Callovian (Middle Jurassic) dinoflagellate cysts from the Algarve Basin, southern Portugal

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ABSTRACT

The palynology of three Callovian (Middle Jurassic) limestone-marl successions from the Algarve Basin in southern Portugal was studied. These localities are Baleeira Harbour, Mareta Beach and Telheiro Quarry; they provide a composite succession, tied to ammonite zones, through the Lower, Middle and Upper Callovian from the western and eastern subbasins of the Algarve Basin. The three sections generally yielded relatively abundant marine and continental palynofloras. Diversity is low to moderate and the dinoflagellate cyst associations are dominated by *Ctenidodinium* spp., the *Ellipsoidictyum/Valensiella* group, *Gonyaulacysta jurassica* subsp. *adecta*, *Korystocysta* spp., *Meiourogonyaulax* spp., *Pareodinia ceratophora, Sentusidinium* spp., *Surculosphaeridium*? *vestitum* and *Systematophora* spp. Some intra-Callovian marker bioevents were recorded; these include the range bases of *Ctenidodinium ornatum, Gonyaulacysta eisenackii, Korystocysta pachyderma, Mendicodinium groenlandicum, Rigaudella* spp. and *Surculosphaeridium*? *vestitum*. The occurrences of *Endoscrinium acroferum* and *Impletosphaeridium varispinosum* in the Early to Middle Callovian of Mareta Beach and Telheiro Quarry are also characteristic of this interval. At Baleeira Harbour, the presence of *Ctenidodinium continuum* and *Gonyaulacysta centriconnata* in the Peltoceras athleta Zone confirms the Late Callovian age of this section. The successions studied were deposited in restricted infralittoral neritic marine environments which lack deep water circulation, and possibly represent restricted embayments. The relatively low diversity nature of the dinoflagellate cyst assemblages appears to be largely due to the highly enclosed nature of this depocentre. Many Callovian index dinoflagellate cyst taxa which are found in northwest Europe are absent in the Algarve Basin. These forms may have been intolerant of enclosed palaeoenvironments which have restricted or no deep circulation. The Callovian marine palynofloras from the Algarve Basin compare well to the few other published records from the Iberian Peninsula of this age. However they are significantly less diverse than coeval floras from elsewhere in the extensive Mid Latitude Callovian phytoprovince. Many typically Callovian dinoflagellate cysts are cosmopolitan, however some provincialism is clearly manifested. The Arctic and Austral Callovian phytoprovinces are characterised by key endemic taxa such as *Paragonyaulacysta retiphragmata* and *Ternia balmei*, which are not present in the Algarve Basin and are assumed to have been polar forms.

Keywords: palynology; biostratigraphy; provincialism; Middle Jurassic (Callovian); Algarve Basin; Portugal

1. Introduction

The Jurassic palynology of the Algarve Basin (Fig. 1) in southern Portugal has not been extensively studied. However the Pliensbachian to Kimmeridgian palynology of the Western Subbasin and the Carrapateira outlier was recently summarised by Borges et al. (2011), who also briefly reviewed previous research. The present contribution is a study of the Callovian (Middle Jurassic) palynology of the Algarve Basin based on three reference sections cropping out in the west and the east of this depocentre. These successions are Baleeira Harbour, Mareta Beach and Telheiro Quarry (Fig. 2); all three have ammonite zonal control (Figs. 3-5). These localities provide a representative west-east transect through the entire Callovian of the Algarve Basin. Borges et al. (2011) included a preliminary study of the Callovian palynology of Mareta Beach.

In comparison to the Iberian Peninsula, the Callovian palynology of northwest and eastern Europe has been relatively well studied. Principal contributions include Woollam (1980), Berger (1986), Riding (1987; 2005), Prauss (1989), Dodekova (1990), Riding and Thomas (1997), Poulsen (1998) and Riding et al. (1999). In contrast, there are very few contributions on the Middle Jurassic palynology of southern Europe (Smelror and Leereveld, 1989; Smelror et al., 1991; Borges et al., 2011). This study aims to comprehensively document the marine palynomorphs throughout the Callovian of the Algarve Basin, comment on their biostratigraphical and palaeoenvironmental significance, and compare them with coeval assemblages elsewhere.

2. Geological background

The Algarve Basin is the southernmost geological province of mainland Portugal, and extends along the entire south coast area (Fig. 1). The area lies immediately south of the “Serra Algarvia”, and is typified by gentle karst topography with west-east trending structural elements. Over 3 km of largely marine limestones, marls and sandstones accumulated during the Late Triassic to Quaternary. This important depocentre was initiated in the Late Triassic by extensional rifting during the opening of the North and Central Atlantic, associated with the breakup of Pangaea. The base of the principal carbonate-dominated succession is of Early Jurassic (Sinemurian) age; this directly overlies earliest Jurassic (Hettangian) volcanic rocks associated with the Central Atlantic Magmatic Province (CAMP) (Martins et al., 2008). The majority of the Jurassic succession comprises marine limestones and marls. By contrast, the overlying Lower Cretaceous is represented by a mixed carbonate and siliciclastic succession (Rey, 2006). Major uplift occurred during the Late Cretaceous, and hence no Upper Cretaceous to Paleogene strata were deposited; Miocene limestones overlie the Jurassic and Lower Cretaceous strata. There were occasional short-lived compressional intervals which at least partially isolated the Algarve Basin and prevented extensive mixing of Tethyan and Boreal biotas (Terrinha et al., 2002). Two of the most intense compressional events occurred during the Aalenian-Bajocian and the Callovian-Oxfordian.

The onset of Callovian deposition in the Algarve Basin coincided with increased levels of subsidence, and a transgressive episode that reached a maximum during the Early Callovian. Depositional settings were therefore unified across the basin, and marl rich in marine microplankton is the dominant Lower Callovian lithotype. The Middle Callovian strata comprise interbedded limestones and marls which are overlain by Late Callovian limestones. These Middle and Upper Callovian limestones and marls were deposited during a major regressive episode that culminated in an unconformity at the Callovian-Oxfordian transition. This hiatus represents a major regional erosional event which was developed in all the Mesozoic basins of Iberia (Mouterde, 1971). A complete Callovian succession is only exposed in the Sagres area in the Western Algarve Subbasin, whereas in the Eastern Algarve Subbasin only the Lower Callovian is preserved (Marques and Rocha, 1988b).

