The Middle Jurassic palynostratigraphy of the northern Lusitanian Basin, Portugal

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With 10 figures

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Abstract. A composite largely Middle Jurassic succession spanning the Toarcian–Aalenian transition to the lowermost Bathonian exposed at Cabo Mondego and São Gião in the northern Lusitanian Basin, western Portugal, was examined palynologically. The 129 samples are correlated to ammonite biozones (ABs) spanning *Pleydellia aalensis* to *Zigzagiceras zigzag*. The Cabo Mondego succession comprises the type section of the Cabo Mondego Formation and spans virtually the entire interval studied. This is a significant interval because it includes the Global Stratotype Section and Point (GSSP) and the Auxiliary Stratigraphical Section and Point (ASSP) for the Bajocian and Bathonian stages respectively. The Cabo Mondego Formation largely yielded relatively abundant palynomorph associations in the 68 productive samples recovered. By contrast, the Póvoa da Lomba Formation at São Gião only includes the Toarcian–Aalenian transition; the 21 productive horizons produced sparse assemblages. The uppermost Toarcian to lowermost Bajocian is characterised by a low diversity dinoflagellate cyst association, typified by *Nannoceratopsis*. Above this is a markedly more diverse assemblage, dominated by the family Gonyaulaceae. This influx, in the *Witchellia laeviuscula* AB, represents a global evolutionary radiation which may be linked to sea level rise. The lower Bajocian yielded significant proportions of gonyaulacacean forms with epicystal and multiplate precingular archaeopyles, representing morphological experimentation as part of this radiation. The trend of increasing dinoflagellate cyst diversity continued at the Bajocian–Bathonian transition, particularly sexiform tabulate gonyaulacaceans with single plate precingular archaeopyles. The Middle Jurassic dinoflagellate cyst associations of the Lusitanian Basin are significantly less diverse than coeval palynobiotas from eastern and northern Europe, and the Arctic. The Toarcian Oceanic Anoxic Event (T-OAE) profoundly inhibited cyst-forming dinoflagellates in this depocentre, and the recovery was protracted. Hence the T-OAE may have suppressed dinoflagellate cyst diversity well into the Middle Jurassic. This phenomenon may have been exacerbated by the absence of typically Arctic taxa through latitudinal controls and/or global cooling during the early Aalenian. These low levels of dinoflagellate cyst species richness may also be related to the palaeogeography of the Lusitanian Basin. This relatively isolated deepwater depocentre close to the Proto Atlantic, may have precluded extensive biotal exchange with the widespread shelfal areas of the western Tethys. The absence of *Dissiliodinium giganteum* in the Lusitanian Basin is consistent with this scenario. The pollen and spores observed in this study are typical of Middle Jurassic assemblages worldwide. Araucarian pollen, largely *Callialasporites*, diversified and became prominent during the Aalenian.

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

1. Introduction

This study documents the marine and terrestrial palynology of the uppermost Lower and Middle Jurassic (uppermost Toarcian to lowermost Bathonian) strata at Cabo Mondego and São Gião near Figueira da Foz in the northern part of the Lusitanian Basin, central western Portugal (Figs. 1, 2). The principal aim of this work is to investigate the biostratigraphy of these palynofloras, especially the dinoflagellate cysts, and to compare them with coeval biotas largely from Europe. The Cabo Mondego section at Murtinheira Beach was ratified as the Global Stratotype Section and Point (GSSP) for the Bajocian Stage in 1996 (Henriques et al., 1994; Pavia and Enay 1997). This succession also includes the Auxiliary Stratigraphical Section and Point (ASSP) for the Bathonian Stage (Fernández-López et al., 2009a, b).

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

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

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

2. Geographical and geological setting

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

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

3. Material and methods

The Cabo Mondego and São Gião sections are located in the northern Lusitanian Basin. Cabo Mondego is ~7 km northwest of Figueira da Foz and ~40 km west of Coimbra, and São Gião is situated about 5 km southwest of Cantanhede village (Fig. 1). Herein, 129 samples were collected from these two important reference sections which span the upper Toarcian *Pleydellia aalensis* AB to the lower Bathonian *Zigzagiceras zigzag* AB (Figs. 2–5). The Cabo Mondego succession comprises the type section of the Cabo Mondego Formation, and spans virtually the entire interval studied except the upper Bajocian *Strenoceras niortense* and *Garantiana garantiana* ABs, which were not sampled (Figs. 3, 4). At São Gião, the Toarcian–Aalenian transition within the Póvoa da Lomba Formation was collected (Fig. 5).

