

1 **The Middle Jurassic palynostratigraphy of the northern Lusitanian Basin, Portugal**

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6 With 10 figures

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20 **Abstract.** A composite largely Middle Jurassic succession spanning the Toarcian–Aalenian
21 transition to the lowermost Bathonian exposed at Cabo Mondego and São Gião in the
22 northern Lusitanian Basin, western Portugal, was examined palynologically. The 129 samples
23 are correlated to ammonite biozones (ABs) spanning *Pleydellia aalensis* to *Zigzagiceras*
24 *zigzag*. The Cabo Mondego succession comprises the type section of the Cabo Mondego
25 Formation and spans virtually the entire interval studied. This is a significant interval because
26 it includes the Global Stratotype Section and Point (GSSP) and the Auxiliary Stratigraphical
27 Section and Point (ASSP) for the Bajocian and Bathonian stages respectively. The Cabo
28 Mondego Formation largely yielded relatively abundant palynomorph associations in the 68

29 productive samples recovered. By contrast, the Póvoa da Lomba Formation at São Gião only
30 includes the Toarcian–Aalenian transition; the 21 productive horizons produced sparse
31 assemblages. The uppermost Toarcian to lowermost Bajocian is characterised by a low
32 diversity dinoflagellate cyst association, typified by *Nannoceratopsis*. Above this is a
33 markedly more diverse assemblage, dominated by the family Gonyaulaceae. This influx, in
34 the *Witchellia laeviuscula* AB, represents a global evolutionary radiation which may be
35 linked to sea level rise. The lower Bajocian yielded significant proportions of gonyaulacacean
36 forms with epicystal and multiplate precingular archaeopyles, representing morphological
37 experimentation as part of this radiation. The trend of increasing dinoflagellate cyst diversity
38 continued at the Bajocian–Bathonian transition, particularly sexiform tabulate
39 gonyaulacaceans with single plate precingular archaeopyles. The Middle Jurassic
40 dinoflagellate cyst associations of the Lusitanian Basin are significantly less diverse than
41 coeval palynofloras from eastern and northern Europe, and the Arctic. The Toarcian Oceanic
42 Anoxic Event (T-OAE) profoundly inhibited cyst-forming dinoflagellates in this depocentre,
43 and the recovery was protracted. Hence the T-OAE may have suppressed dinoflagellate cyst
44 diversity well into the Middle Jurassic. This phenomenon may have been exacerbated by the
45 absence of typically Arctic taxa through latitudinal controls and/or global cooling during the
46 early Aalenian. These low levels of dinoflagellate cyst species richness may also be related to
47 the palaeogeography of the Lusitanian Basin. This relatively isolated deepwater depocentre
48 close to the Proto Atlantic, may have precluded extensive biotal exchange with the
49 widespread shelfal areas of the western Tethys. The absence of *Dissiliodinium giganteum* in
50 the Lusitanian Basin is consistent with this scenario. The pollen and spores observed in this
51 study are typical of Middle Jurassic assemblages worldwide. Araucarian pollen, largely
52 *Callialasporites*, diversified and became prominent during the Aalenian.

53

54 **Key words.** biostratigraphy; Cabo Mondego and São Gião; Lusitanian Basin, Portugal;
55 Middle Jurassic; palaeobiology; palynomorphs

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57

58 1. Introduction

59 This study documents the marine and terrestrial palynology of the uppermost Lower and
60 Middle Jurassic (uppermost Toarcian to lowermost Bathonian) strata at Cabo Mondego and
61 São Gião near Figueira da Foz in the northern part of the Lusitanian Basin, central western
62 Portugal (Figs. 1, 2). The principal aim of this work is to investigate the biostratigraphy of

63 these palynofloras, especially the dinoflagellate cysts, and to compare them with coeval
64 biotas largely from Europe. The Cabo Mondego section at Murtinheira Beach was ratified as
65 the Global Stratotype Section and Point (GSSP) for the Bajocian Stage in 1996 (Henriques et
66 al., 1994; Pavia and Enay 1997). This succession also includes the Auxiliary Stratigraphical
67 Section and Point (ASSP) for the Bathonian Stage (Fernández-López et al., 2009a, b).

68 The Middle Jurassic ammonite faunas at both Cabo Mondego and São Gião have been
69 intensively researched (Henriques 1995, Fernández-López et al. 2006, 2009a, b, Sandoval et
70 al. 2012). These studies have provided a framework for many works on other fossil groups
71 such as brachiopods (Andrade et al. 2016), calcareous nannofossils (Suchéras-Marx et al.
72 2012, 2015) and benthic foraminifera (Canales and Henriques 2008, 2013). This is the first
73 detailed investigation throughout the Middle Jurassic palynology of the Lusitanian Basin.
74 However, this topic has been previously studied by Davies (1985), Smelror et al. (1991),
75 Barrón et al. (1999) and Barrón and Azerêdo (2003).

76 Davies (1985) examined four existing sample collections from outcrops of the Lower
77 to Upper Jurassic (Sinemurian to Oxfordian) at Brenha, Peniche and Zambujal in the
78 Lusitanian Basin. However, the main emphasis of this author was on the Lower Jurassic, this
79 study lacks stratigraphical precision, and the stratigraphy of the Lusitanian Basin was not
80 well established at that time. Of the Middle Jurassic, only the Aalenian to Callovian at
81 Brenha and the Aalenian at Zambujal were studied (Davies 1985, figs. 8, 9). Smelror et al.
82 (1991) described a relatively diverse marine palynoflora from 21 samples from the uppermost
83 Bathonian and lowermost Callovian (*Macrocephalites herveyi* ammonite biozone - AB) of
84 Cabo Mondego. Barrón and Azerêdo (2003) is a study which built on Barrón et al. (1999).
85 The former work is on the Callovian to Oxfordian succession at Pedrógão, south of Cabo
86 Mondego, and the emphasis was mainly on pollen and spores. These authors only recovered
87 three dinoflagellate cysts (Barrón and Azerêdo 2003, p. 285). Other substantial contributions
88 on the Jurassic palynology of Portugal include Mohr and Schmidt (1988), Bucefalo Palliani
89 and Riding (2003), Oliveira et al. (2007), Borges et al. (2011, 2012), Barrón et al. (2013),
90 Rocha et al. (2016), Correia et al. (2017a, 2017b, 2018) and Turner et al. (2017).

91 Dinoflagellate body fossils, which represent resting cysts, first appeared in the Middle
92 Triassic. The group underwent a major evolutionary radiation during the Bajocian, and
93 became abundant and diverse during the rest of Mesozoic and Cenozoic (Fensome et al.
94 1996, MacRae et al. 1996, Wiggan et al. 2017). Many dinoflagellate cyst taxa had relatively
95 short ranges and therefore are used as biostratigraphical markers (e.g. Poulsen and Riding
96 2003). It is hoped that this study on the uppermost Toarcian to lowermost Bathonian

97 palynomorph floras of the Lusitanian Basin will further characterise the biostratigraphy of
98 this important depocentre.

99

100 **2. Geographical and geological setting**

101 The Lusitanian Basin is a centre of deposition located on the western central coastal margin
102 of Portugal. It is a marginal marine basin approximately 300 km long and 150 km wide, and
103 with a NE-SW orientation (Fig. 1). The basin fill is up to 5 km thick; most of this is Jurassic
104 but it ranges from the Middle?–Upper Triassic to the uppermost Lower Cretaceous (Wilson et
105 al. 1989). The breakup of Pangaea and the opening of the North Atlantic initiated the
106 development of the Lusitanian Basin and controlled its development (Rasmussen et al. 1998,
107 Kullberg et al. 2013).

108 Middle Jurassic strata are very well developed in the Lusitanian Basin, especially in
109 the coastal area at Cabo Mondego in the Coimbra District near the city of Figueira da Foz
110 (Figs. 1, 2). These coastal outcrops include the Cabo Mondego Formation, which is late
111 Toarcian to Callovian in age. The GSSP for the Bajocian, and the ASSP for the Bathonian are
112 both within the Cabo Mondego Formation (Pavia and Enay 1997, Fernández-López et al.,
113 2009a, b). This unit comprises almost 500 m of alternating interbeds of fossiliferous grey
114 marls and marly limestones/limestones. It represents a distal platform setting which was
115 established during the Toarcian (Azerêdo et al. 2003). The abundant and diverse molluscan
116 faunas have enabled the establishment of an accurate ammonite-based biostratigraphy for this
117 unit (e.g. Henriques 1995, Fernández-López et al. 2006, Sandoval et al. 2012). The São Gião
118 section exposes the Póvoa da Lomba Formation. This unit is comprised of regularly-bedded
119 marly limestones 10 to 30 cm thick, alternating with slightly thicker beds of grey marl. This
120 succession is coeval with the lower part of Cabo Mondego Formation (Fig. 2, Azerêdo et al.
121 2003).