The Jurassic biotas of the Algarve Basin are dominantly of Tethyan affinity. The presence of Tethyan faunas, the abundance of phylloceratid ammonites and the absence of Boreal forms indicates that the Algarve Basin lies within the Submediterranean Province of the Tethyan Realm (Rocha, 1976; Marques and Rocha, 1988a,b; Azerêdo et al., 2003).

3. Material and methods

The 59 productive samples in this study were collected from a disused quarry at Telheiro, and from coastal outcrops at Mareta Beach and Baleeira Harbour (Figs. 1, 2). The successions sampled at Telheiro Quarry and Baleeira Harbour are entirely Lower and Upper Callovian respectively; the strata studied at Mareta Beach span the entire Callovian (Figs. 3-5). These three sections provide a transect throughout the Lower, Middle and Upper Callovian of the Algarve Basin. All the successions have been studied for ammonites, and the Bullatimorphites bullatus, Macrocephalites gracilis, Erymnoceras coronatum and Peltoceras athleta zones have been recognised (Figs. 3-5). The samples were prepared using standard palynological techniques, however the residues were not oxidised (e.g. Wood et al., 1996). All the residues were sieved with a 15 µm mesh sieve. The unused samples, aqueous residues, microscope slides and figured specimens are curated in the collections of the LGM/LNEG (Portuguese Geological Survey), S. Mamede Infesta, Portugal.

4. Palynology

In this section, the Callovian palynofloras from the three localities studied are described and interpreted. The three palynomorph datasets are presented as Tables 1-3, and quantitative plots of ten palynomorph groups are depicted in Figs. 3-5. The palynomorphs recorded at and below species level are listed, with their respective author citations, in Appendix 1. Selected dinoflagellate cysts are illustrated in Plates I and II. All other dinoflagellate cysts mentioned, with author citations, are included in Appendix 2.

Generally, dinoflagellate cyst associations of moderate diversity dominate the palynomorph associations. These assemblages include large proportions of *Ctenidodinium* spp., the *Ellipsoidictyum/Valensiella* group, *Impletosphaeridium* spp., indeterminate chorate cysts, indeterminate dinoflagellate cysts, *Gonyaulacysta jurassica* subsp *adecta*, *Korystocysta* spp., *Meiourogonyaulax* spp., *Pareodinia ceratophora* and *Sentusidinium* spp. throughout. *Adnatosphaeridium caulleryi, Batiacasphaera* spp., *Endoscrinium acroferum*, *Epiplosphaera gochtii, Mendicodinium groenlandicum, Rigaudella* spp., *Surculosphaeridium*? *vestitum, Systematophora* spp. and *Tubotuberella dangeardii* are also consistently present in lower proportions. Gymnospermous pollen (i.e. bisaccate pollen, *Callialasporites* spp., *Classopollis classoides, Exesipollenites* spp. and *Perinopollenites elatoides*) and foraminiferal test linings are also present in significant proportions. Acritarchs, prasinophytes and pteridophyte spores proved relatively sparse (Figs. 3-5, Tables 1-4).

In terms of the overall dinoflagellate cyst biostratigraphy, the occurrences of forms such as *Endoscrinium acroferum, Gonyaulacysta eisenackii, Gonyaulacysta jurassica* subsp *adecta*, *Meiourogonyaulax* spp., *Mendicodinium groenlandicum, Pareodinia ceratophora*, *Rigaudella* spp., *Surculosphaeridium*? *vestitum, Systematophora* spp., *Tubotuberella dangeardii* and *Wanaea acollaris* are typical of the

Callovian of the Northern Hemisphere (Riding and Thomas, 1992; Riding et al., 1999; Riding, 2005). However, the abundances of the *Ellipsoidictyum/Valensiella* group and the closely-related genera *Ctenidodinium* and *Korystocysta* are far more typical of the Bathonian in northern Europe (Gocht, 1970; Riding et al., 1985). Furthermore, the chorate genus *Systematophora* was recovered throughout (Tables 1-3). Most reports of this genus are Oxfordian and younger, and the reports from the Bathonian and Callovian of the Algarve Basin are among the oldest records known (Borges et al., 2011). The acritarch, pollen/spore and prasinophyte assemblages observed are also consistent with the Middle Jurassic (Guy-Ohlson, 1986; 1989).

The presence of diverse marine microplankton throughout is indicative of a consistent open marine depositional setting. Terrestrial palynomorphs (pollen/spores) are also present; these were transported into the marine realm via water and wind transport. *Classopollis classoides* was recorded in significant proportions throughout all three successions studied. This pollen genus is interpreted as having been produced by a warmth-loving plant. Their abundance declined sharply with palaeolatitude, they were tolerant of semiarid conditions and they lived in both low-lying and upland settings (Traverse, 2007; Quattrocchio et al., 2011).

4.1. Telheiro Quarry

Thirty one samples were studied from the Lower Callovian marls and limestones of a large disused quarry at Telheiro, on the northern slope of Guilhim Hill, northwest of Estoi in the Eastern Algarve Subbasin (Figs. 1-3). Thirteen of these samples yielded palynofloras of variable diversity. The remaining eighteen proved barren of palynomorphs. The productive samples are all from the lowermost part of the succession, assigned to the Bullatimorphites bullatus Zone by Marques and Rocha (1988a). The latter authors reported that the ammonite faunas indicate that the succession is referable to the Bullatimorphites bullatus (= Macrocephalites macrocephalus) and Macrocephalites gracilis zones of the Tethyan/Submediterranean scheme (Fig. 3). The Reineckeia rehmanni (= Reineckeia grossouvrei) and the Reineckeia pictava subzones of the Macrocephalites gracilis Zone were also recognised by Marques and Rocha (1988a, fig. 1). The Bullatimorphites bullatus and Macrocephalites gracilis zones are broadly equivalent to the Macrocephalites herveyi and Proplanulites koenigi zones of northwest Europe respectively (Ogg, 2004, fig. 18.1).

