (1996)
454 is, therefore, interpreted as a marker species for the basal Danian from samples
455 KU14–KU20.

456

457 6.1.4 *Xenicodinium reticulatum* Sub-zone

458 This subzone is only tentatively identified here within the Fiskeler Member as
459 samples from all over southern Scandinavia (as attempted by Kjellström and
460 Hansen, 1981) have not been investigated. *Xenicodinium reticulatum* was observed
461 in samples KU23–KU29 and so is the basis for the identification of this subzone. No
462 dinocysts were observed in samples KU45–KU50, although bisaccate pollen grains
463 were recorded.

464

465 7. Discussion

466 7.1 *K/Pg boundary sections*

467 K/Pg boundary sections world-wide, fall into three categories; those proximal to the
468 Chixculub impact site (e.g., Texas, Alabama, Georgia, Gulf of Mexico), distal sites
469 (e.g., Denmark, Tunisia, Italy, Austria, etc.) and those that are intermediate in
470 character e.g. Demerara Rise (MacLeod et al., 2007) and New Jersey (Olsson et al.,
471 1997).

472 Stevns Klint is an important distal K/Pg boundary site, with others located in
473 Southern Spain, Morocco, Tunisia, Egypt, Italy, Austria, Czech Republic, Poland,
474 etc. These sites extend across a wide range of latitudes from 'Tethyan' to 'Boreal'
475 locations and dinocyst studies from these areas have produced varying results in

476 terms of species diversity and abundance (Molina et al., 2006; Donze and Méon,
477 1997; Brinkhuis and Leereveld, 1988; Brinkhuis and Zachariasse, 1988; Brinkhuis et
478 al., 1998; M'Hamdi et al. 2015; Vellekoop et al., 2015).

479 Our information on the dinocyst stratigraphy of Stevns Klint can be compared
480 to many of these areas with some reliability, including successions from a wide
481 range of different environments and water depths.

482

483 *7.2 Dinocyst occurrences and biostratigraphic markers*

484 In addition to the publications already mentioned, there is extensive literature on
485 K/Pg boundary successions that include dinocyst studies. Many of these studies
486 describe diverse and abundant dinocyst assemblages, characteristic of the
487 uppermost Maastrichtian and lowermost Danian (Wilson, 1974; J.M. Hansen, 1979;
488 De Coninck and Smit, 1982; Firth, 1987, 1993; Hultberg and Malmgren, 1987; Habib
489 et al., 1992; Moshkovitz and Habib, 1993; Schiøler and Wilson, 1993; Olsson et al.,
490 1997; Schiøler et al., 1997; Nøhr-Hansen and Dam, 1997; Mohamed and Wagreich,
491 2013; Vellekoop et al., 2016). Others, often the thinner successions, are usually not
492 very productive and yield poor or barren dinocyst assemblages (Gedl, 2004;
493 Mohamed et al., 2013; Beiranvand et al., 2014; Machalski et al., 2016).

494 Conclusions relevant to this study that can be made from the literature:

- 495 1. *P. gallator* often, and quite widely, typifies the uppermost Maastrichtian
496 (Wilson, 1974; Schiøler and Wilson, 1993) with *C. cornuta*, *D. californicum* and
497 *S. inornata* frequently characterising the lowermost Danian, (Kjellström and
498 Hansen, 1981) though the exact details of their ranges are dependent on the
499 individual site, the sampling interval used and issues relating to re-working of
500 fine sediment across the boundary.

- 501 2. An increase in the abundance of peridinioid species, demonstrated by the G/P
502 and P/G ratios across the K/Pg boundary into the lower Danian, has been
503 recognised previously (Brinkhuis et al., 1998; Prauss, 2009). More specifically,
504 an increase in the abundance of *Trithyrodinium evittii* is noted by Brinkhuis et
505 al. (1998) and Slimani et al. (2010). The predominance of *T. evittii* has also
506 been recognised in central and northern Europe (Schjøler et al., 1997) and the
507 north-eastern USA (Firth, 1987, 1993).
- 508 3. Vellekoop et al. (2015) describes the K/Pg boundary succession at Elles (75 km
509 south of El Kef) and shows very similar results to those from the K/Pg
510 stratotype section. Diverse and abundant dinocyst assemblages were
511 recovered, and an increase in the abundance of *Cribroperidinium* sp. A of
512 Brinkhuis and Schjøler (1996) in the lowermost Danian is noted.

513

514 7.3 Interpretation of results from Stevns Klint

515 In the present study, only four dinocyst taxa are found to be present throughout the
516 productive samples. These are *A. ramulifera*, *S. ramosus ramosus*, *S. ramosus*
517 *gracilis* and *T. xanthiopyxides*. These are all cosmopolitan species (Brinkhuis et al.,
518 1998) and are considered characteristic of normal, marine shelf environments (Sluijs
519 et al., 2005).

