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The upper Hauterivian–Barremian (Lower Cretaceous) Arrifes section (Algarve Basin, Southern Portugal): A palynostratigraphic and palaeoenvironmental approach

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A B S T R A C T

Integrated sedimentological, palynological, and palynofacies analyses of the Arrifes section in the central Algarve Basin (southern Portugal) provided new information on the age and environments of this Lower Cretaceous sequence. The sedimentary succession at the Arrifes section consists of fossiliferous interbedded limestones, marly limestones, and marls, dated as latest Hauterivian to late Barremian age (Lower Cretaceous) based on key dinoflagellate taxa. During this interval, the Arrifes area records climatic shifts and, multiple sea-level fluctuations; overall deposition was in shallow subtidal to intertidal settings, with deposition of carbonate and marly sediments. During the latest Hauterivian to earliest Barremian interval, an evident sea-level fall culminated in the subaerial exposure of the local carbonate ramp with increased influx of clastic sediments. However, during the Barremian, both sedimentological and palynological analyses suggest an overall deepening of the water depth towards the top of the section. These overall increase in the water column are confirmed by oscillation of terrestrial/marine palynomorph groups and supported by dinosaur track levels at the top of the succession; the latter indicate that sedimentation occurred in intertidal to subtidal environments. Finally, an attempt was made to correlate the Arrifes section with other sections from the Algarve Basin, as well as with broader region. These new data suggest a setting in the Tethyan basin influenced during the latest Hauterivian to the end of the Barremian. These new data allow local correlations and new palynological ages and paleoenvironmental interpretations for the Lower Cretaceous succession of the Algarve Basin.

1. Introduction and rationale

The Algarve Basin is a Mesozoic-Cenozoic basin located in southern Portugal, cropping out along the entire south coast, from Cape Saint Vincent in the west to the Portuguese–Spanish border in the east (Fig. 1). Lower Cretaceous successions crop out all extensively in this broad area; however, few palynostratigraphic and palaeoenvironmental studies have been carried out.

The earliest micropaleontological, stratigraphic, and lithostratigraphic studies were by Ramalho (1971), Rey (1972, 1979a, 1979b, 1983, 1984, 1986), Rey and Ramalho (1974), and Ramalho and Rey (1981). In the last decades of the twentieth century, Berthou and Leereveld (1986, 1990) provided the first studies of the Berriasian to Albian deposits in the Algarve and the Lusitanian basins, with emphasis on the use of dinoflagellate cysts. More recently, Heimhofer et al. (2007) documented the diversification of early angiosperm pollen during the late Barremian to middle Albian of the Cretaceous Portuguese basins, including the Algarve Basin.

Extensive biostratigraphic studies have been carried out in the Lower Cretaceous onshore succession of the Lusitanian Basin (e.g., Groot and Groot, 1962; Médus and Berthou, 1980; Berthou et al.,

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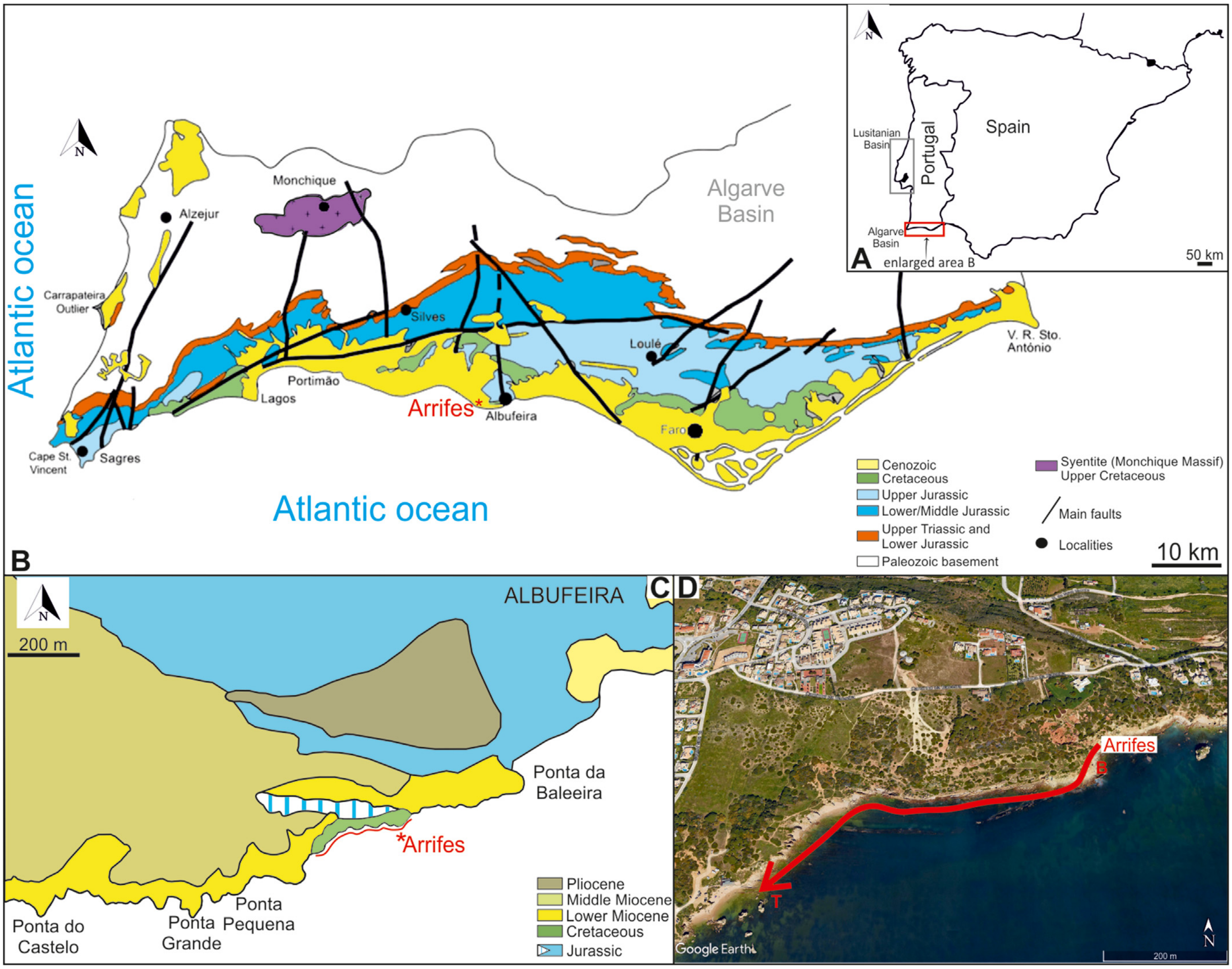