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

4. Palynology

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

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

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

This succession is dominated by foraminiferal test linings and gymnosperm pollen, with subordinate proportions of acritarchs, dinoflagellate cysts, prasinophytes and spores. Overall, pollen is the principal palynomorph type from the uppermost Toarcian to close to the top of the middle Aalenian (samples M2 to M237), with foraminiferal test linings and pollen exhibiting subequal proportions in the uppermost middle Aalenian to much of the lower Bajocian (samples M245 to AB178a) (Supplementary Fig. 1).

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

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

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

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

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

This upper part of the Cabo Mondego succession is overwhelmingly dominated by gymnospermous pollen, with relatively abundant dinoflagellate cysts. The proportions of acritarchs, foraminiferal test linings, prasinophytes and spores are markedly subordinate. The most profound difference with the underlying succession at this locality is the significant diminution of foraminiferal test linings and prasinophytes, with the former group being most profoundly affected (Supplementary Fig. 1). An association between foraminiferal test linings and prasinophytes has not been previously noted. The foraminiferal test linings from the Toarcian to Lower Bajocian in this study are most likely to be benthic taxa. It is possible that the early planktonic foraminifera, which may not have produced these test linings, somehow suppressed their benthic counterparts (Hart et al. 2003).

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

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

The dinoflagellate associations in the *Parkinsonia parkinsoni* and *Zigzagiceras zigzag* ABs are highly variable in relative proportions, and exhibit several marked abundance peaks (Supplementary Fig. 1). These associations are substantially higher in diversity than their counterparts in the underlying succession (Supplementary Table 1); a total of 32 forms were recognised. *Chytroeisphaeridia chytroeides, Ctenidodinium sellwoodii, Dissiliodinium* spp., indeterminate forms, *Sentusidinium* spp. and *Valensiella ovulum* are present consistently and in significant numbers. The other taxa however, are present either sporadically, or have restricted ranges within this succession. For example *Gonyaulacysta pectinigera*, *Korystocysta pachyderma*, *Mendicodinium* spp., *Pareodinia ceratophora* are present intermittently, and *Bradleyella adela* and *Rhynchodiniopsis*? *regalis* are confined to sample Bt94 (*Parkinsonia parkinsoni* AB). *Meiourogonyaulax* spp. are confined to the *Parkinsonia* *parkinsoni* AB, and several taxa are confined to the overlying *Zigzagiceras zigzag* AB. The latter include *Ctenidodinium cornigerum*, *Gonyaulacysta jurassica* subsp. *adecta*, indeterminate complex chorate dinoflagellate cysts, ?*Korystocysta gochtii*, *Mendicodinium groenlandicum* and *Tubotuberella dangeardii* (Supplementary Table 1). The assemblage is overwhelmingly dominated by the gonyaulacacean lineage, and genera with epicystal archaeopyles such as *Ctenidodinium, Korystocysta* and *Mendicodinium* are prominent. However, many forms recognised in this interval are present in a single sample, or low numbers of horizons and are relatively rare. Furthermore, many of them are difficult to assign to existing species (Supplementary Table 1).

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

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

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

The productive samples from the Póvoa da Lomba Formation are dominated by gymnospermous pollen, largely *Spheripollenites* spp. (Supplementary Fig. 2). Bisaccate pollen (*Alisporites* spp.) is also present consistently, but in moderate to low proportions. *Classopollis* spp. is confined to the Upper Toarcian, and *Araucariacites australis* and *Callialasporites* spp. are restricted to the Lower Aalenian. *Cerebropollenites macroverrucosus* was present in the lower part of the succession sporadically in low numbers. The spore associations are also of low diversity. *Cyathidites* spp., indeterminate forms, *Kraeuselisporites reissingeri* and *Leptolepidites* spp. are present throughout. The proportions of these forms are generally relatively low, but indeterminate forms and *Leptolepidites* spp. intermittently attained significant numbers. *Ischyosporites variegatus* is confined to sample SG10t in the uppermost Toarcian *Pleydellia aalensis* AB (Supplementary Fig. 2, Supplementary Table 2).