520 The K8/7 and K8/5 samples of the coccolith-rich chalk both contain *P.*
521 *grallator* (112 and 110 specimens, respectively) and *T. xanthiopyxides* (9 and 4
522 specimens, respectively) and, therefore, confirm previous research on the uppermost
523 Maastrichtian (Wilson, 1974; Hultberg, 1986; Schjøler and Wilson, 1993). The
524 predominance of *P. grillator* and, to a lesser extent, species of *Achomosphaera* (29
525 and 32 specimens, respectively) and subspecies of *Spiniferites ramosus* (51 and 49

526 specimens, respectively), is consistent with other findings at Stevns Klint (e.g., J.M.
527 Hansen, 1977; Hultberg, 1986; Brinkhuis et al., 1998). *Palaeoperidinium pyrophorum*
528 is the only peridinioid cyst encountered in the Maastrichtian samples. Its highest
529 abundance (15 specimens) occurs in sample K8/7.

530 Of the other Kulstirenden samples within the coccolith-rich chalk, KUL/I was
531 barren but KUL/K yielded assemblages very similar to K8/7 and K8/5 samples, with
532 a predominance of *P.grallator*, *I. cristatum* and the associated *Achomosphaera*
533 /*Spiniferites* complex of species. Consequently, the G/P^{species} ratio for the
534 Maastrichtian is also at its highest here (based on one peridinioid species), although
535 it still remains low (K8/7 G/P ratio = 25). Samples with a G/P^{species} ratio of 18 are
536 considered by Harland (1973) as being indicative of a marine environment. Hultberg
537 (1986) is the only other author to have calculated the G/P ratio at Stevns Klint
538 showing values of 1–300, using the number of specimens. Our findings here are
539 consistent with Hultberg (1986) for the Maastrichtian, which also shows
540 gonyaulacacean–dominated assemblages for the upper Maastrichtian. The G/P^{species}
541 ratio calculated here varies between 0 and 29 and G/P^{specimens} ratio varies from 0 to
542 304, both showing a decreasing trend through the Maastrichtian and into the Danian.
543 Hultberg's (1986) G/P ratio varied between 75 and 300 in the Maastrichtian chalks,
544 decreasing to <50 at the base of the Fiskeler Member. *Palynodinium grallator* and *H.*
545 *tubiferum tubiferum* are both considered to be indicative of high-latitude climates
546 (Brinkhuis et al., 1998), with the latter "*Hystrichosphaeridium*-type" being noted for its
547 ability to tolerate stressed environments (Schjøler et al., 1997). Their combined
548 presence and the high abundances of *P. grallator* are, therefore, indicative of
549 relatively cool climatic conditions at this time.

550 Within the Højerup (L5) samples of the 'Grey Chalk', the *Achomosphaera*–
551 *Spiniferites* complex cysts dominate the flora, replacing *P. grallator* as the major
552 taxon, although *T. xanthiopyxides* becomes increasingly abundant (14–37
553 specimens) and is one of the most common species in the three uppermost samples.
554 *Spiniferites ramosus ramosus* and *S. ramosus gracilis* are also very common in these
555 samples. While *P. grallator* remains present, its abundance is relatively low
556 compared to the K8 samples. In contrast, *Impagidinium* spp. becomes a major
557 component of the assemblage, their highest abundances occurring in the lowermost
558 samples.

559 The biostratigraphy shows that *P. grallator* was observed rarely at the base of
560 the Fiskeler Member. This agrees with Brinkhuis et al. (1998) who found this species
561 in the bottom layer of the Fiskeler Member. Moreover, Hultberg (1986) had
562 previously noted *P. grallator*, in parts of Stevns Klint, in Layer 3 (Christensen et al.,
563 1973) of the Fiskeler Member; while in other parts of the peninsula its range was
564 found to extend only to Layer 1. Hultberg drew two main conclusions from these
565 findings: (i) that the Fiskeler Member is Maastrichtian in age, and (ii) had been
566 deposited diachronously over Denmark. This was in marked contrast to other fossil
567 and geochemical evidence, including the large negative shift in the $\delta^{13}\text{C}$ record (e.g.,
568 Hart et al., 2005, fig. 10) record from Stevns Klint. The top of the Højerup Member
569 and therefore, the end of the Maastrichtian in higher latitudes can be defined by the
570 last common occurrence of *P. grallator*. Our data clearly support a Danian age for
571 the Fiskeler Member at this location. The 'diachronism' reported by Rasmussen et al.
572 (2005) for the planktic foraminiferal zonation is considered an artefact of the variation
573 in thickness of the Fiskeler Member and the position of the facies change to the
574 Cerithium Limestone Member. The iridium spike that is recorded within K/Pg

575 boundary sediments from a variety of locations (Alvarez et al., 1980), however,
576 precludes diachronous deposition as does the global correlation of the $\delta^{13}\text{C}$ data
577 (Hart et al., 2005; Hart et al., 2014).