122

123 **3. Material and methods**

124 The Cabo Mondego and São Gião sections are located in the northern Lusitanian Basin. Cabo
125 Mondego is ~7 km northwest of Figueira da Foz and ~40 km west of Coimbra, and São Gião
126 is situated about 5 km southwest of Cantanhede village (Fig. 1). Herein, 129 samples were
127 collected from these two important reference sections which span the upper Toarcian
128 *Pleydellia aalensis* AB to the lower Bathonian *Zigzagiceras zigzag* AB (Figs. 2–5). The Cabo
129 Mondego succession comprises the type section of the Cabo Mondego Formation, and spans

130 virtually the entire interval studied except the upper Bajocian *Strenoceras niortense* and
131 *Garantiana garantiana* ABs, which were not sampled (Figs. 3, 4). At São Gião, the
132 Toarcian–Aalenian transition within the Póvoa da Lomba Formation was collected (Fig. 5).

133 The samples were prepared using traditional acid-digestion techniques (Riding and
134 Warny 2008), however the post-acid residues were not oxidised. All residues were screened
135 using a 15 µm mesh sieve and the final palynomorph concentrates were stained. If possible,
136 at least 300 palynomorphs were counted. However, if the material was sparse, as many
137 specimens as possible from two microscope slides were counted. The unused sample
138 material, aqueous residues, microscope slides and the figured specimens in Plates I to III are
139 curated in the collections of LNEG (Portuguese Geological Survey), São Mamede de Infesta,
140 Portugal.

141

142 **4. Palynology**

143 In this section, the palynomorph associations from Cabo Mondego and São Gião encountered
144 in this study are described in three sections. These palynobiotas are fully documented in
145 Supplementary Figs. 1, 2, and Supplementary Tables 1, 2. Selected specimens are illustrated
146 in Plates I–III. The Supplementary Appendix is a list of all the palynomorph taxa at and
147 below the species level which were recovered from the material studied herein, or mentioned
148 in the text, with full author citations.

149

150 *4.1. The uppermost Toarcian to lower Bajocian part of the Cabo Mondego Formation at* 151 *Murtinheira Beach, Cabo Mondego (samples M2 to AB192)*

152 In the lower part of Cabo Mondego succession at Murtinheira beach, 68 samples (numbered
153 M2 to AB192), were collected from the Cabo Mondego Formation. The succession includes
154 the Bajocian GSSP, and it spans the *Pleydellia aalensis* to *Stephanoceras humphriesianum*
155 ABs (Figs. 2, 3). These samples were generally moderately well-preserved, however nine of
156 the horizons samples proved barren of palynomorphs (Supplementary Table 1).

157 This succession is dominated by foraminiferal test linings and gymnosperm pollen,
158 with subordinate proportions of acritarchs, dinoflagellate cysts, prasinophytes and spores.
159 Overall, pollen is the principal palynomorph type from the uppermost Toarcian to close to the
160 top of the middle Aalenian (samples M2 to M237), with foraminiferal test linings and pollen

161 exhibiting subequal proportions in the uppermost middle Aalenian to much of the lower
162 Bajocian (samples M245 to AB178a) (Supplementary Fig. 1).

163 Indeterminate pollen is prominent, and *Araucariacites australis*, *Classopollis* spp. and
164 *Exesipollenites* spp. are relatively common. Bisaccate pollen (*Alisporites* spp.),
165 *Callialasporites* spp., *Cerebropollenites macroverrucosus*, *Chasmatosporites* spp.,
166 *Cycadopites granulatus*, *Perinopollenites elatoides* and *Spheripollenites* spp. are relatively
167 sparse. The overall diversity of pollen increased steadily up section. In sample M361, in the
168 *Hyperlioceras discites* AB and above, the numbers of *Araucariacites australis* and the
169 diversity of *Callialasporites* increased markedly. Moreover, *Exesipollenites* spp. was less
170 prominent, and this genus became present only sporadically. Furthermore, the inception of
171 *Chasmatosporites* spp. is in sample AB164, within the *Sonninia propinquans* AB. Like the
172 pollen, the pteridophyte spore assemblages increased in diversity upsection in this interval.
173 Most taxa recognised occur in low relatively proportions. *Anapiculalatisporites* spp., the
174 smooth genus *Cyathidites*, indeterminate forms, *Leptolepidites* spp., *Lycopodiacidites*
175 *rugulatus* and *Marattisporites* sp. were present consistently throughout. By contrast,
176 *Kraeuselisporites reissingeri* is confined to the interval between samples M14 and M91
177 (uppermost Toarcian to lowermost Aalenian). The single occurrence of the distinctive spore
178 *Kekryphalospora distincta* is in sample M24 (uppermost Toarcian). Notable range bases
179 include those of *Osmundacidites wellmanii*, *Ischyosporites variegatus*, *Striatella*
180 *seebergensis*, *Todisporites* sp., *Auritulinasporites triclavus* and *Retitriletes austroclavatidites*
181 in samples M34, M83t, M225, M305, M319 and M328 respectively (Supplementary Table
182 1).

183 Foraminiferal test linings are consistently very common, and attained a maximum of
184 67.7% in sample M396. By contrast, dinoflagellate cysts are of low diversity and low
185 abundance in the uppermost Toarcian and the lower Bajocian *Hyperlioceras discites* AB
186 (samples M2 to M398). In this interval *Mancodinium semitabulatum*, *Nannoceratopsis*
187 *gracilis*, *Nannoceratopsis senex* and *Scriniocassis priscus* were encountered reasonably
188 consistently. All of these species, except *Nannoceratopsis gracilis*, are confined to this
189 interval. By contrast, *Dissiliodinium* sp. 1, *Impletospheridium* sp., *Mendicodinium* spp.,
190 *Phallocysta elongata* and *Scriniocassis weberi* were observed extremely sporadically (Fig. 3,
191 Supplementary Fig. 1, Supplementary Table 1).

192 However from sample AB55, at the top of the *Hyperlioceras discites* AB, and above
193 (to sample AB192), the dinoflagellate cyst associations abruptly became substantially more
194 common and diverse (Supplementary Fig. 1). In this part of the lower Bajocian, spanning the
195 *Witchelluia laeviuscula* to *Stephanoceras humphriesianum* ABs, 17 forms have their range
196 bases. These are virtually all gonyaulacean forms, and comprise *Acanthaulax* sp. cf. *A.*
197 *crispa*, *Ctenidodinium sellwoodii*, *Dissiliodinium* sp. 2, *Dissiliodinium* spp., *Durotrigia*
198 *daveyi*, *Durotrigia* sp., *Epiplosphaera gochtii*, *Kallosphaeridium?* sp., *Korystocysta* sp. cf. *K.*
199 *aldridgeii*, *Meiourogonaulax* spp., *Pareodinia* sp., *Rhynchodiniopsis* spp., *Sentusidinium* sp.
200 cf. *S. asymmetrum*, *Sentusidinium* sp. cf. *S. explanatum*, *Sentusidinium* sp. 1, *Sentusidinium*
201 spp. and *Wanaea* sp. Of these, *Acanthaulax* sp. cf. *A. crispa*, *Dissiliodinium* spp., *Durotrigia*
202 *daveyi*, *Durotrigia* sp., *Epiplosphaera gochtii*, *Kallosphaeridium?* sp., *Korystocysta* sp. cf. *K.*
203 *aldridgeii*, *Pareodinia* sp. and *Wanaea* sp. are sporadic and rare; the other forms are
204 relatively consistently present (Fig. 3). Low diversity acritarch (largely *Micrhystridium* spp.)
205 and prasinophytes (mainly large forms such as *Tasmanites*) assemblages were present
206 throughout in relatively low numbers (Supplementary Table 1).

207

208 4.2. The uppermost Bajocian and lowermost Bathonian part of the Cabo Mondego 209 Formation at Murtinheira Beach, Cabo Mondego (samples Bt94 to Bt220)

210 The Bajocian–Bathonian transition in the Cabo Mondego Formation was sampled at Cabo
211 Mondego; 14 horizons were collected (numbers Bt94 to Bt220). This unit includes the
212 Bathonian ASSP, and the succession comprises the *Parkinsonia parkinsoni* and *Zigzagiceras*
213 *zigzag* ABs (Figs. 2, 4). Again the preservation of palynomorphs proved moderately good,
214 but one sample was barren (Supplementary Table 1).

215 This upper part of the Cabo Mondego succession is overwhelmingly dominated by
216 gymnospermous pollen, with relatively abundant dinoflagellate cysts. The proportions of
217 acritarchs, foraminiferal test linings, prasinophytes and spores are markedly subordinate. The
218 most profound difference with the underlying succession at this locality is the significant
219 diminution of foraminiferal test linings and prasinophytes, with the former group being most
220 profoundly affected (Supplementary Fig. 1). An association between foraminiferal test linings
221 and prasinophytes has not been previously noted. The foraminiferal test linings from the
222 Toarcian to Lower Bajocian in this study are most likely to be benthic taxa. It is possible that

223 the early planktonic foraminifera, which may not have produced these test linings, somehow
224 suppressed their benthic counterparts (Hart et al. 2003).