Prominent dinoflagellate cysts include the *Ctenidodinium sellwoodii* group, *Ctenidodinium* spp., the *Meiourogonyaulax caytonense* group and *Meiourogonyaulax* spp. (Fig. 3, Table 1). The range bases of *Ctenidodinium ornatum*, consistent *Gonyaulacysta jurassica* subsp *adecta*, *Korystocysta pachyderma*, *Rigaudella* spp. and *Surculosphaeridium*? *vestitum* in this succession are indicative that this succession is no older than Early Callovian by comparison with elsewhere in Europe (Woollam, 1980; Riding, 2005). *Endoscrinium acroferum* was observed between samples TL17 and TL4 (Table 1). This species ranges from the Late Bathonian to the Late Callovian (Riding et al., 1985; Prauss, 1989).

Species of *Ctenidodinium* declined in relative abundance up-section, and cysts with apical archaeopyles and chorate cysts peaked in sample TL8. The maxima of *Gonyaulacysta* and relatives, *Korystocysta* spp., *Pareodinia* spp., prasinophytes and acritarchs, and pollen are all within the middle of the succession, between samples

TL12 and TL10. The relative abundances of foraminiferal test linings and spores do not exhibit any major perturbations or definite trends (Fig. 3).

The association is of low diversity compared to coeval floras recorded elsewhere. Some species characteristic of the Early Callovian in northern Europe such as *Aldorfia aldorfensis, Chytroeisphaeridia hyalina, Ctenidodinium combazii, Impletosphaeridium varispinosum, Meiourogonyaulax valensii, Nannoceratopsis pellucida, Pareodinia prolongata, Rhynchodiniopsis cladophora, Sirmiodinium grossii* and *Wanaea acollaris* were not recorded.

4.2. Mareta Beach

The Jurassic succession exposed in marine cliff sections at Mareta Beach, south of Sagres in the western Algarve Subbasin, comprises over 140 m of Upper Bajocian to ?Upper Oxfordian/Kimmeridgian limestones and marls (Choffat, 1887; Rocha, 1976; Borges et al., 2011, fig. 4). The palynology of 14 productive samples from the Callovian of this succession were previously studied by Borges et al. (2011). In this study, the palynology of 23 samples from the Lower, Middle and Upper Callovian of Mareta Beach were examined; these substages are assigned to the Bullatimorphites bullatus, Erymnoceras coronatum and Peltoceras athleta zones respectively (Figs. 2, 4). In this study, 10 additional samples (i.e. M66-M77, excluding M70) are included which were not studied by Borges et al. (2011) (Figs. 2, 4).

Prominent dinoflagellate cysts include the *Ctenidodinium sellwoodii* group, *Ctenidodinium* spp., indeterminate chorate cysts, *Korystocysta gochtii* and the

Meiourogonyaulax caytonense group (Fig. 4, Table 2). The occurrences of consistent *Gonyaulacysta jurassica* subsp *adecta*, and prominent *Meiourogonyaulax caytonense* group are typical of the Callovian (Riding and Thomas, 1992). Furthermore, the range bases of *Ctenidodinium ornatum*, *Gonyaulacysta eisenackii, Korystocysta pachyderma*, *Liesbergia liesbergensis, Mendicodinium groenlandicum* and *Surculosphaeridium*? *vestitum*, and the range top of *Endoscrinium acroferum* in this succession indicate that this succession is Callovian by comparison with elsewhere in Europe (Berger, 1986; Prauss, 1989; Riding and Thomas, 1997).

Impletosphaeridium varispinosum ranges from samples M25 and M72 and spans the Lower and Middle Callovian (Fig. 4, Table 2). This species is typically Early Callovian (Riding, 1987), but has been recorded from the Late Callovian of Russia (Riding et al., 1999). The range base of *Ctenidodinium ornatum* in sample M75 close to the base of the Middle Callovian (Table 2) is coeval with this datum in northern Europe (Berger, 1986). The Middle Callovian to earliest Oxfordian marker *Liesbergia liesbergensis* was found in sample M27 from the Lower Callovian (Borges et al., 2011). This is a rare species and its full range may not be fully known. *Endoscrinium acroferum* was encountered in the Middle Callovian (samples M47 to M45). This species has been recorded from the Late Bathonian and Callovian (Riding et al., 1985; Prauss, 1989). *Gonyaulacysta eisenackii* is confined to sample M73 in the Middle Callovian. The range base of this distinctive species is normally of Middle Callovian age in northern Europe (Berger, 1986; Riding and Thomas, 1997; Riding, 2005). *Rhynchodiniopsis*? *regalis* was noted in sample M47 in the Middle Callovian (Borges et al., 2011). This species is known from the Late Bajocian and Bathonian of northern Europe (Riding et al., 1985; Prauss, 1989), hence this material may be reworked. The occurrence of *Wanaea acollaris* in the Middle Callovian (sample M45) is consistent with other reports. This species is especially common in the Callovian (Riding, 2005), but may be present in the Bajocian and Bathonian (Riding and Helby, 2001a). *Ctenidodinium cornigerum* was recorded in samples M46 and M32 (Middle and Upper Callovian). This taxon has been recorded from the underlying Lower Bathonian in this section (Borges et al., 2011, table 1) and the Bajocian and Bathonian interval elsewhere (Jan du Chêne et al., 1985). It was deemed to be Tethyan in affinity by Jan du Chêne et al. (1985).

The relative abundances of the six major dinoflagellate cyst groups fluctuated sharply in the Lower and Middle Callovian of Mareta Beach. Chorate cysts peaked in samples M48 and M44 which may be indicative of proximal marine conditions (Sluijs et al., 2005), and there is a major peak of *Pareodinia* spp. in sample M42. *Ctenidodinium* spp. and *Korystocysta* spp. increased slightly in relative proportions up-section, but other than that, no major trends were discerned. The relative abundances of foraminiferal test linings fluctuated markedly with no apparent overall trend. Pollen and spores are especially abundant between samples M68 and M43 (Fig. 4).