578 The *D. californicum* Zone is representative of the Danian. In contrast to data
579 presented by Kjellström and Hansen (1981), however, the expanded section of the
580 Fiskeler Member studied here documents only an intermittent presence of *D.*
581 *californicum* and in reduced numbers. Hultberg (1986) and Brinkhuis et al. (1998) did
582 not record *D. californicum* at Stevns Klint, confirming its rareness. This suggests
583 that, although the *D. californicum* Zone has been applied relatively successfully to
584 the rest of southern Scandinavia, this zonation is difficult to apply at Stevns Klint, or
585 at least a part of it. The rare occurrence of *S.inornata*, a species that is supposed to
586 be coincident with *D. californicum* throughout the lower parts of the Danian, supports
587 this zonation. With the mass extinction of calcareous nannofossils and almost all
588 planktic foraminifera at the K/Pg boundary, there is a dramatic loss of sediment
589 supply leaving only a thin clay-rich succession and an apparent concentration of
590 organic-walled microfossils. Even our small samples, therefore, represent a
591 significant interval of time as indicated by the precessional cyclicity in the $\delta^{13}\text{C}$ data
592 (Hart et al., 2005; Leighton et al., 2017). If this is true in the expanded succession
593 seen at Kulstirenden then it is particularly so in the thinner successions (e.g., at
594 Højerup). If greater condensation of sediments has occurred in these thinner
595 sections, then each sample represents a longer period of time. Consequently,
596 species that were only intermittently present might appear to be present throughout
597 the whole time represented by the sediment. For this location, therefore, it is
598 proposed that the lowermost Danian is defined by the appearance of
599 *Cribopteridinium* sp. A of Brinkhuis and Schiøler (1996) together with the

600 appearance of *S. inornata* and *D. californicum* because *C. cornuta* s.s. is not present.
601 In the middle of the Fiskeler Member (sample KU23), *X. reticulatum* appears and
602 characterises an *X. reticulatum* Sub-zone. With all dinocyst taxa disappearing in the
603 Cerithium Limestone Member and the overlying Korsnæb Member the vertical
604 extension of this sub-zone is not currently known.

605 Another feature of the KU (14–50) samples of the Fiskeler Member is the
606 predominance of *T. xanthiopyxides*, where it commonly represents approximately
607 one-third of the assemblage. Previous studies have shown this species to be present
608 in all stratigraphic levels at Stevns Klint, but no one has commented on its
609 predominance within this stratigraphic level. Indeed, both H.J. Hansen et al. (1986)
610 and Brinkhuis et al. (1998) show *T. evittii* to be the dominant species through layers
611 2 and 3 of the Fiskeler Member. *Trithyrodinium evittii* is also found to be common to
612 very common (19–48 specimens in samples KU18–27) within the Fiskeler Member in
613 our study and becomes abundant in the topmost samples (KU28 and KU29,
614 recording 163–214 specimens, respectively). Another peridinioid, *Manumiella*
615 *seelandica* (as *M. druggii*) has previously been reported to be abundant in these
616 sediments at the base of the Danian (Hultberg, 1986) but these data are not
617 confirmed here. In the current study occasional specimens of *M. seelandica* are
618 found at the base of the Fiskeler Member, becoming more common (5–14
619 specimens) in the topmost samples (KU26–KU29). Instead of abundant *M.*
620 *seelandica*, large numbers of *T. evittii* are recorded here and this confirms the results
621 of Brinkhuis et al. (1998).

622 The lack of dinocysts, and the presence of bisaccate pollen, which have a
623 hinterland provenance (Schiøler et al., 1997), could be due to variable preservation

624 and/or complex diagenesis of the Cerithium Limestone Member (Rasmussen et al.
625 2005).

626

627 7.4 Palaeoenvironmental interpretation

628 The Gonyaulacoid/Peridinioid (G/P) and Protoperidinioid /Gonyaulacoid (P/G) ratios
629 were calculated here based on the data collected; the former after Harland (1973),
630 and the latter follows Versteegh (1994). Note that these methods produce different
631 results to those obtained by Hultberg (1986,1987) for samples from Stevns Klint but
632 the overall decreasing trend in the G/P^{species} and $G/P^{\text{specimens}}$ ratios is similar . The
633 method of calculation for the G/P ratio used in Hultberg (1986, 1987) is not clear but
634 probably involved using the number of specimens.

635 The G/P ratio, based on specimen percentage, was calculated by Prauss
636 (2009) for the K/Pg boundary at Brazos River, Texas. An overall increase in
637 peridinioid cysts was recorded across the K/Pg boundary. This is interpreted as
638 reflecting an increase in palaeoproductivity through the succession, into the Danian.
639 Brinkhuis et al. (1998) found that their P/G ratios did not correlate with the drop in
640 $\delta^{13}\text{C}$ values across the K/Pg boundary at El Kef and interpreted this as reflecting
641 changes in temperature as well as productivity.