225 Gymnosperm pollen is substantially more abundant than in the majority of the
226 underlying succession at Cabo Mondego, and the relatively high diversity which developed in
227 the Lower Bajocian is maintained. The pollen associations are largely similar to those from
228 the underlying lower Bajocian (subsection 4.1). They are characterised by a dominance of
229 *Araucariacites australis*; the saccate genus *Callialasporites*, *Cycadopites granulatus* and
230 indeterminate pollen are also prominent. *Callialasporites segmentatus* and *Callialasporites*
231 spp. are more common than in the underlying succession. Bisaccate pollen (*Alisporites* spp.)
232 and *Chasmatosporites* spp. are consistently present throughout in very low proportions, and
233 *Exesipollenites* spp. and *Spheripollenites* spp. were encountered somewhat intermittently.
234 *Cerebropollenites macroverrucosus* and *Classopollis* spp. are both sporadic and relatively
235 sparse, only being recorded in samples Bt 122 and Bt184 respectively. The inception of
236 consistent *Perinopollenites elatoides* in sample Bt94 at the base of the *Parkinsonia*
237 *parkinsoni* AB appears to be a notable local bioevent (Supplementary Table 1).

238 The pteridophyte spore assemblages in the uppermost Bajocian and lowermost
239 Bathonian succession are not prominent. They are substantially similar in relative proportions
240 and taxonomic spectrum to those in the underlying Aalenian and Lower Bajocian part of the
241 Cabo Mondego Formation. Diversity, however, is relatively low; the assemblages are largely
242 comprised of *Cyathidites* spp., *Ischyosporites variegatus*, indeterminate spores and
243 *Leptolepidites* spp. (Supplementary Table 1).

244 The dinoflagellate associations in the *Parkinsonia parkinsoni* and *Zigzagiceras zigzag*
245 ABs are highly variable in relative proportions, and exhibit several marked abundance peaks
246 (Supplementary Fig. 1). These associations are substantially higher in diversity than their
247 counterparts in the underlying succession (Supplementary Table 1); a total of 32 forms were
248 recognised. *Chytroeisphaeridia chytroeides*, *Ctenidodinium sellwoodii*, *Dissiliodinium* spp.,
249 indeterminate forms, *Sentusidinium* spp. and *Valensiella ovulum* are present consistently and
250 in significant numbers. The other taxa however, are present either sporadically, or have
251 restricted ranges within this succession. For example *Gonyaulacysta pectinigera*,
252 *Korystocysta pachyderma*, *Mendicodinium* spp., *Pareodinia ceratophora* are present
253 intermittently, and *Bradleyella adela* and *Rhynchodiniopsis? regalis* are confined to sample
254 Bt94 (*Parkinsonia parkinsoni* AB). *Meiourogonyaux* spp. are confined to the *Parkinsonia*

255 *parkinsoni* AB, and several taxa are confined to the overlying *Zigzagiceras zigzag* AB. The
256 latter include *Ctenidodinium cornigerum*, *Gonyaulacysta jurassica* subsp. *adecta*,
257 indeterminate complex chorate dinoflagellate cysts, ?*Korystocysta gochtii*, *Mendicodinium*
258 *groenlandicum* and *Tubotuberella dangeardii* (Supplementary Table 1). The assemblage is
259 overwhelmingly dominated by the gonyaulacacean lineage, and genera with epicystal
260 archaeopyles such as *Ctenidodinium*, *Korystocysta* and *Mendicodinium* are prominent.
261 However, many forms recognised in this interval are present in a single sample, or low
262 numbers of horizons and are relatively rare. Furthermore, many of them are difficult to assign
263 to existing species (Supplementary Table 1).

264 Foraminiferal test linings dominate the miscellaneous microplankton, however these
265 forms do not exceed 8.1% (sample Bt164). Acritarchs (largely *Micrhystridium* spp.) and large
266 prasinophytes occur throughout this interval in relatively low proportions (Supplementary
267 Table 1).

268

269 4.3. The uppermost Toarcian and lowermost Aalenian part of the Póvoa da Lomba 270 Formation at São Gião (samples SG8 to SG102)

271 The Póvoa da Lomba Formation at São Gião was also sampled herein. At this outcrop, 47
272 samples were collected from the Toarcian–Aalenian transition; the material is from the
273 *Pleydellia aalensis* and *Leioceras opalinum* ABs (Figs. 2, 5). Overall the palynofloras from
274 these samples were relatively sparse and poorly preserved, and 26 horizons proved entirely
275 devoid of palynomorphs (Supplementary Table 2).

276 The productive samples from the Póvoa da Lomba Formation are dominated by
277 gymnospermous pollen, largely *Spheripollenites* spp. (Supplementary Fig. 2). Bisaccate
278 pollen (*Alisporites* spp.) is also present consistently, but in moderate to low proportions.
279 *Classopollis* spp. is confined to the Upper Toarcian, and *Araucariacites australis* and
280 *Callialasporites* spp. are restricted to the Lower Aalenian. *Cerebropollenites*
281 *macroverrucosus* was present in the lower part of the succession sporadically in low
282 numbers. The spore associations are also of low diversity. *Cyathidites* spp., indeterminate
283 forms, *Kraeuselisporites reissingeri* and *Leptolepidites* spp. are present throughout. The
284 proportions of these forms are generally relatively low, but indeterminate forms and
285 *Leptolepidites* spp. intermittently attained significant numbers. *Ischyosporites variegatus* is

286 confined to sample SG10t in the uppermost Toarcian *Pleydellia aalensis* AB (Supplementary
287 Fig. 2, Supplementary Table 2).

288 The marine microplankton are, like the terrestrially-derived palynomorphs, of low
289 diversity. These associations are dominated by prasinophytes, with clumps of
290 *Halosphaeropsis liassica* and large indeterminate types being especially prominent. These are
291 both present throughout, but are most prominent in the uppermost Toarcian and the *Leioceras*
292 *opalinum* AB of the lowermost Aalenian (samples SG8 to SG50b). *Tasmanites* spp. are also
293 present. The high levels of prasinophytes at São Gião may indicate a continuation of the
294 stressed environmental conditions associated with the T-OAE (section 6, Correia et al.
295 2017b). Dinoflagellate cysts and acritarchs are both somewhat sporadic in occurrence and
296 relatively rare. Of the former, *Mancodinium semitabulatum* and *Nannoceratopsis senex* are
297 present throughout the succession in very low numbers, and *Valvaeodinium* sp. cf. *V.*
298 *armatum* was observed in sample SG10t in the uppermost Toarcian (*Pleydellia aalensis* AB).
299 The acritarchs are largely referable to the genus *Micrhystridium*. Foraminiferal test linings
300 are entirely absent (Supplementary Fig. 2, Supplementary Table 2). It is possible that the
301 more proximal position of São Gião, with respect to Cabo Mondego (Fig. 1), at least in part
302 explains the relative sparsity of marine microplankton.

303

304 **5. Palynostratigraphy**

305 In this section, the dinoflagellate cyst and the pollen-spore biostratigraphy are discussed. The
306 other palynomorph groups, i.e. acritarchs, foraminiferal test linings and prasinophytes, do not
307 exhibit significant evolutionary change throughout the succession studied.

308

309 **5.1. Dinoflagellate cyst biostratigraphy**

310 In this study a formal dinoflagellate cyst biozonation is not proposed, principally because
311 much of the upper Bajocian succession was not sampled at Cabo Mondego. For example the
312 *Strenoceras niortense* and *Garantiana garantiana* ABs were not studied here (Fig. 2).

313 Furthermore, the interval studied does not overlap with the upper Pliensbachian to upper
314 Toarcian dinoflagellate cyst biozonation for the Lusitanian Basin proposed by Correia et al.
315 (2018).

316 The stratigraphical extents of selected dinoflagellate cysts at Cabo Mondego and São
317 Gião plotted against the samples were depicted in Figs. 3–5, and the entire palynofloras
318 recognised documented in Supplementary Tables 1, 2. Ranges of fifteen of the most
319 biostratigraphically significant dinoflagellate cysts are depicted in Fig. 6. The succession
320 examined is readily subdivided once. A low diversity association, typified by the genus
321 *Nannoceratopsis*, is present between the uppermost Toarcian (*Pleydellia aalensis* AB) and
322 the lowermost Bajocian (*Hyperlioceras discites* AB). Above this is a substantially more
323 diverse flora, dominated by representatives of the family Gonyaulaceae, between the lower
324 Bajocian (*Witchellia laeviuscula* AB) and the lowermost Bathonian (*Zigzagiceras zigzag*
325 AB).