The Callovian dinoflagellate cyst assemblages from Mareta Beach are of markedly lower diversity in comparison with coeval palynofloras in northern Europe (Table 1). In northwest Europe the Callovian was a time of rapidly increasing diversity, with many inceptions occurring in the Middle and Late Callovian (e.g. Riding, 1987, fig. 4; Riding, 2005, figs. 3, 4). Many of these forms which have inceptions in the Middle to Late Callovian throughout northern Europe are absent in the Algarve Basin. These include *Chytroeisphaeridia cerastes, Clathroctenocystis asaphes, Compositosphaeridium*? *polonicum, Endoscrinium galeritum, Fromea tornatilis, Kalyptea stegasta, Limbodinium absidatum, Rigaudella aemula, Sirmiodiniopsis orbis, Stephanelytron* spp., *Trichodinium scarburghense* and *Wanaea thysanota*.

4.3. Baleeira Harbour

The section exposed in cliffs at Baleeira Harbour, east of Sagres in the western Algarve Subbasin, comprises an expanded (ca. 90 m) Upper Callovian succession of interbedded marls and limestones overlain by thick limestones (Figs. 2, 5). The section has been assigned entirely to the Peltoceras athleta Zone (Rocha, 1976). Palynomorph assemblages from 23 productive samples, from a total of 31, were studied herein (Fig. 5, Table 3).

The *Ctenidodinium sellwoodii* group, *Ctenidodinium* spp., *Gonyaulacysta jurassica* subsp *adecta*, indeterminate chorate cysts, *Korystocysta gochtii*, the *Meiourogonyaulax caytonense* group and *Meiourogonyaulax* spp. proved consistently prominent throughout this section (Fig. 5, Table 3). The presence of *Ctenidodinium ornatum, Korystocysta pachyderma* and *Rigaudella* spp. is consistent with a Late Callovian age by comparison with elsewhere in Europe (Riding and Thomas, 1997). The key bioevents are the range top of *Ctenidodinium continuum* (sample BA3) and the single occurrence of *Gonyaulacysta centriconnata* (sample BA10), which are consistent with a Late Callovian age. The inception of *Gonyaulacysta centriconnata* is close to the Middle-Late Callovian transition (Riding, 1983; 1987; 2005; Riding and Thomas, 1997). The apparent extinction of *Ctenidodinium continuum* is typically latest Callovian in northern Europe (Woollam, 1980; Riding, 1987; Riding et al., 1999). *Ctenidodinium cornigerum* was observed throughout the succession. This study represents the first Callovian reports of this Tethyan species (Jan du Chêne et al., 1985). The Upper Callovian marine palynofloras from Baleeira Harbour are of relatively low diversity when compared to their coeval counterparts from northwest Europe (Table 1). The Late Callovian was a time of extremely rapidly increasing dinoflagellate cyst diversity in England, Germany and Scotland. Many northern European Late Callovian markers are absent at Baleeira Harbour (see section 4.2 above).

The relative proportions of the six groups of dinoflagellate cysts proved highly variable in the lowermost 16 m (samples BA7 to BA21). Chorate cysts and *Ctenidodinium* spp. were especially common in samples BA10 and BA11. Similar peaks in relative dinoflagellate cyst abundance are present in BA7, BA18, BA23, BA25 and BA6. There was less variability above sample BA21; this probably reflects sample spacing. However *Gonyaulacysta* and relatives and *Pareodinia* exhibit their maxima in sample BA6. The four non-dinoflagellate cyst palynomorph groups exhibit similar trends. These are also highly variable in the lowermost 16 m, but are otherwise relatively uniform (Fig. 5).

5. Comparison of the Callovian marine palynofloras of the Algarve Basin with coeval assemblages

In this section, the Callovian dinoflagellate cysts from the Algarve Basin are compared with other reports from southern Europe, from northern Europe and adjacent areas, and from other regions such as the Arctic and Australasia.

5.1. Southwest Europe

There are few published data on the marine Callovian palynofloras from southwest Europe. Davies (1985) and Smelror et al. (1991) studied marine palynofloras from the Lower, Middle and Upper Callovian of Portugal and Spain. Davies (1985) examined a single sample from the undifferentiated Callovian of the Brenha Road section in the Lusitanian Basin, central western Portugal. This horizon proved extremely sparse with only *Korystocysta pachyderma* present.

Smelror et al. (1991) worked on the lowermost Callovian of Cape Mondego in the Lusitanian Basin of Portugal, and the Lower to Upper Callovian strata at Aguilón and Tosos in northeast Spain. The material from Cape Mondego is of moderate diversity (Smelror et al., 1991, fig. 7). The marine palynofloras are very similar to their counterparts in the Algarve Basin with chorate cysts, the *Ctenidodinium sellwoodii* group, *Ellipsoidictyum* spp., *Meiourogonyaulax* spp. and *Sentusidinium* spp. all prominent, together with lower abundances of *Chytroeisphaeridia chytroeides, Ctenidodinium continuum*, *Gonyaulacysta eisenackii*, *Gonyaulacysta jurassica* and *Tubotuberella dangeardii*. However, these authors recorded taxa which are apparently absent in the Algarve Basin including *Chlamydophorella* spp., *Compositosphaeridium*? *polonicum, Kalyptea stegasta* and *Stephanelytron* sp. This may reflect more open marine conditions in the Lusitanian Basin. By contrast, the Spanish material of Smelror et al. (1991) is very similar to the coeval dinoflagellate cysts of the Algarve basin. The material from northeast Spain is of low diversity with abundant chorate cysts, the *Ctenidodinium sellwoodii* group, *Meiourogonyaulax* spp. and *Sentusidinium* spp., alongside accessory species typical of southern Portugal (Smelror et al., 1991, figs. 3-5).

Smelror and Leereveld (1989) studied the Late Bathonian to Early Oxfordian of Mt. Crussol in southeast France. The dinoflagellate cyst associations recovered are relatively diverse and are entirely typical of northern Europe, North Africa, Eastern North America and the Middle East. The majority of the key marker taxa are present. This supports the contention that the Algarve Basin was a restricted depocentre during the Jurassic, and furthermore indicates that the low diversity floras in southern Portugal are not simply due to latitudinal control.