642 Both G/P^{species} and $G/P^{\text{specimens}}$ ratios calculated here display an overall
643 decreasing trend from the uppermost Maastrichtian into the Danian, while the P/G
644 ratio increases. The interpretation here is of a marine environment with increasing
645 nutrients and productivity.

646 Small numbers of *Impagidinium cristatum* (10 specimens) occur in the
647 Sigerslev Member (K8/7) with an increased abundance occurring in the
648 stratigraphically younger K8/5 (20 specimens). *I. cristatum* is considered to be

649 indicative of more oceanic rather than neritic conditions (Schjøler et al., 1997), and
650 so its presence indicates that there was still an open marine influence to the
651 environment in the Danish Basin. This is recognised by Sheldon et al. (2010) as an
652 anti-clockwise circulatory system in the Danish Basin with possible warmer water
653 influences coming from the southeast. The decrease in abundance of *I. cristatum*
654 and other *Impagidinium* spp. implies a shallowing-upward sequence.

655 Bromley (1979) and Hart et al. (2004, 2005) suggest that the succession of the
656 Højerup Member represented a shallower environment compared to the white
657 coccolith chalk below (Sigerslev Member). The stable isotope data derived from
658 benthic foraminifera (Schmitz et al., 1992; Hart et al., 2005) provide evidence that,
659 although shallower, the environment was still open marine.

660 This shallowing upwards is confirmed by the occurrence of *Senoniaspharea*
661 *inornata* in the Fiskeler Member (KU14-29). This species belongs to the *Areoligera*
662 group of Gv cysts (Fensome et al., 2008) which has been interpreted as reflecting
663 high energy, shallower environments (Sluijs et al., 2005). The occurrence of this
664 species at Stevns Klint, reflects the shallower conditions both above, and near to the
665 Rynkøbing-Fyn High in comparison to the more basinal area of northern Jutland
666 (Jylland).

667 Brinkhuis et al. (1998, p.77) indicate that the differences between their results
668 and those of Hultberg (1986) were the result of the processing techniques employed
669 and then conclude (Brinkhuis et al. 1998, p.80) that there were warm, stable
670 conditions in the latest Maastrichtian, and cooler but fluctuating conditions in the
671 earliest Danian, with water masses controlling the migration and distribution of taxa.
672 In the past, *T. evittii* has been used as a warmer-water, low latitude indicator species
673 and as a peridinioid, it also indicates increased primary productivity (Brinkhuis et al.,

674 1998, fig.6). The abundance of *T.evittii* in the lower Danian at Stevns Klint agrees
675 with observations made by Brinkhuis et al. (1998) and others (e.g., Aydin, 2013;
676 Pross and Brinkhuis, 2005).

677

678 **8 Conclusions**

679 The evidence obtained from this investigation of the dinocysts provides data that
680 helps to document the changes across the Maastrichtian/Danian (K/Pg) boundary.
681 Our results do not replicate those of earlier studies, although, this may be due to the
682 limited number of samples analysed in previous investigations, the sample interval,
683 sampling from thinner sections of the Fiskeler Member or the processing techniques
684 adopted (e.g. Hultberg, 1986). Also previous authors have rarely identified their
685 precise sample locations on Stevns Klint, so lateral variations, as indicated by the
686 variable lithology may account for some of these differences.

687 The top of the Højerup Member and, therefore, the top of the Maastrichtian is
688 characterised by the last common appearance of *P. grallator*. Within the Fiskeler
689 Member, the intermittent presence of *D. californicum* precludes its use as a primary
690 biostratigraphical indicator although, when used together with other
691 biostratigraphically useful species such as *S.inornata*, *X. reticulatum* and *T.evittii*, the
692 lowermost Danian can be characterised. Conditions throughout the latest
693 Maastrichtian and the early Danian, as indicated by the G/P ratio, were changing and
694 becoming dominated by peridinioid dinocysts at the base of the Danian, reflecting an
695 increase in primary productivity (Sluijs et al. 2005).

696 Although our sampling was at a much higher resolution than earlier
697 investigations and from an expanded succession of Fiskeler Member, there is still
698 the potential for further dinocyst work at Stevns Klint and additional refinement of the

699 biostratigraphy, especially if coupled with data from successions in North Jutland
700 (Jylland) and off-shore.

701

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710

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942 **Figures, Table and Plate Captions**

943

944 **Fig. 1.** Locality map of Stevns Peninsula, eastern Denmark and its location in
945 Southern Scandinavia.