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

5. Palynostratigraphy

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

5.1. Dinoflagellate cyst biostratigraphy

In this study a formal dinoflagellate cyst biozonation is not proposed, principally because much of the upper Bajocian succession was not sampled at Cabo Mondego. For example the *Strenoceras niortense* and *Garantiana garantiana* ABs were not studied here (Fig. 2). Furthermore, the interval studied does not overlap with the upper Pliensbachian to upper Toarcian dinoflagellate cyst biozonation for the Lusitanian Basin proposed by Correia et al. (2018).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2. Pollen and spore biostratigraphy

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

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

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

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

6. Dinoflagellate cyst palaeobiology

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

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

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

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

The large and distinctive dinoflagellate cyst species *Dissiliodinium giganteum* was not recorded herein. This taxon is extremely prominent in the lower Bajocian (*Witchellia laeviuscula* and *Sonninia propinquan*s ABs) of Germany and eastern Europe (Gedl 2008, Gedl and Józsa 2015, Wiggan et al. 2017). This species apparently thrived in regions with high terrestrial runoff input, elevated nutrient levels and perhaps reduced salinities (Wiggan et al. 2017). By contrast, *Dissiliodinium giganteum* is rare in the lower Bajocian carbonate facies of southern England and northern France (Feist-Burkhardt and Monteil 1997, unpublished data). Thus the absence of *Dissiliodinium giganteum* in the Lusitanian Basin is consistent with the deepwater environment, relatively far from sources of terrigenous input, of this region.

7. Conclusions

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

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

The dinoflagellate cysts exhibit significant species turnover, and several bioevents have local and regional significance. For example, the lower Bajocian range top of *Nannoceratopsis gracilis* in the *Stephanoceras humphriesianum* AB is consistent with other European records (e.g. Prauss 1989). Furthermore, the range bases of complex chorate dinoflagellate cysts, *Gonyaulacysta jurassica* subsp. *adecta* and *Tubotuberella dangeardii* were recorded in the earliest Bathonian at Cabo Mondego. These datums are reliable biomarkers for the earliest Bathonian throughout Europe. (e.g. Wiggan et al. 2017). The pollen and spores recorded herein are characteristic of Middle Jurassic associations in both hemispheres. It is noticeable that araucarian pollen, such as *Araucariacites* and *Callialasporites*, diversified and became prominent during the Aalenian.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1. *Micrhystridium* sp. 1 (acanthomorph acritarch). São Gião, upper Toarcian (*Pleydellia aalensis* AB), sample SG8, slide 1, G40. Note the long and slender spines and the unusual equatorial pylome.

2. *Cymatiosphaera* sp. cf. *C. pachytheca* Eisenack 1957 (prasinophyte). Cabo Mondego, lower Aalenian (*Leioceras opalinum* AB), sample M38, slide 1, O27/3.

3. *Tasmanites* sp. (prasinophyte). São Gião, lower Aalenian (*Leioceras opalinum* AB), sample SG94, slide 1, M40.

4. *Ischyosporites variegatus* (Couper 1958) Schulz 1967 (spore). Cabo Mondego, lower Bathonian (*Zigzagiceras zigzag* AB), sample Bt184, slide 1, H49.

5. *Striatella seebergensis* Mädler 1964 (spore). Cabo Mondego, middle Aalenian (*Brasilia bradfordensis* AB), sample M237, slide 1, U26.

6. *Auritulinasporites triclavus* Nilsson 1958 (spore). Cabo Mondego, upper Aalenian (*Graphoceras concavum* AB), sample M319, slide 1, L33/2.

7. *Callialasporites dampieri* (Balme 1957) Dev 1961 (pollen). Cabo Mondego, lower Bathonian (*Zigzagiceras zigzag* AB), sample Bt184, slide 1, U55/2.

8. *Callialasporites turbatus* (Balme 1957) Schulz 1967 (pollen). Cabo Mondego, lower Bajocian (*Hyperlioceras discites* AB) sample M341, slide 1, N23/2.

9. *Callialasporites segmentatus* (Balme 1957) Srivastava 1963 (pollen). Cabo Mondego, lower Bathonian (*Zigzagiceras zigzag* AB), sample Bt184, slide 1, H29/2.

10. *Araucariacites australis* Cookson 1947 ex Couper 1958 (pollen). Cabo Mondego, lower Bajocian (*Sonninia propinquans* AB), sample AB178a, slide 1, Q23/2.