5.2. Northern Europe and adjacent areas

In section 4 above, it was stated that the Callovian dinoflagellate cyst floras of northern Europe and adjacent regions (i.e. North Africa, North America and the Middle East) are typically of relatively high diversity in comparison to the Algarve Basin. Forms such as *Fromea tornatilis, Nannoceratopsis pellucida, Rhynchodiniopsis cladophora* and *Rigaudella aemula* are present throughout the Callovian of northern Europe, but have not been recorded from the Algarve Basin. In northern Europe and adjacent areas, diversity increased rapidly throughout the Callovian. Marker taxa such as *Aldorfia aldorfensis, Chytroeisphaeridia hyalina* and *Meiourogonyaulax valensii* in the Early Callovian, and *Kalyptea stegasta, Scriniodinium crystallinum, Trichodinium scarburghense* and *Wanaea thysanota* in the Middle and Late Callovian are apparently absent in the Algarve Basin. This is especially noteworthy as many key typically Callovian taxa such as *Endoscrinium galeritum, Nannoceratopsis pellucida, Rhynchodiniopsis cladophora, Scriniodinium crystallinum* and *Stephanelytron* spp. have extremely wide geographical distributions due to the presence of wide, open seaways at this time (Pocock, 1972; Johnson and Hills, 1973; Bujak and Williams, 1977; Helby et al., 1987; Thusu et al., 1988; Conway, 1990; Riding et al., 1999; Riding and Fensome, 2002).

5.3. The Arctic, South America and Australasia

The majority of published data on Callovian dinoflagellate cyst floras are from northwest Europe and the immediately adjacent regions. However there are key publications on regions such as the Arctic, South America and Australasia which allow comparisons to be made, and to allow assessments of global provincialism at this time.

There are several relevant studies on the Callovian palynology of the Arctic region. The Callovian strata of areas close to the Viking Corridor such as the Barents Sea, Arctic Canada, East Greenland, Arctic Russia and the Svalbard archipelago generally yield moderately diverse and rich marine palynofloras which are similar in character to coeval assemblages from northwest Europe (Johnson and Hills, 1973; Bjaerke, 1977; 1980; Davies, 1983; Poulsen, 1985; Smelror, 1987; 1988a,b; Smelror and Below, 1992; Riding et al., 1999; Piasecki et al. 2004). However, some endemic Arctic taxa are present and these include *Evansia dalei, Evansia perireticulata, Paraevansia brachythelis, Lacrymodinium warrenii, Paragonyaulacysta calloviensis, Paragonyaulacysta retiphragmata*, *Valvaeodinium leneae* and *Valvaeodinium thereseae. Chytroeisphaeridia* spp., *Paragonyaulacysta* spp., *Pareodinia* and its relatives, and *Valvaeodinium* spp. were both diverse and prominent at high northerly palaeolatitudes at this time. These associations comprise the Arctic phytoprovince (Fig. 6). It seems clear that dinoflagellate cyst diversity increased during the Middle and Late

Callovian in the Arctic region, as it does in the Subboreal Realm further south, and that the maximum provincialism was attained during the Early Callovian. There were effective marine connections between northwest Europe and the Arctic throughout the Callovian (Zeigler, 1982; Larsen, 1987). Hence dinoflagellates could be passively dispersed between the Tethyan and Boreal Realms. Any provincialism at this time was most likely due to the preferences of taxa in terms of current characteristics, nutrient availability and temperature.

Riding et al. (2011) investigated the Upper Callovian Lotena Formation of the Neuquén Basin, Argentina and found that the assemblages are of northwest European affinity. Endemic and typically Australasian forms are entirely absent. These authors postulated that some open marine connection between the shallow marine western Tethys and the Neuquén Basin existed during the Late Callovian. This connection was interpreted as being via the Hispanic Corridor, a seaway which passed through Central America, with the palynofloras being dispersed in a southwest direction by the circum-Tropical Marine Current (Irurralde-Vinent, 2003). However the currents operating in the eastern Pacific during the Middle Jurassic would most likely to have flowed south to north, like the modern Humboldt (Peru) current (Penven et al., 2005). Despite this, the similarities between the dinoflagellate cyst assemblages of the Neuquén Basin and Europe are consistent with the distribution of other marine biotas and marine facies belts.

The most profound Callovian dinoflagellate cyst provincialism was between Northern Europe and adjacent areas, and Australasia. Callovian dinoflagellate cyst associations from Australia, New Zealand and surrounding regions are dominated by endemic taxa such as *Ternia balmei*, and species described by, for example, Riding and Helby (2001b) and Mantle (2005; 2009a,b). These floras define the Austral Callovian phytoprovince (Fig. 6). Diversity increased during the Callovian, however the stratigraphical succession in the Southern Hemisphere appears to be significantly different in terms of taxonomic spectrum to that in northwest Europe and surrounding areas (see Helby et al., 1987, fig. 15). Some cosmopolitan taxa are present in Australia and surrounding regions; these include *Chytroeisphaeridia chytroeides, Gonyaulacysta jurassica* subsp. *adecta, Mendicodinium groenlandicum, Nannoceratopsis pellucida, Pareodinia ceratophora, Rhynchodiniopsis cladophora, Rigaudella aeumla* and *Tubotuberella dangeardii* (see Mantle, 2009a,b; Riding et al., 2010). Davey (1987, figs. 6, 14) described Callovian marine palynofloras from Papua New Guinea, and these are of far more reminiscent of coeval Northern Hemisphere floras. This provincialism cannot be fully evaluated at present because the geographical extents of the endemic Austral Callovian species throughout areas to the north and west such as China and India are not fully understood.

5.4. Synthesis

Based on the review above, the Callovian dinoflagellate cyst floras of the world can be subdivided into the Arctic, Mid Latitude and Austral Callovian phytoprovinces. The extents of these floral realms are illustrated in Fig. 6. The control on these phytoprovinces appears to be largely due to palaeoecological preferences (assumed to be chiefly sea surface temperature and nutrient levels) because of the extensive open marine connections which operated at this time. Despite this, many taxa (e.g. *Gonyaulacysta jurassica*, *Nannoceratopsis pellucida* and *Rigaudella aemula*) are cosmopolitan, but the Arctic and Austral phytoprovinces are characterised by key endemic polar forms. More detailed research, especially in East Africa, southeast Asia, India, Indonesia and Madagascar will refine our understanding of this provincialism. The Callovian marine microplankton floras from the Algarve Basin described here clearly lie within the Mid Latitude phytoprovince. However, the diversity is markedly lower than in surrounding areas such as North Africa, Eastern Canada and France. This is explained here as resulting from the highly enclosed and restricted nature of the Algarve Basin (see section 6 below).