946

947 **Fig. 2.** Revised lithostratigraphy of the succession exposed on Stevns Peninsula,
948 following Hart et al. (2005) and Surlyk et al. (2006).

949

950 **Fig. 3.** Photograph of the beach section north of Højerup church, showing the
951 horizontal chalk in the lower part of the cliff, the prominent flint line (above which is
952 the incipient hardground) and the Fiskeler Member deposited in troughs picked out
953 by the dune-like structures in the Højerup Member.

954

955 **Fig. 4.** (a) Photograph of the Fiskeler Member at Kulstirenden prior to sampling. The
956 distinctive Fe-stained horizon is just below the scale card, at the base of the Fiskeler
957 Member; (b) the marked thinning of the Fiskeler Member to the north of the sampling
958 location.

959

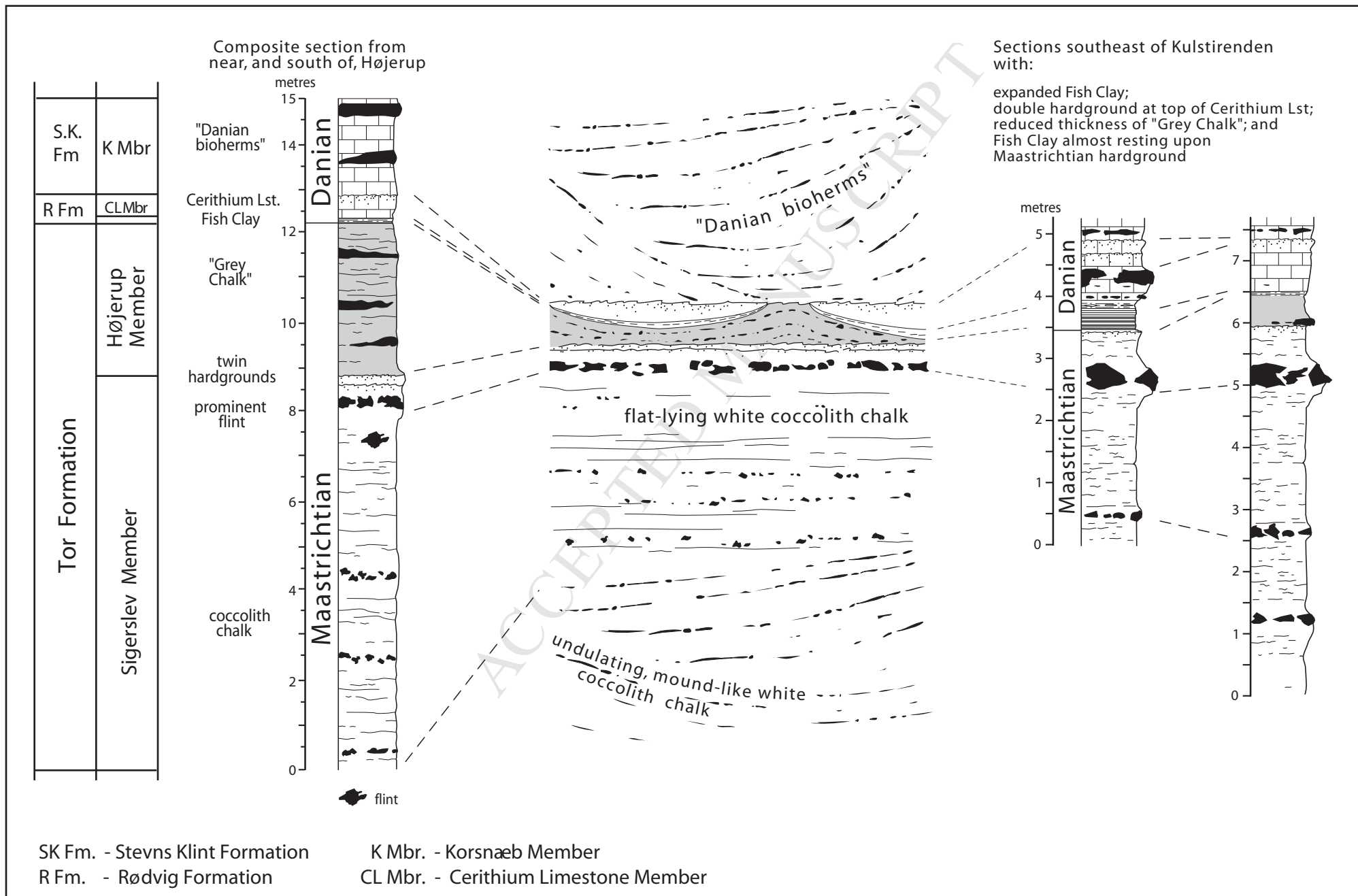
960 **Fig. 5.** Composite log of the Cretaceous/Palaeogene boundary succession.