Fig. 1. A – Iberian Peninsula with Lusitanian Basin (grey) and Algarve Basin (red) shown as boxes (adapted from Oliveira et al., 1992); B – General geology of the Algarve Basin; C – Simplified geological map of the Albufeira region showing the location of the Arrifes section (adapted from Rocha et al., 1989); D – Location of the study area along the Arrifes section (red arrow indicates stratigraphic sequence younging to the west; B = base and T = top of the Arrifes section). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

1981; Hasenboehler, 1981; Médus, 1982; Berthou and Hasenboehler, 1982; Heimhofer et al., 2012; Mendes et al., 2017). Additionally, several works in the offshore region focused on dinoflagellate cyst biostratigraphy (e.g., Habib, 1979; Taugourdeau-Lantz et al., 1982; Masure, 1984, 1988). Nevertheless, Lower Cretaceous successions of the Algarve Basin still lack detailed aged assessments, and regional palaeoenvironment models are often contradictory or challenging to interpret (e.g., Rey and Ramalho, 1974; Rey, 2006; Dinis et al., 2020).

According to the latest research, Dinis et al. (2020) supported the prevalence of drier climatic conditions from the late Hauterivian to early Barremian (based on clay mineralogy and whole-rock geochemistry), with conditions becoming increasingly humid into the Aptian. Ruffell and Batten (1990) also documented this progressive humidity increase, contrary to the interpretations of Rodríguez-López et al. (2006). Another challenge concerns the lack of a formal lithostratigraphic scheme for the Arrifes section, which has been considered as a key section for the concerned interval in southwest Iberian range.

The present work is the first detailed and integrated sedimentological, palynological and palynofacies study of the Lower Cretaceous Arrifes section of the Algarve Basin.

We aim to: i) establish a detailed age framework using palynostratigraphy; ii) characterise qualitatively and quantitatively the palynomorph and palynofacies assemblages to provide additional data for interpretation of the depositional setting and paleoenvironments; iii) contribute to the development of bioevent-based age of the Lower Cretaceous of the Algarve Basin; and iv) correlate the data with interregional information known for the Iberia Peninsula and other regions of the Tethyan Realm during this interval.

2. Geologic setting and stratigraphy

The Algarve Basin is located in southernmost Portugal and comprises sedimentary and volcanic rocks ranging from the Upper Triassic to Recent. The exposed tectonic inverted part of this basin trends east-west and extends ca. 140 km from the Atlantic Coast to the Portuguese–Spanish border, having a maximum width of about 25 km (Terrinha et al., 2013) (Fig. 1). The Algarve Basin's sedimentary rocks lie above folded and faulted Carboniferous metasedimentary rocks of the Variscan South Portuguese Zone (Oliveira, 1990). The Mesozoic succession of the Algarve Basin begins with Carnian to Hettangian continental red beds deposits, volcanic sedimentary rocks and evaporites (Silves Group) (Vilas-Boas et al., 2022), followed upsection by mainly marine carbonates ranging in age from Lower Jurassic to Upper Cretaceous (Rey and Ramalho, 1974; Rocha, 1976; Rocha et al., 1983, 1989; Manuppella, 1992). The Mesozoic succession records depositional environments and tectonic structures of the initial rifting phases related to the breakup of Pangea, followed by the formation and development of carbonate platforms on a passive continental margin.

The Lower Cretaceous succession (Fig. 2), can be divided into three major sectors: Western, Central, and Eastern Algarve (Rey, 2006, 2009). For each sector, several lithostratigraphic units are recognised and correlated (Fig. 2).