6. Overview of the Callovian palynofloras of the Algarve Basin

A composite range chart of selected Callovian dinoflagellate cysts from the Algarve Basin is presented as Table 4. This shows that the associations are consistently dominated by chorate cysts, the *Ctenidodinium sellwoodii* group, *Ctenidodinium* spp., the *Ellipsoidictyum/Valensiella* group, *Gonyaulacysta jurassica* subsp. *adecta*, *Korystocysta* spp., the *Meiourogonyaulax caytonensis* group, *Meiourogonyaulax* spp., *Pareodinia ceratophora*, *Sentusidinium* spp., *Surculosphaeridium*? *vestitum* and *Systematophora* spp. The majority of these are prominent throughout the Callovian of Europe (Woollam, 1980; Riding et al., 1999). Proximate and proximochorate gonyaulacoid forms generally predominate over chorate cysts; this is consistent with relatively deep water conditions (Sluijs et al., 2005).

Ctenidodinium ornatum, *Korystocysta pachyderma* and *Surculosphaeridium*? *vestitum* were found in all three sections, *Mendicodinium groenlandicum* was recorded at Mareta Beach and *Rigaudella* spp. were encountered at Baleeira Harbour and Telheiro Quarry. The range bases of all these forms are intra-Callovian. The presence throughout of consistent *Gonyaulacysta jurassica* subsp. *adecta* is also highly characteristic of the Callovian. The occurrences of *Endoscrinium acroferum* and *Impletosphaeridium varispinosum* in the Lower to Middle Callovian of Mareta Beach and Telheiro Quarry are also typical of this interval. *Gonyaulacysta eisenackii* was recorded from the Middle Callovian of Mareta Beach, which is consistent with the range base of this species elsewhere. In the Baleeira Harbour section, the occurrences of *Ctenidodinium continuum* and *Gonyaulacysta centriconnata* are indicative of a Late Callovian age, which is consistent with the evidence from ammonites. *Ctenidodinium cornigerum* was encountered in the Middle and Upper Callovian at Baleeira Harbour and Mareta Beach. These records represent the youngest reports of this Tethyan taxon.

The 59 productive Callovian samples from the Algarve Basin studied herein have yielded relatively abundant dinoflagellate cyst assemblages of moderate diversity. They compare well in terms of taxonomic spectrum and relative proportions to those reported from the Iberian Peninsula by Smelror et al. (1991) and Borges et al. (2011), however are markedly less diverse than coeval floras from northern Europe. Borges et al (2011) contended that the relatively low diversity nature of the Callovian dinoflagellate cyst assemblages from the Algarve Basin is due to the highly enclosed nature of this depocentre. The successions studied represent deposition in infralittoral neritic environments, possibly restricted bays which lack deep water circulation. The macrofaunas are dominated by nektonic and planktonic forms such as ammonites and belemnites; benthonic forms are very scarce or entirely absent (Rocha, 1976). Living cyst-producing dinoflagellates thrive and are most diverse in shallow shelfal environments, especially in estuarine-neritic settings, and many forms are adapted to unstable-unpredictable regimes (Wall et al., 1977). Despite this, it is contended that the relatively restricted nature of the Algarve Basin during the Callovian explains the low diversity dinoflagellate cyst associations. Typically Callovian species which were not recorded here, such as *Scriniodinium crystallinum* and *Trichodinium scarburghense,* may have been especially sensitive to enclosed depositional settings.

Acknowlegements

The contribution of Marisa E.N. Borges represents part of PhD scholarship number SFRH/BD/40428/2007 awarded by the Portuguese Foundation for Science and Technology. This study is also a contribution to the project entitled ‘Hydrocarbon source-rock potential of the Algarve Basin’ (PTDC/CTE-GEX/72694/2006), also funded by the Portuguese Foundation for Science and Technology. The input of James B. Riding was completed under BGS Individual Merit project entitled *Global Jurassic dinoflagellate cyst palaeobiology and its applications*. Drs Javier Helenes (CICESE, Mexico) and Daniel J. Mantle (Morgan Goodall Palaeo Associates, Australia) are thanked for their very constructive reviews of an early draft of the manuscript. James B. Riding publishes with the approval of the Executive Director, British Geological Survey (NERC).

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Appendix 1

This Appendix lists all the palynomorph taxa below generic level which were recovered from the material studied herein with full author citations. The palynomorphs are listed alphabetically within their constituent groups. References to the dinoflagellate cyst author citations can be found in Fensome and Williams (2004). With regard to Figs. 3-5, the informal grouping where the respective form/taxon has been placed is indicated in parentheses where appropriate.

Dinoflagellate cysts:

Adnatosphaeridium caulleryi (Deflandre 1938) Williams & Downie 1969 (chorate cysts)

Chytroeisphaeridia chytroeides (Sarjeant 1962) Downie & Sarjeant 1965

Ctenidodinium continuum Gocht 1970 (*Ctenidodinium* spp.)

Ctenidodinium cornigerum (Valensi 1953) Jan du Chêne et al. 1985 (*Ctenidodinium* spp.)

Ctenidodinium ornatum (Eisenack 1935) Deflandre 1938 (*Ctenidodinium* spp.)

Ctenidodinium sellwoodii (Sarjeant 1975) Stover & Evitt 1978 (*Ctenidodinium* spp.)

Endoscrinium acroferum (Prauss 1989) Riding & Fensome 2002

Epiplosphaera gochtii (Fensome 1979) Brenner 1988 (cysts with apical archaeopyles)

Gonyaulacysta centriconnata Riding 1983 (*Gonyaulacysta* and relatives)

Gonyaulacysta eisenackii (Deflandre 1938) Górka 1965 (*Gonyaulacysta* and relatives)

Gonyaulacysta jurassica (Deflandre 1938) Norris & Sarjeant 1965 subsp. *adecta* Sarjeant 1982 (*Gonyaulacysta* and relatives)

Gonyaulacysta jurassica (Deflandre 1938) Norris & Sarjeant 1965 subsp. *adecta* Sarjeant 1982 var. *longicornis* (Deflandre 1938) Downie & Sarjeant 1965 (*Gonyaulacysta* and relatives)

Impletosphaeridium varispinosum (Sarjeant 1959) Islam 1993 (chorate cysts)

Korystocysta gochtii (Sarjeant 1976) Woollam 1983 (*Korystocysta* spp.)