326

327 **5.1.1. Uppermost Toarcian to lowermost Bajocian (*Pleydellia aalensis* to *Hyperlioceras*** 328 ***discites* ABs)**

329 The older, uppermost Toarcian to lowermost Bajocian, assemblage at Cabo Mondego and
330 São Gião only yielded 10 taxa. These are *Dissiliodinium* sp. 1, *Impletosphaeridium* sp.,
331 *Mancodinium semitabulatum*, *Mendicodinium* spp., *Nannoceratopsis gracilis*,
332 *Nannoceratopsis senex*, *Phallocysta elongata*, *Scrinocassis priscus*, *Scrinocassis weberi* and
333 *Valvaedinium* sp. cf. *V. armatum* (Supplementary Tables 1, 2).

334 This low diversity association is prior to the major, geographically extensive,
335 diversification of dinoflagellate cysts in the Bajocian documented by Wiggan et al. (2017).
336 This evolutionary radiation is largely manifested by the expansion of the family
337 Gonyaulaceae. Tabulate sexiform gonyaulacacean taxa are virtually absent from this interval
338 (Evitt 1985, Wiggan et al. 2017, table 3). In the uppermost Toarcian to lowermost Bajocian
339 of the Lusitanian Basin, these forms are entirely lacking. *Scrinocassis* is partiform, and the
340 precise antapical tabulation of *Dissiliodinium* and *Impletosphaeridium* is not known.

341 The range top of *Mancodinium semitabulatum* is in the lowermost Aalenian
342 (*Leioceras opalinum* AB) at both Cabo Mondego and São Gião (Fig. 6, Supplementary
343 Tables 1, 2). The consistent range top is in the *Stephanoceras humphriesianum* AB of
344 northwest Europe (Riding et al. 1991, Feist-Burkhardt and Wille 1992, Riding and Thomas
345 1992, Feist-Burkhardt and Götz 2016). Hence this bioevent is apparently substantially older
346 in the Lusitanian Basin than further north.

347 The range top of *Scriniocassis priscus* is within the middle Aalenian (*Brasilia*
348 *bradfordensis* AB) (Fig. 6). This is consistent with records from Germany (Prauss 1989,
349 Feist-Burkhardt and Wille 1992, Feist-Burkhardt and Pross 2010), but not the UK where this
350 datum has been placed in the lower Bajocian *Otoites sauzei* AB (e.g. Riding and Thomas
351 1992). In the Lusitanian Basin, *Nannoceratopsis senex* apparently became extinct in the
352 lowermost Bajocian (*Hyperlioceras discites* AB). This bioevent may be highly significant as
353 there are few records of this species in northwest Europe. Also in the *Hyperlioceras discites*
354 AB, the oldest representatives of *Dissiliodinium* were observed (Fig. 6). This is consistent
355 with the records of Prauss (1989) and Riding et al. (1991) from further north, although Feist-
356 Burkhardt (1990), Feist-Burkhardt and Wille (1992) and Feist-Burkhardt and Pross (2010)
357 recorded this genus from the Aalenian in Germany.

358

359 **5.1.2. Lower Bajocian (*Witchellia laeviuscula* to *Stephanoceras humphriesianum* ABs)**

360 The diversity of dinoflagellate cysts increased markedly within the *Witchellia laeviuscula*
361 AB, and the taxonomic richness rose further throughout the remainder of the lower Bajocian
362 which was studied herein, up to the *Stephanoceras humphriesianum* AB (Supplementary
363 Table 1). This diversity increase in the *Witchellia laeviuscula* AB at Cabo Mondego appears
364 to represent a significant influx, and the transition between this and the underlying
365 *Hyperlioceras discites* AB is far less incremental than in northwest Europe (Riding et al.
366 1991, Feist-Burkhardt and Monteil 1997, Wiggan et al. 2017). Range bases in the lower
367 Bajocian above the *Hyperlioceras discites* AB include those of *Acanthaulax* sp. cf. *A. crista*,
368 *Ctenidodinium sellwoodii*, *Durotrigia* spp., *Epipllosphaera gochtii*, *Meiourogonyaulax* spp.,
369 *Pareodinia* sp., *Sentusidinium* spp. and *Wanaea* sp. The range top of *Nannoceratopsis*
370 *gracilis* is in the *Stephanoceras humphriesianum* AB (Fig. 6). *Dissiliodinium giganteum*, a
371 species characteristically abundant in the lower Bajocian is entirely absent in the Lusitanian
372 Basin (section 6).

373 This assemblage is typical of the Bajocian of Europe. Gonyaulacacean forms with
374 epicystal and multiplate precingular archaeopyles are common. These genera, typified by
375 *Ctenidodinium*, *Dissiliodinium* and *Durotrigia*, appear to be part of a group which
376 experimented with their morphology, in this case the excystment aperture, during a
377 significant evolutionary radiation (Fensome et al. 1996). Wiggan et al. (2017) linked this to
378 significant and widespread increases in sea level.

379 The inception of *Ctenidodinium sellwoodii* in the *Sonninia propinquans* AB herein
380 precedes this bioevent further north in Europe. Most reports place this in the upper Bajocian
381 (e.g. Riding and Thomas 1992), but Wiggan et al. (2017) recorded this range base in the
382 *Stephanoceras humphriesianum* AB of Germany. The trend of earlier range bases in the
383 Lusitanian Basin is continued with *Meiourogonyaaulax* spp. In this study, this genus emerged
384 in the *Sonninia propinquans* AB, and in northern Europe the earliest representatives are
385 recorded in the *Stephanoceras humphriesianum* AB of France and Germany (Prauss 1989,
386 Feist-Burkhardt and Monteil 1997, Wiggan et al. 2017). *Durotrigia daveyi* has a similar range
387 base in the lower Bajocian throughout Europe. In this study, this species was recorded in the
388 *Sonninia propinquans* AB, and it occurs elsewhere in the *Hyperlioceras discites* to
389 *Stephanoceras humphriesianum* ABs (Bailey 1987, Riding et al. 1991, Butler et al. 2005,
390 Wiggan et al. 2017). The records of *Acanthaulax* sp. cf. *A. crispa*, *Korystocysta* sp. cf. *K.*
391 *aldridgei* and *Wanaea* sp. within the *Sonninia propinquans* AB in this study may represent
392 ‘precursor forms’ which appeared prior to the *sensu stricto* representatives (Wiggan et al.
393 2017). This concept was previously explored in the context of the Bajocian of Europe by
394 Feist-Burkhardt and Götz (2016).

395 The most significant range top in the lower Bajocian of the Lusitanian Basin is that of
396 *Nannoceratopsis gracilis* in the *Stephanoceras humphriesianum* AB (Fig. 6). This may be an
397 artefact due to the intra-Bajocian sampling gap here, but it is consistent with other European
398 records (Prauss 1989, Gowland and Riding 1991, Riding et al. 1991, Feist-Burkhardt and
399 Monteil 1997, Wiggan et al. 2017).

400

401 **5.1.3. Uppermost Bajocian and lowermost Bathonian (*Parkinsonia parkinsoni* and** 402 ***Zigzagiceras zigzag* ABs)**

403 The trend of increasing dinoflagellate cyst diversity, instigated in the lower Bajocian,
404 continued in the uppermost Bajocian and lowermost Bathonian at Cabo Mondego. Many
405 inceptions were observed, several of which are biostratigraphically significant. By contrast,
406 no regionally significant apparent extinctions were noted. In general terms, the diversity of
407 sexiform tabulate gonyaulacaceans increased dramatically, especially those genera with
408 single plate precingular archaeopyles such as *Gonyaulacysta* and *Rhynchodiniopsis* and
409 *Tubotuberella* (Supplementary Table 1). This tendency is entirely consistent with the

410 Bajocian–Bathonian transition elsewhere in the world (Mantle and Riding 2012, Wiggan et
411 al. 2017).

412 There are several inceptions in sample Bt94 (*Parkinsonia parkinsoni* AB); these are
413 those of *Bradleyella adela*, *Rhynchodiniopsis? regalis* and *Valensiella ovulum*. The holotype
414 of *Bradleyella adela* is from the *Parkinsonia parkinsoni* AB of southern England (Fenton et
415 al. 1980, p. 156). It is a characteristically Bajocian species with a range from the
416 *Hyperlioceras discites* to *Parkinsonia parkinsoni* ABs (Prauss 1989, Riding and Thomas
417 1992). It is never common, but is most characteristic of the upper Bajocian. Similarly, the
418 oldest range base reported for *Rhynchodiniopsis? regalis* is the *Stephanoceras*
419 *humphriesianum* AB in northwest Europe (e.g. Feist-Burkhardt and Monteil 1997), but this
420 species is most prevalent in the upper Bajocian and Bathonian (Riding et al. 1985, Prauss
421 1989). Other range bases in the *Parkinsonia parkinsoni* AB include those of
422 *Chytroisphaeridia chytrooides*, *Gonyaulacysta pectinigera*, *Korystocysta pachyderma* and
423 *Pareodinia ceratophora* (Supplementary Table 1). *Chytroisphaeridia chytrooides* was been
424 reported from the lower Bajocian *Witchellia laeviuscula* AB by Wiggan et al. (2017) but the
425 range base is most frequently observed in the upper Bajocian (e.g. Prauss 1989). Prauss
426 (1989) also noted the inception of *Korystocysta pachyderma* in the *Parkinsonia parkinsoni*
427 AB in Germany.