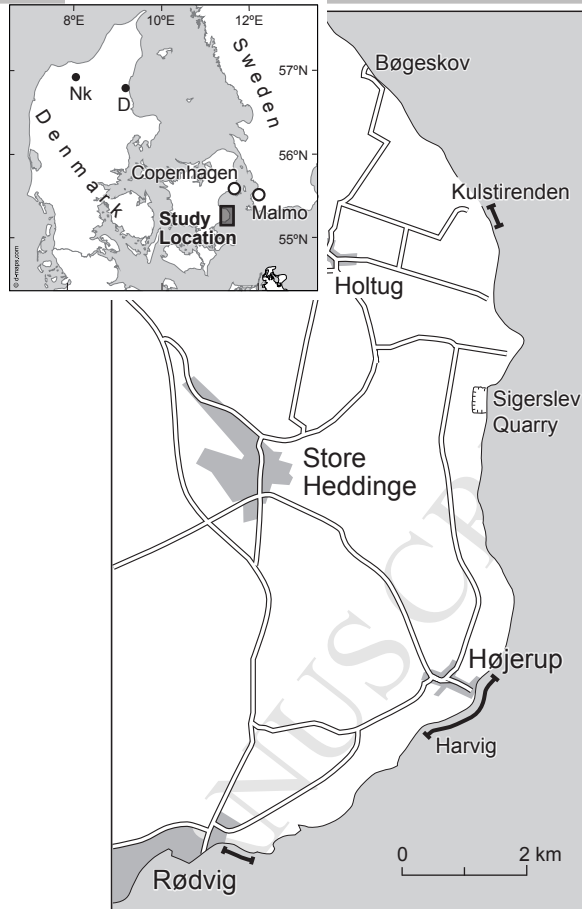
961
962 **Fig. 6.** A) *Palynodinium grillator*; B) *Thalassiphora pelagica*; C) *Palaeoperidinium*
963 *pyrophorum*; D) *Hystrichosphaeridium tubiferum*; E) *Spiniferites ramosus reticulatus*;
964 F) *Spiniferites ramosus*; G) *Impagidinium cristatum*; H) *Tanyosphaeridium*
965 *xanthiopyxides*; I) *Damassadinium californicum*; J) *Cribroperidinium* sp. A of
966 Brinkhuis and Schiøler (1996); K) *Xenicodinium reticulatum*; L) *Manumiella*
967 *seelandica*; M) *Cerodinium diebelii*; N) *Trithyrodinium evitti*. Scale bar 10µm in all
968 images.

969
970 **Fig. 7.** Gonyaulacacean/Peridiniacean (G/P) ratio calculated using species and
971 specimen numbers. Peridiniacean/Gonyaulacacean (P/G) ratio ((Versteegh, 1994).
972 Total number of species counted in each sample.

973
974 **Table 1.** Occurrences of selected taxa. ○ < 5 specimens; ● >5 specimens.
975 CLM - Cerithium Limestone Member; SM - Sigerslev Member

976
977 **Appendix 1.** Raw data of dinocyst counts. * marks taxa which require further
978 taxonomic investigation.