Korystocysta pachyderma (Deflandre 1938) Woollam 1983 (*Korystocysta* spp.)

Liesbergia liesbergensis Berger 1986

Meiourogonyaulax caytonensis (Sarjeant 1959) Sarjeant 1969 (cysts with apical archaeopyles)

Mendicodinium groenlandicum (Pocock & Sarjeant 1972) Davey 1979

Pareodinia ceratophora Deflandre 1947 (*Pareodinia* spp.)

Rhynchodiniopsis? *regalis* (Gocht 1970) Jan du Chêne et al. 1985 (*Gonyaulacysta* and relatives)

Surculosphaeridium? *vestitum* (Deflandre 1938) Davey et al. 1966 (chorate cysts)

Systematophora areolata Klement 1960 (chorate cysts)

Systematophora penicillata (Ehrenberg 1843 ex Ehrenberg 1854) Sarjeant 1980 (chorate cysts)

Tubotuberella dangeardii (Sarjeant 1968) Stover & Evitt 1978 (*Gonyaulacysta* and relatives)

Wanaea acollaris Dodekova 1975

Pteridophyte spores:

Ischyosporites variegatus (Couper 1958) Schulz 1967

Leptolepidites rotundus Tralau 1968

Sestrosporites pseudoalveolatus (Couper 1958) Dettmann 1963

Gymnospermous pollen:

Callialasporites dampieri (Balme 1957) Sukh Dev 1961

Callialasporites minus (Tralau 1968) Guy 1971

Callialasporites trilobatus (Balme 1957) Sukh Dev 1961

Callialasporites turbatus (Balme 1957) Schulz 1967

Classopollis classoides (Pflug 1953) Pocock & Jansonius 1961

Perinopollenites elatoides Couper 1958

Appendix 2

This Appendix alphabetically lists all the dinoflagellate cyst taxa below generic level mentioned in this contribution, but not recovered from the material studied herein, with full author citations. References to the author citations can be found in Fensome and Williams (2004).

Aldorfia aldorfensis (Gocht 1970) Stover & Evitt 1978

Chytroeisphaeridia cerastes Davey 1979

Chytroeisphaeridia hyalina (Raynaud 1978) Lentin & Williams 1981

Clathroctenocystis asaphes (Drugg 1978) Stover & Helby 1987

Compositosphaeridium? *polonicum* (Górka 1965) Lentin & Williams 1981

Ctenidodinium combazii Dupin 1968

Endoscrinium galeritum (Deflandre 1938) Vozzhennikova 1967

Evansia dalei (Smelror & Århus 1989) Below 1990

Evansia perireticulata (Århus et al. 1989) Lentin & Williams 1993

Fromea tornatilis (Drugg 1978) Lentin & Williams 1981 [listed as an acritarch in Fensome and Williams (2004, appendix A)]

Kalyptea stegasta (Sarjeant 1961) Wiggins 1975

Lacrymodinium warrenii Albert at al. 1986

Limbodinium absidatum (Drugg 1978) Riding 1987

Meiourogonyaulax valensii Sarjeant 1966

Nannoceratopsis pellucida Deflandre 1938

Pareodinia prolongata Sarjeant 1959

Paraevansia brachythelis (Fensome 1979) Below 1990

Paragonyaulacysta calloviensis Johnson & Hills 1973

Paragonyaulacysta retiphragmata Dörhöfer & Davies 1980

Rhynchodiniopsis cladophora (Deflandre 1938) Below 1981

Rigaudella aemula (Deflandre 1938) Below 1982

Scriniodinium crystallinum (Deflandre 1939) Klement 1960

Sirmiodiniopsis orbis Drugg 1978

Sirmiodinium grossii Alberti 1961

Ternia balmei Helby & Stover 1987

Trichodinium scarburghense (Sarjeant 1964) Williams et al. 1993

Valvaeodinium leneae Piasecki 2001

Valvaeodinium thereseae Smelror 1991

Wanaea thysanota Woollam 1982

Display material captions:

Fig. 1. The location and geology of the Algarve Basin, illustrating the three sections studied herein, and the geographical extents of the western (Sagres), Budens-Lagoa and Eastern (Faro) subbasins (adapted from Manuppella, 1992).

Fig. 2. The locations of the three sections investigated herein. The left-hand map illustrates the geology of the Western (Sagres) Subbasin of the Algarve Basin and the locations of the sections at Baleeira Harbour and Mareta Beach (after Manuppella and Perdigão, 1972). The geology of the Estoi area, near Loulé, north of Faro, in the Eastern Subbasin of the Algarve Basin and the location of Telheiro Quarry is illustrated in the right-hand panel.

Fig. 3. Lithological log of the Lower Callovian section at Telheiro Quarry, southeast of Loulé in the Eastern Subbasin of the Algarve Basin, modified from Marques and Rocha (1988a, fig. 1) with sample positions. The relative proportions of the 10 main palynomorph groups, expressed as percentages of the overall palynoflora, are illustrated. Note that samples TL20 to TL31 inclusive are palynologically barren.

Fig. 4. Lithological log of the Lower to Upper Callovian section at Mareta Beach, south of Sagres in the Western (Sagres) Subbasin of the Algarve Basin, modified from Borges et al. (2011, fig. 4) with sample positions. The relative proportions of the 10 main palynomorph groups, expressed as percentages of the overall palynoflora, are illustrated.

Fig. 5. Lithological log of the Upper Callovian section at Baleeira Harbour, south of Sagres in the Western (Sagres) Subbasin of the Algarve Basin, modified from Rocha (1976) with sample positions. The relative proportions of the 10 main palynomorph groups, expressed as percentages of the overall palynoflora, are illustrated.