11. *Perinopollenites elatoides* Couper 1958 (pollen). Cabo Mondego, lower Aalenian (*Leioceras opalinum* AB), sample M121, slide 1, V32/3.

12. *Cycadopites granulatus* (de Jersey 1962) de Jersey 1964 (pollen). Cabo Mondego, lower Bathonian (*Zigzagiceras zigzag* AB), sample Bt126, slide 1, Q23/4.

ONLINE SUPPLEMENTARY MATERIAL

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

Edits to the figure needed:

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

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

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

Supplementary Appendix

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

Dinoflagellate cysts:

Acanthaulax crispa (Wetzel 1967) Woollam & Riding 1983
Bradleyella adela (Fenton et al. 1980) Woollam 1983
Chytroeisphaeridia chytroeides (Sarjeant 1962) Downie & Sarjeant 1965
**Ctenidodinium combazii* Dupin 1968
Ctenidodinium cornigerum (Valensi 1953) Jan du Chêne 1985
Ctenidodinium sellwoodii (Sarjeant 1975) Stover & Evitt 1978
**Dissiliodinium giganteum* Feist-Burkhardt 1990
Durotrigia daveyi Bailey 1987
Epiplosphaera gochtii (Fensome 1979) Brenner 1988

Gonyaulacysta jurassica (Deflandre 1938) Norris & Sarjeant 1965 subsp. *adecta* Sarjeant 1982
Gonyaulacysta pectinigera (Gocht 1970) Fensome 1979
Korystocysta aldridgeii Wiggan et al. 2017
Korystocysta gochtii (Sarjeant 1976) Woollam 1983
Korystocysta pachyderma (Deflandre 1938) Woollam 1983
Mancodinium semitabulatum Morgenroth 1970
Mendicodinium groenlandicum (Pocock & Sarjeant 1972) Davey 1979
**Mendicodinium spinosum* Bucefalo Palliani et al. 1997
**Nannoceratopsis dictyambonis* Riding 1984
Nannoceratopsis gracilis Alberti 1961
**Nannoceratopsis plegas* Drugg 1978
Nannoceratopsis senex van Helden 1977
**Nannoceratopsis spiculata* Stover 1966
**Nannoceratopsis triceras* Drugg 1978
Pareodinia ceratophora Deflandre 1947
**Pareodinia halosa* (Filatoff 1975) Prauss 1989
Parvocysta nasuta Bjaerke 1980
Phallocysta elongata (Beju 1971) Riding 1994
Rhynchodiniopsis ?regalis (Gocht 1970) Jan du Chêne 1985
Scriniocassis priscus (Gocht 1979) Below 1990
Scriniocassis weberi Gocht 1964
Sentusidinium asymmetrum (Fenton et al. 1980) Lentin & Williams 1981
Tubotuberella dangeardii (Sarjeant 1968) Stover & Evitt 1978
Valensiella ovulum (Deflandre 1947) Eisenack 1963
Valvaeodinium armatum Morgenroth 1970

Pollen:
Araucariacites australis Cookson 1947 ex Couper 1958
Callialasporites dampieri (Balme 1957) Dev 1961
Callialasporites microvelatus Schulz 1967
Callialasporites minus (Tralau 1968) Guy 1971
Callialasporites segmentatus (Balme 1957) Srivastava 1963
Callialasporites trilobatus (Balme 1957) Dev 1961

Callialasporites turbatus (Balme 1957) Dev 1961
Cerebropollenites macroverrucosus (Thiergart 1949) Schulz 1967
Cycadopites granulatus (de Jersey 1962) de Jersey 1964
Perinopollenites elatoides Couper 1958

Prasinophytes:

Cymatiosphaera pachytheca Eisenack 1957
Halosphaeropsis liassica Mädler 1968

Spores:

Auritulinasporites triclavus Nilsson 1958
Calamospora tener (Leschik 1955) Mädler 1964
Concavisporites granulosus Tralau 1968
Ischyosporites variegatus (Couper 1958) Schulz 1967
Kekryphalospora distincta Fenton & Riding 1987
Kraeuselisporites reissingeri (Harris 1957) Morbey 1975
Lycopodiacidites rugulatus (Couper 1958) Schulz 1967
Osmundacidites wellmanii Couper 1953
Retitriletes austroclavatidites (Cookson 1953) Doring et al. in Krutzsch 1963
Striatella seebergensis Madler 1964

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