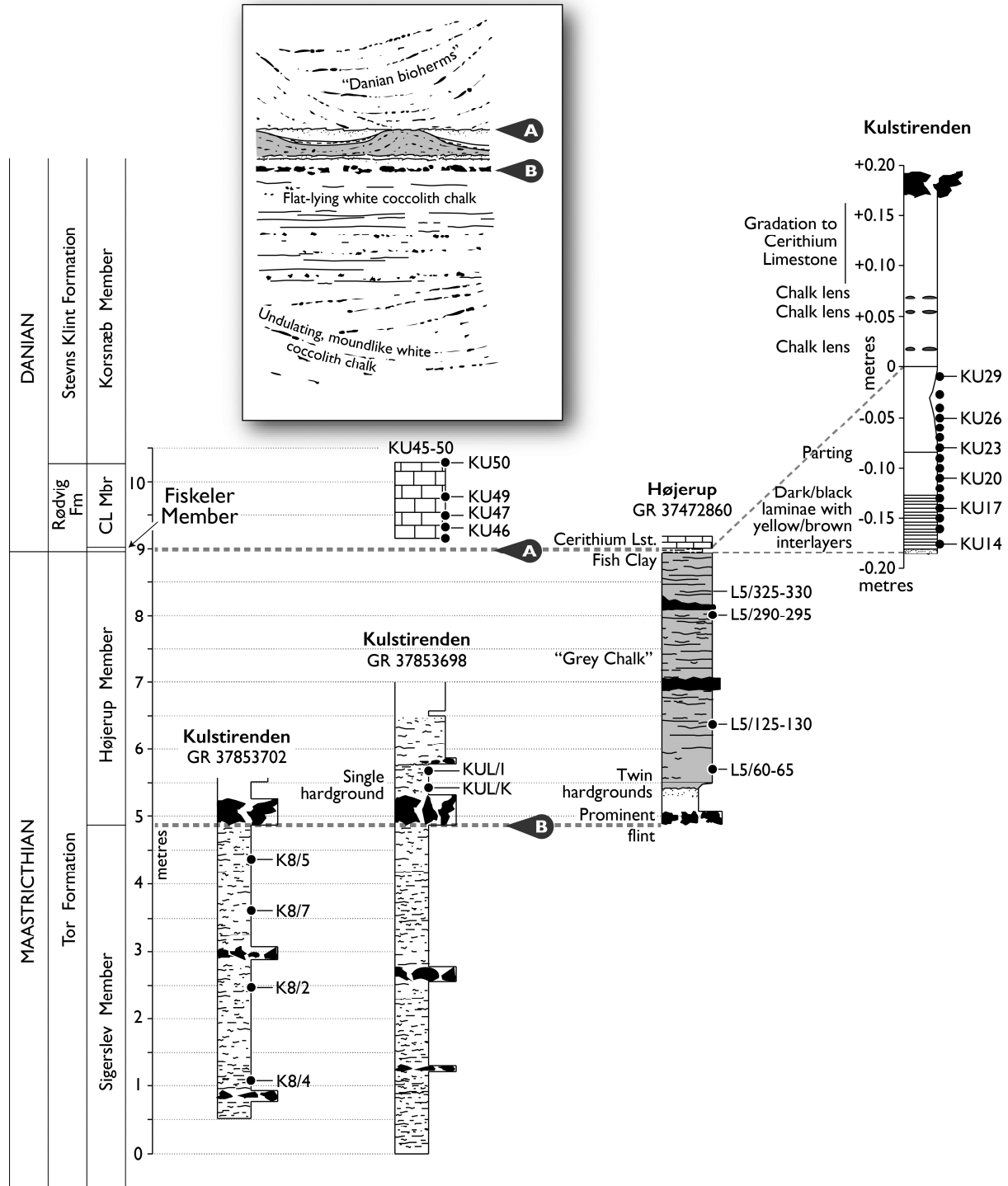
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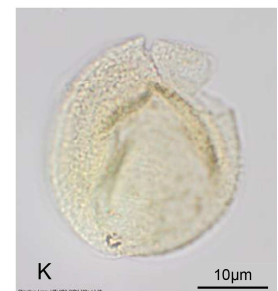
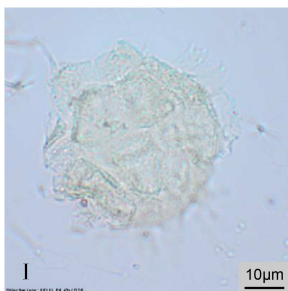
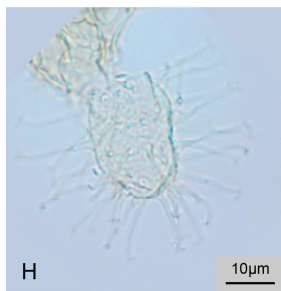
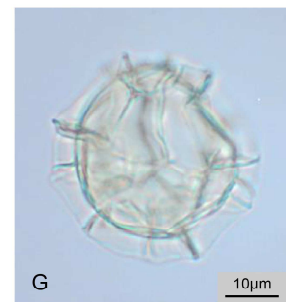
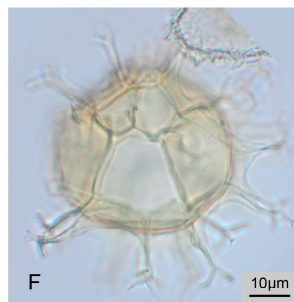
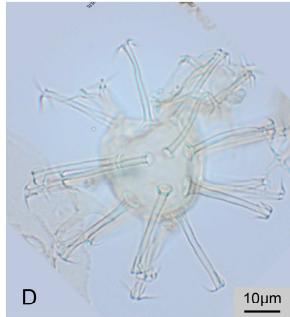
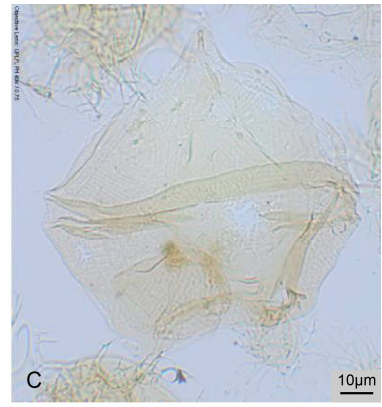
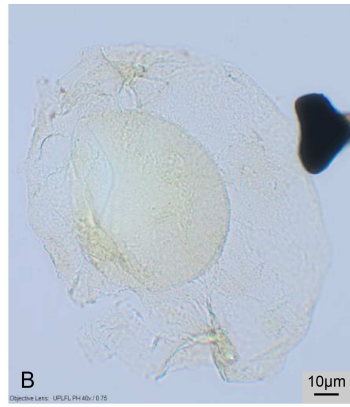
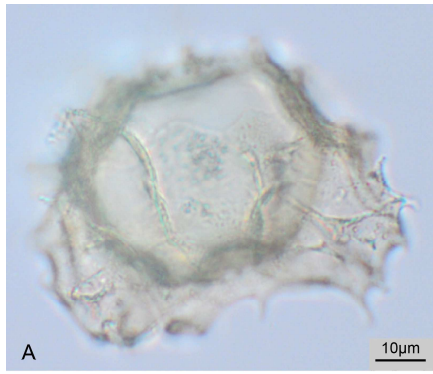