428 Finally in this study, more inceptions occurred in the lowermost Bathonian. These
429 include those of *Ctenidodinium cornigerum*, *Gonyaulacysta jurassica* subsp. *adecta*,
430 indeterminate complex chorate dinoflagellate cysts, *?Korystocysta gochtii*, *Mendicodinium*
431 *groenlandicum* and *Tubotuberella dangeardii*. *Ctenidodinium cornigerum* is a characteristic
432 Tethyan species, the range base of which is typical of the Bajocian–Bathonian transition (Jan
433 du Chêne et al. 1985, Feist-Burkhardt and Monteil 1997, Wiggan et al. 2017). The large
434 numbers of *Ctenidodinium combazii* observed in southern Germany during this interval by
435 Wiggan et al. (2017) are not present in the Lusitanian Basin. This phenomenon was attributed
436 to the effects of the maximum flooding of a transgression by Wiggan et al. (2017), and the
437 low numbers of *Ctenidodinium* is further evidence of the restricted nature of the Lusitanian
438 Basin (section 6). The range bases of *Gonyaulacysta jurassica* subsp. *adecta* and
439 *Tubotuberella dangeardii* are consistently recorded in the lowermost Bathonian (e.g. Fenton
440 et al. 1980, Feist-Burkhardt and Wille 1992, Wiggan et al. 2017). This study confirms that the
441 inception of complex chorate dinoflagellate cysts lies in the lowermost Bathonian (Riding et
442 al. 1985, Feist-Burkhardt and Wille 1992). The earliest records of these forms are frequently

443 difficult to adequately assign to genera or species, however this morphostratigraphical
444 bioevent clearly has significant regional significance.

445

446 **5.2. Pollen and spore biostratigraphy**

447 The pollen and spores observed in this study are typical of the Toarcian to Bathonian interval
448 in Europe (e.g. Srivastava 1987, Guy-Ohlson 1989). In terms of species turnover they are
449 substantially more conservative than the dinoflagellate cysts. Despite this, there are several
450 notable pollen and spore bioevents in the succession studied. Moreover, significant shifts in
451 abundance are observed which may have local biostratigraphical significance. For example,
452 *Exesipollenites* is common and consistent throughout the Aalenian and lower Bajocian, but
453 *Cycadopites granulatus* is more prominent at the Bajocian–Bathonian transition at Cabo
454 Mondego (Supplementary Table 1).

455 The inception and diversification of the characteristic monosaccate pollen genus
456 *Callialasporites*, and an increase in the relative proportions of the closely related
457 *Araucariacites australis*, are significant. The oldest records of *Callialasporites* are the
458 somewhat isolated and rare specimens of *Callialasporites dampieri* in the uppermost
459 Toarcian of Cabo Mondego. The genus then substantially increased in diversity and relative
460 abundance throughout the Aalenian of Cabo Mondego and São Gião (Supplementary Tables
461 1, 2). These records confirm that this araucarian genus expanded significantly close to the
462 base of the Middle Jurassic (Guy-Ohlson 1988a, Riding et al. 1991). The rise of
463 *Callialasporites*, and the relative demise of *Classopollis*, close to the Early–Middle Jurassic
464 transition is a global phenomenon (Helby et al. 1997, fig. 13), and appears to be related to the
465 marked decrease in in palaeotemperatures at this time (Korte et al. 2015, fig. 2).

466 The cavate spore *Krauselisporites reissingeri* is present at the Toarcian–Aalenian
467 transition at Cabo Mondego and São Gião (Supplementary Tables 1, 2). In northern Europe,
468 the range of this species is latest Triassic to Early Jurassic (Rhaetian–Pliensbachian)
469 according to Morbey (1978). There is an isolated occurrence of the spore *Kekryphalospora*
470 *distincta* in the uppermost Toarcian of Cabo Mondego (Supplementary Table 1). This form
471 ranges from the upper Pliensbachian to lower Bajocian in northwest Europe and the Toarcian
472 of Australia (Fenton and Riding 1987, Riding and Helby 2001 respectively). The range base
473 of *Chasmatosporites* spp. is in the lower Bajocian (*Sonninia propinquans* AB) of Cabo

474 Mondego (Supplementary Table 1). Elsewhere in Europe, this genus ranges from the
475 uppermost Triassic to the Middle Jurassic (Rhaetian–Bathonian) (Guy-Ohlson 1988b, fig. 2).

476

477 **6. Dinoflagellate cyst palaeobiology**

478 The uppermost Toarcian to lowermost Bathonian dinoflagellate cyst associations of the
479 Lusitanian Basin described herein are consistently and substantially less diverse than their
480 counterparts further east and north in Europe. For example, relatively diverse dinoflagellate
481 cyst floras are present throughout the Aalenian and Bajocian of Germany and Poland (e.g.
482 Feist-Burkhardt 1990, Prauss 1989, Feist-Burkhardt and Pross 2010, Feist-Burkhardt and
483 Götz 2017, Gedl 2008, Segit et al. 2015 and Wiggan et al. 2017). Moreover, Bathonian
484 dinoflagellate cysts from northwest Europe typically exhibit substantially higher species
485 richness than in the Lusitanian Basin (e.g. Riding et al., 1985). The causal factors for this
486 phenomenon may include: amount and availability of nutrients; latitude/temperature controls;
487 marine current regime; salinity; seawater depth; or a combination of these parameters.

488 Correia et al. (2017b) established that cyst-forming dinoflagellates were very slow to
489 recover from the severe environmental pressures (principally anoxia, high temperatures and
490 lowered salinities) caused by the Toarcian Oceanic Anoxic Event (T-OAE). It seems
491 probable that the enclosed setting of the Lusitanian Basin intensified and prolonged the
492 anoxia which developed in the water column at this time. This protracted recovery may have
493 suppressed the diversity of dinoflagellate cyst associations throughout the Toarcian and well
494 into the Aalenian. Moreover the lack of Arctic/Boreal forms, such as the diverse genera and
495 species of the *Parvocysta* suite of Riding (1984), appears also to have contributed to the
496 relatively low diversity of dinoflagellate cysts around the Toarcian–Aalenian transition in
497 Portugal. The upper Toarcian to lower Aalenian successions of northern England, Scotland
498 and the Arctic (Riding 1984, Riding et al. 1991, Riding et al. 1999) are significantly more
499 diverse than this interval in Portugal, largely due to the presence of the *Parvocysta* suite. The
500 dinoflagellate cysts from the Toarcian–Aalenian transition in southwest France are also more
501 diverse than in the Lusitanian Basin (de Vains 1988, Bucefalo Palliani and Riding 1997).
502 Notwithstanding the lack of the *Parvocysta* suite, the Lusitanian Basin floras also lack other
503 typically European Toarcian–Aalenian dinoflagellate cysts such as *Mendicodinium spinosum*,
504 *Nannoceratopsis dictyambonis*, *Nannoceratopsis plegas*, *Nannoceratopsis spiculata*,
505 *Nannoceratopsis tricerias*, *Pareodinia halosa* and *Sentusidinium* spp.

506 It is possible that the slow recovery of cyst-forming dinoflagellates following the
507 early Toarcian T-OAE suppressed diversity until the earliest Aalenian. Subsequently, it is
508 possible that the marked early Aalenian cooling (Korte et al. 2015) continued to suppress
509 these planktonic biotas. The latter phenomenon, however, is inconsistent with the expansion
510 of diverse coldwater forms from the Boreal Realm, as envisaged for the Callovian–Oxfordian
511 transition by Riding and Michoux (2013). The latter authors envisaged the Arctic region as a
512 plankton diversity hotspot during the Jurassic. Moreover it is conceivable that, by the time the
513 *Parvocysta* suite had become extinct in the earliest Aalenian, the Arctic floras could not have
514 contributed many species to colonise further south.