Fig. 6. A palaeogeographical map of the world for the Callovian (164.7-161.2 Ma) modified from Smith and Briden (1977) illustrating the extents of the Arctic, Mid Latitude and Austral dinoflagellate cyst phytoprovinces as defined herein, and the position of the Algarve Basin (asterisked). The dots indicate the localities of the principal published studies on Callovian dinoflagellate cysts in each of the three dinoflagellate cyst phytoprovinces.

Table 1. The palynomorph assemblages from the Lower Callovian section at Telheiro Quarry, southeast of Loulé in the Eastern Subbasin of the Algarve Basin. The numbers represent the percentages of the respective taxon within the overall palynoflora. Pras. = prasinophytes. Var. = various.

Table 2. The palynomorph assemblages from the Lower to Upper Callovian section at Mareta Beach, south of Sagres in the Western (Sagres) Subbasin of the Algarve Basin. The numbers represent the percentages of the respective taxon within the overall palynoflora. Pras. = prasinophytes. Var. = various.

Table 3. The palynomorph assemblages from the Upper Callovian of Baleeira Harbour, south of Sagres in the Western (Sagres) Subbasin of the Algarve Basin. The numbers represent the percentages of the respective taxon within the overall palynoflora. Pras. = prasinophytes. Var. = various.

Table 4. A semiquantitative compilation of the occurrences of 28 key dinoflagellate cyst taxa/groups throughout the Callovian of the Algarve Basin from the three successions studied herein. AB = abundant (>10%); C = common (5-10%); P = present (1-5%); R = rare (<1%). The taxa/groups which are in bold font have biostratigraphical significance.

Plate I. Selected dinoflagellate cysts from the Lower, Middle and Upper Callovian of Baleeira Harbour, Mareta Beach and Telheiro Quarry in the Algarve Basin, southern Portugal. All specimens are housed in the collections of the LGM/LNEG (Portugese Geological Survey), S. Mamede Infesta, Portugal. The sample number, slide number and England Finder coordinates are provided.

1, 2, 5. *Gonyaulacysta jurassica* (Deflandre 1938) Norris & Sarjeant 1965 subsp. *adecta* Sarjeant 1982. 1 - Baleeira Harbour, Upper Callovian, sample BA25, slide 2, N25/2. 2 - Telheiro Quarry, Lower Callovian, sample TL10, slide 1, R25/4. 5 - Baleeira Harbour, Upper Callovian, sample BA26, slide 1, Q15/3.

3, 4. *Tubotuberella dangeardii* (Sarjeant 1968) Stover & Evitt 1978. 3 - Mareta Beach, Lower Callovian, sample M27, slide 1, N65/3. 4 – an elongate, spinose specimen from Telheiro Quarry, Lower Callovian, sample TL10, slide 2, N45/4.

6, 8. *Ctenidodinium sellwoodii* (Sarjeant 1975) Stover & Evitt 1978 group. 6 - Baleeira Harbour, Upper Callovian, sample BA10, slide 2, S15. 8 - Telheiro Quarry, Lower Callovian, sample TL10, slide 1, O41.

7, 10. *Endoscrinium acroferum* (Prauss 1989) Riding & Fensome 2002. 7 - Telheiro Quarry, Lower Callovian, sample TL12, slide 1, K23/2. 10 - Telheiro Quarry, Lower Callovian, sample TL17, slide 1, K35/1.

9, 13. *Ctenidodinium cornigerum* (Valensi 1953) Jan du Chêne et al. 1985. 9 - Baleeira Harbour, Upper Callovian, sample BA23, slide 1, T13/4. 13 - Baleeira Harbour, Upper Callovian, sample BA10, slide 1, W40.

11. *Ctenidodinium ornatum* (Eisenack 1935) Deflandre 1938. Mareta Beach, Middle Callovian, sample M47, slide 1, D54.

12. *Ctenidodinium continuum* Gocht 1970. Baleeira Harbour, Upper Callovian, sample BA24, slide 1, N32.

Plate II. Selected dinoflagellate cysts from the Lower, Middle and Upper Callovian of Baleeira Harbour, Mareta Beach and Telheiro Quarry in the Algarve Basin, southern Portugal. All specimens are housed in the collections of the LGM/LNEG (Portugese Geological Survey), S. Mamede Infesta, Portugal. The sample number, slide number and England Finder coordinates are provided.

1. *Pareodinia ceratophora* Deflandre 1947. Baleeira Harbour, Upper Callovian, sample BA10, slide 1, M14.

2, 3. *Korystocysta gochtii* (Sarjeant 1976) Woollam 1983. 2 - Mareta Beach, Lower Callovian, sample M27, slide 1, M51/3. 3 – Baleeira Harbour, Upper Callovian, sample BA9, slide 1, U44/1.

4. *Epiplosphaera gochtii* (Fensome 1979) Brenner 1988. Baleeira Harbour, Upper Callovian, sample BA9, slide 2, N24/3.

5. *Chytroeisphaeridia chytroeides* (Sarjeant 1962) Downie & Sarjeant 1965. Mareta Beach, Lower Callovian, sample M28, slide 1, K62/4.

6. *Korystocysta pachyderma* (Deflandre 1938) Woollam 1983. Mareta Beach, Upper Callovian, sample M32, slide 1, O14/3.

7. *Impletosphaeridium varispinosum* (Sarjeant 1959) Islam 1993. Mareta Beach, Lower Callovian, sample M27, slide 1, O31.

8. *Systematophora areolata* Klement 1960. Mareta Beach, Middle Callovian, sample M75, slide 1, Q7.

9. *Surculosphaeridium*? *vestitum* (Deflandre 1938) Davey et al. 1966. Telheiro Quarry, Lower Callovian, sample TL10, slide 1, Q42/1.

10. *Meiourogonyaulax caytonensis* (Sarjeant 1959) Sarjeant 1969 group. Baleeira Harbour, Upper Callovian, sample BA23, slide 1, R31/1.

11. *Adnatosphaeridium caulleryi* (Deflandre 1938) Williams & Downie 1969. Telheiro Quarry, Lower Callovian, sample TL10, slide 1, T30/4.

12. *Wanaea acollaris* Dodekova 1975. Mareta Beach, Middle Callovian, sample M45, slide 1, Q37/2.