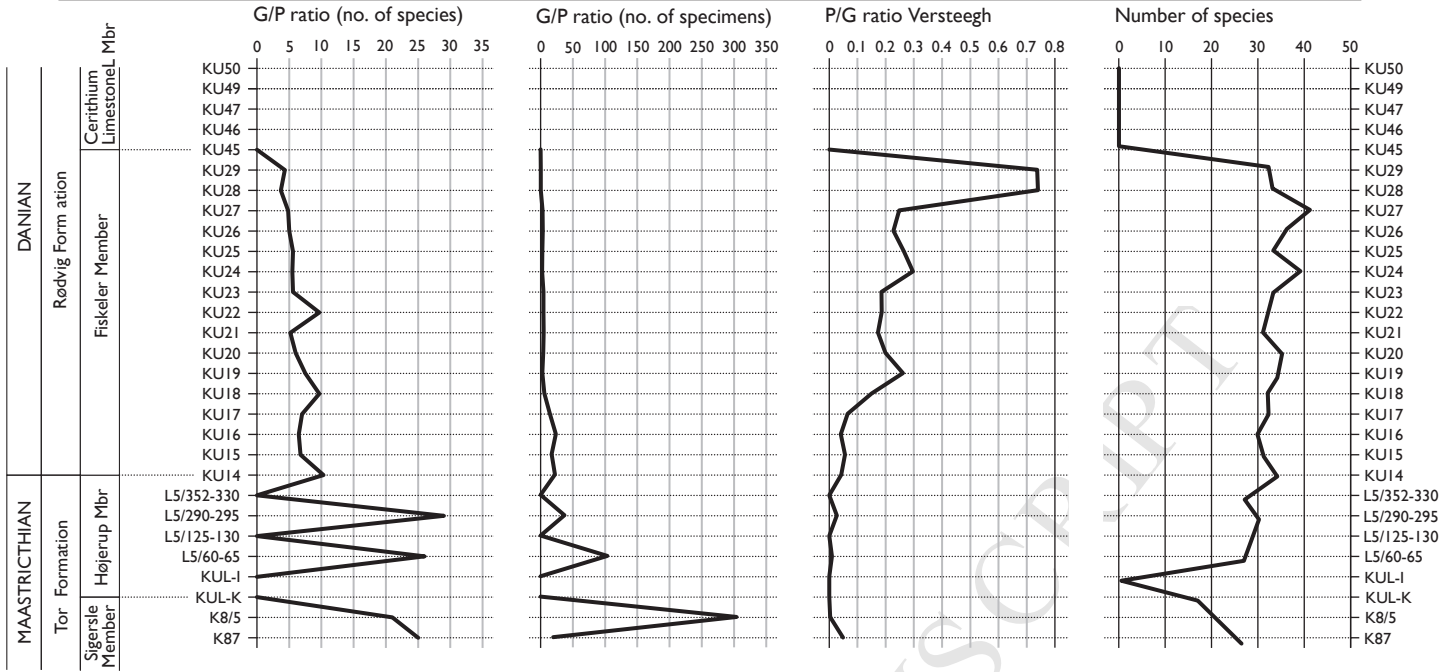
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b







Highlights – Fitzpatrick *et al.*

The Cretaceous-Paleogene boundary succession at Stevns Klint is world famous and been a reference point for stratigraphy since the mid-nineteenth century. It is now a World Heritage Site and one of the most important of the distal K/Pg sites. Previous dinocyst research on the Stevns Klint succession has caused controversy, with some strange assemblages being described that may have been the result of preparation techniques. Unfortunately most of the sampling across the boundary has been limited to only a few sample points, often where the boundary clay (Fiskeler Member) is at its thinnest. Our research, using a large number of samples from an expanded succession of the boundary clay, has resolved many of the earlier problems and allowed us to identify a dinocyst stratigraphy across the boundary. This dinocyst stratigraphy can be used to compare the Stevns Klint succession with other boundary sections in Tunisia and Texas. One of the earlier suggestions, that the boundary clay is diachronous (despite containing the iridium anomaly), has been refuted.