515 Dinoflagellate cyst diversity continued to be relatively low in the Lusitanian Basin
516 throughout the Aalenian and Bajocian, and into the earliest Bathonian (Supplementary Table
517 1). The assemblages increased in species richness, but the major diversification of the family
518 Gonyaulaceae, which is present throughout northwest Europe (Wiggan et al. 2017) is not
519 manifested. Borges et al. (2011) and Borges et al. (2012) explained the relatively low Middle
520 and Upper Jurassic dinoflagellate cyst assemblages in the Algarve Basin of Portugal by the
521 fact that this depocentre was a relatively deep water and partially enclosed (restricted) setting.
522 The Lusitanian Basin is very close to the relatively deep waters of the Proto Atlantic (Fig. 7).
523 This relatively isolated position, well away from the widespread shelf settings of the
524 northwest Tethys, prevented extensive mutual biotic exchange with southeast Europe and
525 surrounding areas. Further evidence of the restricted nature of the Lusitanian Basin is that
526 *Valensiella* is common and *Ctenidodinium* is relatively rare in the lowermost Bathonian
527 (Supplementary Table 1). The former genus is cosmopolitan and hence may represent a
528 eurytopic taxon, whereas *Ctenidodinium* is abundant during maximum transgressions in open
529 basins (Wiggan et al. 2017).

530 The large and distinctive dinoflagellate cyst species *Dissiliodinium giganteum* was not
531 recorded herein. This taxon is extremely prominent in the lower Bajocian (*Witchellia*
532 *laeviuscula* and *Sonninia propinquans* ABs) of Germany and eastern Europe (Gedl 2008,
533 Gedl and Józsa 2015, Wiggan et al. 2017). This species apparently thrived in regions with
534 high terrestrial runoff input, elevated nutrient levels and perhaps reduced salinities (Wiggan
535 et al. 2017). By contrast, *Dissiliodinium giganteum* is rare in the lower Bajocian carbonate
536 facies of southern England and northern France (Feist-Burkhardt and Monteil 1997,
537 unpublished data). Thus the absence of *Dissiliodinium giganteum* in the Lusitanian Basin is

538 consistent with the deepwater environment, relatively far from sources of terrigenous input,
539 of this region.

540

541 7. Conclusions

542 The Lusitanian Basin of central western Portugal exposes an extremely important southern
543 European Middle Jurassic reference section. This includes the GSSP and the ASSP for the
544 Bajocian and Bathonian stages respectively within the type Cabo Mondego Formation. The
545 palynology of the uppermost Toarcian to the lowermost Bathonian of Cabo Mondego and
546 São Gião was studied herein. The composite Aalenian and Bajocian, and their lower and
547 upper transitions, studied here from outcrops at Cabo Mondego and São Gião yielded 89
548 palynologically productive samples, all of which are correlated to the *Pleydellia aalensis* to
549 *Zigzagiceras zigzag* ABs. The upper Bajocian *Strenoceras niortense* and *Garantiana*
550 *garantiana* ABs were not studied.

551 The Cabo Mondego Formation generally produced abundant, well-preserved
552 assemblages, but the Póvoa da Lomba Formation at São Gião yielded sparse assemblages
553 with low levels of species richness (?distality). A low diversity assemblage of dinoflagellate
554 cysts, typified by the genus *Nannoceratopsis*, was recovered from the uppermost Toarcian to
555 lowermost Bajocian (*Pleydellia aalensis* to *Hyperlioceras discites* ABs) interval. In the
556 overlying succession, between the lower Bajocian and the lowermost Bathonian (*Witchellia*
557 *laeviuscula*–*Zigzagiceras zigzag* ABs), a substantially more diverse biota, dominated by
558 gonyaulacacean taxa was encountered. The principal influx of species is within the *Witchellia*
559 *laeviuscula* AB, and is the manifestation of an evolutionary burst which may have been
560 caused by increases in sea level. Gonyaulacacean forms with epicystal and multiplate
561 precingular archaeopyles are prominent in the lower Bajocian; this phenomenon is an
562 example of morphological experimentation during an evolutionary radiation. Dinoflagellate
563 cyst diversity continued to increase at the Bajocian–Bathonian transition, and this was chiefly
564 driven by the increase in sexiform tabulate gonyaulacaceans with single plate precingular
565 archaeopyles.

566 The dinoflagellate cysts exhibit significant species turnover, and several bioevents
567 have local and regional significance. For example, the lower Bajocian range top of
568 *Nannoceratopsis gracilis* in the *Stephanoceras humphriesianum* AB is consistent with other
569 European records (e.g. Prauss 1989). Furthermore, the range bases of complex chorate

570 dinoflagellate cysts, *Gonyaulacysta jurassica* subsp. *adecta* and *Tubotuberella dangeardii*
571 were recorded in the earliest Bathonian at Cabo Mondego. These datums are reliable
572 biomarkers for the earliest Bathonian throughout Europe. (e.g. Wiggan et al. 2017). The
573 pollen and spores recorded herein are characteristic of Middle Jurassic associations in both
574 hemispheres. It is noticeable that araucarian pollen, such as *Araucariacites* and
575 *Callialasporites*, diversified and became prominent during the Aalenian.

576 The Middle Jurassic dinoflagellate cyst floras of the Lusitanian Basin are markedly
577 less diverse than their counterparts further north and east in the northern hemisphere. The
578 Toarcian Oceanic Anoxic Event (T-OAE) at ~183 Ma was a relatively short-lived
579 environmental perturbation (e.g. Xu et al. 2017). This global event suppressed dinoflagellate
580 cysts in the Lusitanian Basin, and the recovery from it was extremely protracted. Hence the
581 T-OAE may have inhibited early Middle Jurassic dinoflagellate cyst diversity in the
582 Lusitanian Basin. This downward pressure on diversity may have been intensified by the
583 absence of characteristic Boreal dinoflagellate cysts. Moreover, it is also possible that global
584 cooling during the early Aalenian further affected species richness at this time (Korte et al.
585 2015). These low dinoflagellate cyst diversities in Portugal may also be as a result of the
586 palaeogeography of the Lusitanian Basin. This was a relatively isolated, deepwater setting
587 close to the Proto Atlantic, and this may have prevented large-scale biotic exchange with the
588 widespread shelfal areas of the western Tethys to the east and northeast. The distinctive, large
589 dinoflagellate cyst *Dissiliodinium giganteum* was not recovered from the Lusitanian Basin.
590 This species is very abundant in the lower Bajocian of Europe (Wiggan et al. 2017), and
591 appears to be characteristic of regions with high levels of terrestrial runoff and nutrients.
592 Thus its absence in the deepwater environment of the Lusitanian Basin, relatively distant
593 from sources of terrigenous input, is unsurprising.

594

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912

913 **Display material captions:**

914

915 **Fig. 1.** The Lower, Middle and Upper Jurassic outcrops in the Lusitanian Basin of western
916 Portugal, the major faults in this depocentre and the locations of the two sections studied
917 herein. The Cabo Mondego succession is northwest of Figueira da Foz city at 40° 12' 1.26"
918 N; 8° 54' 10.4" W. The latter coordinate represents the base of the section at Murtinheira
919 beach; the Bathonian Auxiliary Stratigraphical Section and Point (ASSP) is at 40° 11' 17.11"
920 N; 8° 54' 32.17" W. The section at São Gião, south of Catanhede village, is at 40° 18' 12.63"
921 N; 8° 37' 17.58" W. This figure is adapted from Figueiredo (2009) and Kullberg et al. (2013).

922

923 **Fig. 2.** The ammonite biostratigraphy and the lithostratigraphy of the uppermost Toarcian to
924 lowermost Bathonian successions at Cabo Mondego and São Gião in the northern Lusitanian
925 Basin, western Portugal based on Azerêdo et al. (2003). The grey shading indicates the parts
926 of the Cabo Mondego and Póvoa da Lomba formations which were studied herein.

927

928 **Fig. 3.** The lithological log of the lower part of Cabo Mondego Formation, spanning the
929 uppermost Toarcian to lower Bajocian succession at Cabo Mondego, adapted from
930 Fernández-López et al. (1988), and Canales and Henriques (2008, 2013). This succession
931 includes the Global Stratotype Section and Point (GSSP) for the Bajocian Stage at
932 Murtinheira Beach. The positions of the palynologically productive samples M2 through
933 M398 and AB55 to AB192 are indicated. Semi-quantitative data for 26 selected
934 dinoflagellate cysts are depicted.

935

936 **Fig. 4.** The lithological log of the upper part of Cabo Mondego Formation, spanning the
937 uppermost Bajocian to lowermost Bathonian succession at Cabo Mondego, adapted from
938 Fernández-López et al. (2006). This succession includes the Bathonian ASSP. The positions
939 of the palynologically productive samples Bt94 through Bt220 are indicated, and semi-
940 quantitative data for 31 selected dinoflagellate cysts are depicted.

941

942 **Fig. 5.** The lithological log of the Póvoa da Lomba Formation (uppermost Toarcian to
943 lowermost Aalenian) at São Gião, adapted from Canales-Fernández et al. (2014), with the
944 positions of the palynologically productive samples SG8 to SG102 indicated. Semi-
945 quantitative data for three dinoflagellate cysts are illustrated.

946

947 **Fig. 6.** The ranges of 15 stratigraphically significant dinoflagellate cysts and selected
948 bioevents plotted against the ammonite biozones from the uppermost Toarcian to lowermost
949 Bathonian of Cabo Mondego, Lusitanian Basin, Portugal. The key dinoflagellate cyst
950 bioevents herein are compared with bioevent successions and zonal schemes from Denmark,
951 Germany and the UK (Riding and Thomas 1992, Poulsen and Riding 2003 and Wiggan et al.
952 2017).

953

954 **Fig. 7.** The Middle Jurassic palaeogeography of the western Tethys region and the proto-
955 Atlantic Ocean, modified from Gómez and Fernández-López (2006) and Korte et al. (2015).

956

957 **Plate I.** Selected dinoflagellate cysts from the Lower and Middle Jurassic (Toarcian to
958 Bajocian) of the Lusitanian Basin, in west central Portugal. All specimens are housed in the
959 collections of LNEG (Portuguese Geological Survey), S. Mamede de Infesta, Portugal. The
960 sample number, slide number and England Finder coordinates are provided. All the scale bars
961 represent 20 μm . All photomicrographs were taken using plain transmitted light unless
962 otherwise stated. The references in the author citations are not listed in the bibliography
963 herein, but may be found in Williams et al. (2017).

- 964 1. *Mancodinium semitabulatum* Morgenroth 1970. Cabo Mondego, upper Toarcian
965 (*Pleydellia aalensis* AB), sample M28, slide 1, F35.
- 966 2. *Nannoceratopsis senex* van Helden 1977. São Gião, upper Toarcian (*Pleydellia*
967 *aalensis* AB), sample SG22m, slide 1, W38/4. Note that the taxonomic
968 recommendations of Correia et al. (2017a, appendix 2) regarding this species are
969 followed herein.
- 970 3. *Nannoceratopsis gracilis* Alberti 1961. Cabo Mondego, lower Bajocian (*Witchellia*
971 *laeviuscula*–*Sonninia propinquans* ABs) sample AB116, slide 1, H40.
- 972 4. *Scriniocassis priscus* (Gocht 1979) Below 1990. Cabo Mondego, middle Aalenian
973 (*Brasilia bradfordensis* AB), sample M150, slide 1, W28.
- 974 5. *Dissiliodinium* sp. 1. Cabo Mondego, lower Bajocian (*Stephanoceras*
975 *humphriesianum* AB), sample AB192, slide 1, R42. Note the psilate autophragm.
- 976 6. *Dissiliodinium* sp. 2. Cabo Mondego, lower Bajocian (*Stephanoceras*
977 *humphriesianum* AB), sample AB192, slide 1, W29. Note the granulate autophragm.
- 978 7. *Sentusidinium* sp. cf. *S. explanatum* (Bujak in Bujak et al. 1980) Wood et al. 2016.
979 Cabo Mondego, lower Bajocian (*Witchellia laeviuscula*–*Sonninia propinquans* ABs),
980 sample AB108, slide 1, J32. Note the psilate autophragm.
- 981 8. *Sentusidinium* sp. 1. Cabo Mondego, lower Bajocian (*Witchellia laeviuscula*–
982 *Sonninia propinquans* ABs) sample AB116, slide 1, W51/2. Note the scabrate to
983 granulate autophragm.
- 984 9. *Sentusidinium* sp. 2. Cabo Mondego, upper Bajocian (*Parkinsonia parkinsoni* AB),
985 sample Bt106, slide 1, W28. Note the scabrate autophragm with dense short spines.
- 986 10. *Kallosphaeridium?* sp. Cabo Mondego, lower Bajocian (*Sonninia propinquans*–
987 *Stephanoceras humphriesianum* ABs), sample AB178a, slide 1, N25. The arrow
988 points to what appears to be the attached apical operculum.

- 989 11. *Korystocysta* sp. cf. *K. aldridgeii* Wiggan et al. 2017. Cabo Mondego, lower Bajocian
 990 (*Sonninia propinquans*–*Stephanoceras humphriesianum* ABs), sample AB178a, slide
 991 1, J37/4. This specimen is slightly smaller (width: 78 µm; length: 65 µm) compared
 992 with those of Wiggan et al. (2017). Photomicrograph taken using differential
 993 interference contrast.
- 994 12. *Rhynchodiniopsis* sp. Cabo Mondego, lower Bajocian (*Sonninia propinquans*–
 995 *Stephanoceras humphriesianum* ABs), sample AB178a, slide 2, L37/1.
 996 Photomicrograph taken using differential interference contrast.

997

998 **Plate II.** Selected dinoflagellate cysts from Middle Jurassic (Bajocian and Bathonian) of the
 999 Lusitanian Basin, in west central Portugal. All specimens are housed in the collections of
 1000 LNEG (Portuguese Geological Survey), S. Mamede de Infesta, Portugal. The sample number,
 1001 slide number and England Finder coordinates are provided. All the scale bars represent 20
 1002 µm. The references in the author citations are not listed in the bibliography herein, but may
 1003 be found in Williams et al. (2017).

- 1004 1. *Durotrigia daveyi* Bailey 1987. Cabo Mondego, lower Bajocian (*Sonninia*
 1005 *propinquans* AB), sample AB138, slide 2, S47/3.
- 1006 2. *Meiourogonyaaulax* sp. Cabo Mondego, upper Bajocian (*Parkinsonia parkinsoni* AB),
 1007 sample Bt110, slide 1, N24/1.
- 1008 3. *Pareodinia ceratophora* Deflandre 1947. Cabo Mondego, upper Bajocian
 1009 (*Parkinsonia parkinsoni* AB), sample Bt106, slide 1, R31.
- 1010 4. *Epiplosphaera gochtii* (Fensome 1979) Brenner 1988. Cabo Mondego, lower
 1011 Bajocian (*Witchellia laeviuscula*–*Sonninia propinquans* ABs), sample AB108, slide
 1012 1, J45/4. Note the short, capitate processes and the cingulum.
- 1013 5. *Ellipsoidictyum* sp. Cabo Mondego, lower Bathonian (*Zigzagiceras zigzag* AB),
 1014 sample Bt200, slide 1, P44. Note the strongly reticulate ornamentation and the
 1015 cingulum.
- 1016 6. *Valensiella ovulum* (Deflandre 1947) Eisenack 1963. Cabo Mondego, lower
 1017 Bathonian (*Zigzagiceras zigzag* AB), sample Bt134, slide 1, H33.
- 1018 7. *Ctenidodinium sellwoodii* (Sarjeant 1975) Stover & Evitt 1978. Cabo Mondego, upper
 1019 Bajocian (*Parkinsonia parkinsoni* AB), sample Bt106, slide 1, R25/1.

- 1020 8. *Ctenidodinium cornigerum* Valensi 1953. Cabo Mondego, lower Bathonian
 1021 (*Zigzagiceras zigzag* AB), sample Bt220, slide 1, H24.
 1022 9. *Gonyaulacysta pectinigera* (Gocht 1970) Fensome 1979. Cabo Mondego, lower
 1023 Bathonian (*Zigzagiceras zigzag* AB), sample Bt200, slide 1, J25/3.
 1024 10. *Chytroeisphaeridia chytroeides* (Sarjeant 1962) Downie & Sarjeant 1965. Cabo
 1025 Mondego section, lower Bathonian (*Zigzagiceras zigzag* AB), sample Bt164, slide 1,
 1026 N35. Note the precingular (1P) archaeopyle.
 1027 11. *Tubotuberella dangeardii* (Sarjeant 1968) Stover & Evitt 1978. Cabo Mondego, lower
 1028 Bathonian (*Zigzagiceras zigzag* AB), sample Bt126, slide 1, O25/1.
 1029 12. *Mendicodinium* sp. Cabo Mondego, upper Bajocian (*Parkinsonia parkinsoni* AB),
 1030 sample Bt106, slide 1, V29/1. Note the autophragm with short spines and baculae.

1031

1032 **Plate III.** Selected indigenous marine and terrestrially-derived palynomorphs from the Lower
 1033 and Middle Jurassic (Toarcian to Bathonian) of the Lusitanian Basin, in west-central
 1034 Portugal. All specimens are housed in the collections of LNEG (Portuguese Geological
 1035 Survey), S. Mamede de Infesta, Portugal. The sample number, slide number and England
 1036 Finder coordinates are provided. All the scale bars represent 20 μm .

- 1037 1. *Micrhystridium* sp. 1 (acanthomorph acritarch). São Gião, upper Toarcian (*Pleydellia*
 1038 *aalensis* AB), sample SG8, slide 1, G40. Note the long and slender spines and the
 1039 unusual equatorial pylome.
 1040 2. *Cymatiosphaera* sp. cf. *C. pachythea* Eisenack 1957 (prasinophyte). Cabo Mondego,
 1041 lower Aalenian (*Leioceras opalinum* AB), sample M38, slide 1, O27/3.
 1042 3. *Tasmanites* sp. (prasinophyte). São Gião, lower Aalenian (*Leioceras opalinum* AB),
 1043 sample SG94, slide 1, M40.
 1044 4. *Ischyosporites variegatus* (Couper 1958) Schulz 1967 (spore). Cabo Mondego, lower
 1045 Bathonian (*Zigzagiceras zigzag* AB), sample Bt184, slide 1, H49.
 1046 5. *Striatella seebergensis* Mädler 1964 (spore). Cabo Mondego, middle Aalenian
 1047 (*Brasilia bradfordensis* AB), sample M237, slide 1, U26.
 1048 6. *Auritulasporites triclavus* Nilsson 1958 (spore). Cabo Mondego, upper Aalenian
 1049 (*Graphoceras concavum* AB), sample M319, slide 1, L33/2.

- 1050 7. *Callialasporites dampieri* (Balme 1957) Dev 1961 (pollen). Cabo Mondego, lower
1051 Bathonian (*Zigzagiceras zigzag* AB), sample Bt184, slide 1, U55/2.
- 1052 8. *Callialasporites turbatus* (Balme 1957) Schulz 1967 (pollen). Cabo Mondego, lower
1053 Bajocian (*Hyperlioceras discites* AB) sample M341, slide 1, N23/2.
- 1054 9. *Callialasporites segmentatus* (Balme 1957) Srivastava 1963 (pollen). Cabo Mondego,
1055 lower Bathonian (*Zigzagiceras zigzag* AB), sample Bt184, slide 1, H29/2.
- 1056 10. *Araucariacites australis* Cookson 1947 ex Couper 1958 (pollen). Cabo Mondego,
1057 lower Bajocian (*Sonninia propinquans* AB), sample AB178a, slide 1, Q23/2.
- 1058 11. *Perinopollenites elatoides* Couper 1958 (pollen). Cabo Mondego, lower Aalenian
1059 (*Leioceras opalinum* AB), sample M121, slide 1, V32/3.
- 1060 12. *Cycadopites granulatus* (de Jersey 1962) de Jersey 1964 (pollen). Cabo Mondego,
1061 lower Bathonian (*Zigzagiceras zigzag* AB), sample Bt126, slide 1, Q23/4.

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ONLINE SUPPLEMENTARY MATERIAL

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1066 **Supplementary Figure 1.** The left hand panel illustrates the relative abundances, expressed
1067 in percentages, of the six main palynomorph groups recorded from the uppermost Toarcian to
1068 lowermost Bathonian of the Cabo Mondego Formation at the type section at Cabo Mondego.
1069 The right hand panel depicts the percentages of indigenous marine and terrestrially-derived
1070 palynomorphs.

1071

1072 Edits to the figure needed:

1073

1074 **Supplementary Figure 2.** The left hand panel illustrates the relative abundances, expressed
1075 in percentages, of the six main palynomorph groups recorded from the uppermost Toarcian to
1076 lowermost Aalenian of the Póvoa da Lomba Formation at São Gião. The right hand panel
1077 depicts the percentages of indigenous marine and terrestrially-derived palynomorphs.

1078

1079 **Supplementary Table 1.** The palynomorph assemblages from the Cabo Mondego Formation
1080 at the type section at Cabo Mondego subdivided into six groups. The numbers in the cells
1081 represent percentages of the specified taxon within the overall palynoflora; blank spaces
1082 indicate the absence of the respective form and the grey shading corresponds to barren
1083 samples.

1084

1085 **Supplementary Table 2.** The palynomorph assemblages from the São Gião succession
1086 subdivided into six groups. The numbers in the cells represent percentages of the specified
1087 taxon within the overall palynoflora; blank spaces indicate the absence of the respective form
1088 and the grey shading corresponds to barren samples.

1089

1090 **Supplementary Appendix**

1091 This is a listing of all palynomorphs at and below the species level which were recovered
1092 from the material studied herein, or mentioned in the text **and figures**, with full author
1093 citations. The taxa are listed alphabetically in four groups. All **nine** dinoflagellate cyst taxa
1094 mentioned herein, but not found in the material from the Lusitanian Basin are asterisked.
1095 References to the dinoflagellate cyst author citations can be found in Williams et al. (2017).
1096 The recommendations of Correia et al. (2017, appendix 2) regarding the taxonomy of
1097 *Nannoceratopsis senex* are followed herein.

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1099 **Dinoflagellate cysts:**

1100 *Acanthaulax crispa* (Wetzel 1967) Woollam & Riding 1983

1101 *Bradleyella adela* (Fenton et al. 1980) Woollam 1983

1102 *Chytroisphaeridia chytrooides* (Sarjeant 1962) Downie & Sarjeant 1965

1103 **Ctenidodinium combazii* Dupin 1968

1104 *Ctenidodinium cornigerum* (Valensi 1953) Jan du Chêne 1985

1105 *Ctenidodinium sellwoodii* (Sarjeant 1975) Stover & Evitt 1978

1106 **Dissiliodinium giganteum* Feist-Burkhardt 1990

1107 *Durotrigia daveyi* Bailey 1987

1108 *Epiplosphaera gochtii* (Fensome 1979) Brenner 1988

- 1109 *Gonyaulacysta jurassica* (Deflandre 1938) Norris & Sarjeant 1965 subsp. *adecta* Sarjeant
 1110 1982
- 1111 *Gonyaulacysta pectinigera* (Gocht 1970) Fensome 1979
- 1112 *Korystocysta aldridgeii* Wiggan et al. 2017
- 1113 *Korystocysta gochtii* (Sarjeant 1976) Woollam 1983
- 1114 *Korystocysta pachyderma* (Deflandre 1938) Woollam 1983
- 1115 *Mancodinium semitabulatum* Morgenroth 1970
- 1116 *Mendicodinium groenlandicum* (Pocock & Sarjeant 1972) Davey 1979
- 1117 **Mendicodinium spinosum* Bucefalo Palliani et al. 1997
- 1118 **Nannoceratopsis dictyambonis* Riding 1984
- 1119 *Nannoceratopsis gracilis* Alberti 1961
- 1120 **Nannoceratopsis plegas* Drugg 1978
- 1121 *Nannoceratopsis senex* van Helden 1977
- 1122 **Nannoceratopsis spiculata* Stover 1966
- 1123 **Nannoceratopsis triceras* Drugg 1978
- 1124 *Pareodinia ceratophora* Deflandre 1947
- 1125 **Pareodinia halosa* (Filatoff 1975) Prauss 1989
- 1126 *Parvocysta nasuta* Bjaerke 1980
- 1127 *Phallocysta elongata* (Beju 1971) Riding 1994
- 1128 *Rhynchodiniopsis ?regalis* (Gocht 1970) Jan du Chêne 1985
- 1129 *Scriniocassis priscus* (Gocht 1979) Below 1990
- 1130 *Scriniocassis weberi* Gocht 1964
- 1131 *Sentusidinium asymmetrum* (Fenton et al. 1980) Lentin & Williams 1981
- 1132 *Tubotuberella dangeardii* (Sarjeant 1968) Stover & Evitt 1978
- 1133 *Valensiella ovulum* (Deflandre 1947) Eisenack 1963
- 1134 *Valvaeodinium armatum* Morgenroth 1970
- 1135
- 1136 **Pollen:**
- 1137 *Araucariacites australis* Cookson 1947 ex Couper 1958
- 1138 *Callialasporites dampieri* (Balme 1957) Dev 1961
- 1139 *Callialasporites microvelatus* Schulz 1967
- 1140 *Callialasporites minus* (Tralau 1968) Guy 1971
- 1141 *Callialasporites segmentatus* (Balme 1957) Srivastava 1963
- 1142 *Callialasporites trilobatus* (Balme 1957) Dev 1961

- 1143 *Callialasporites turbatus* (Balme 1957) Dev 1961
- 1144 *Cerebropollenites macroverrucosus* (Thiergart 1949) Schulz 1967
- 1145 *Cycadopites granulatus* (de Jersey 1962) de Jersey 1964
- 1146 *Perinopollenites elatoides* Couper 1958
- 1147
- 1148 **Prasinophytes:**
- 1149 *Cymatiosphaera pachythea* Eisenack 1957
- 1150 *Halosphaeropsis liassica* Mädlar 1968
- 1151
- 1152 **Spores:**
- 1153 *Auritulasporites triclavus* Nilsson 1958
- 1154 *Calamospora tener* (Leschik 1955) Mädlar 1964
- 1155 *Concavisporites granulatus* Tralau 1968
- 1156 *Ischyosporites variegatus* (Couper 1958) Schulz 1967
- 1157 *Kekryphalospora distincta* Fenton & Riding 1987
- 1158 *Kraeuselisporites reissingeri* (Harris 1957) Morbey 1975
- 1159 *Lycopodiacidites rugulatus* (Couper 1958) Schulz 1967
- 1160 *Osmundacidites wellmanii* Couper 1953
- 1161 *Retitriteles austroclavatidites* (Cookson 1953) Doring et al. in Krutzsch 1963
- 1162 *Striatella seebergensis* Madler 1964

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