The studied section in this work is part of the Central Algarve sector. It is 194 m thick and its uplifted, subvertical strata form the seashore cliffs that outcrop between Praia dos Arrifes and Ponta da Baleeira, located ca. 2 km southwest of the town of Albufeira (Fig. 1). For simplicity hereafter, the studied section will be referred to as the Arrifes section. The sectionconsists of interbedded fossiliferous limestones, variegated marls and mudstones, and minor sandstones and conglomerates (Correia, 1989; Descamps, 2021). The whole succession is tilted vertically due to the post-Lower Cretaceous halokinetic movements of the Albufeira Diapir, located north of the Arrifes section (Terrinha, 1998; Ramos et al., 2016) (Fig. 1). Horizontal Miocene fossiliferous limestones unconformably overlie the vertical Lower Cretaceous beds (Terrinha et al., 2006). Post-Miocene karstification processes affected both Lower Cretaceous and Miocene limestones (Terrinha et al., 2006).

The lack of ammonite-bearing shelf carbonate facies in the Lower Cretaceous strata of the Algarve Basin prevents the use of

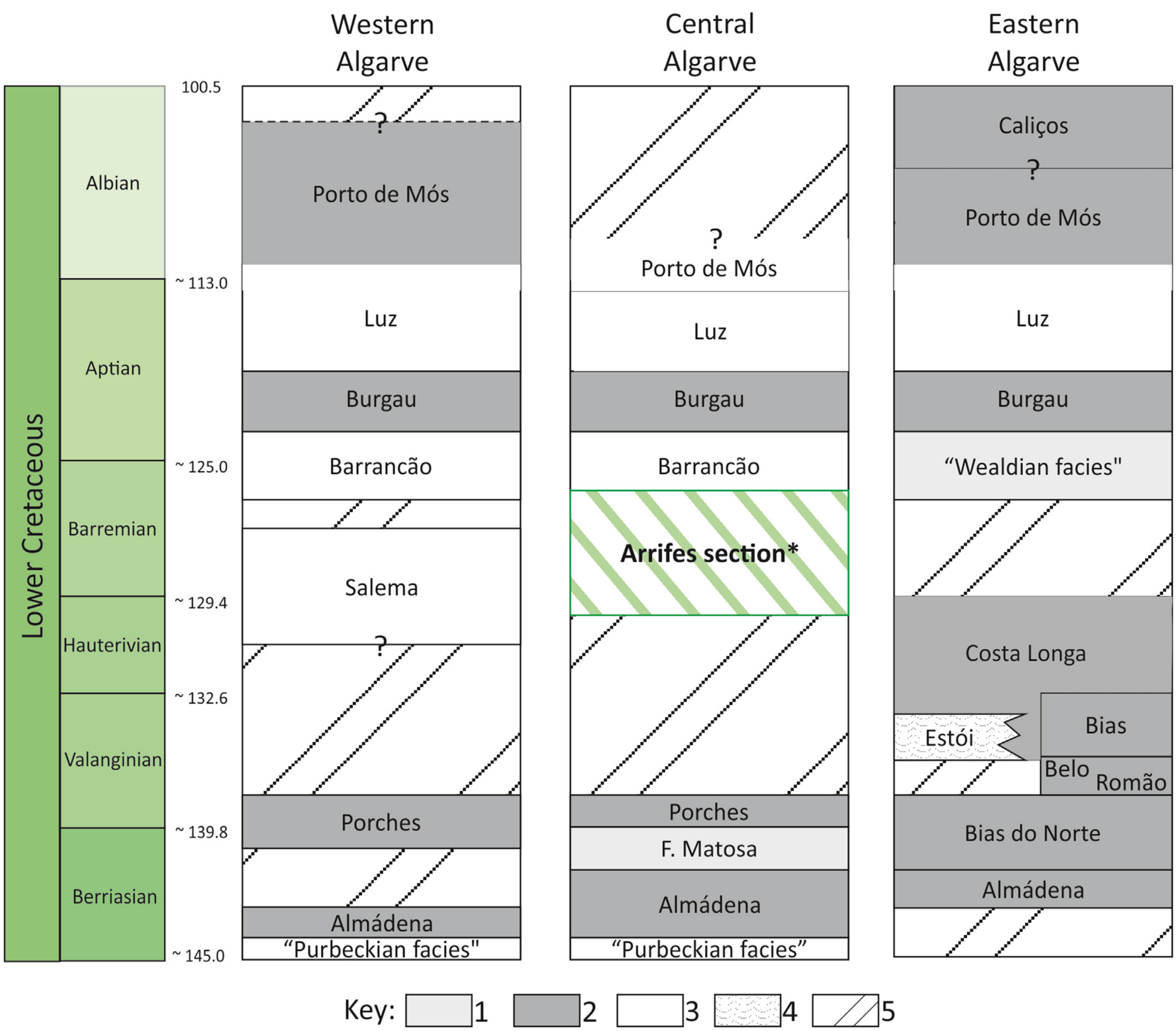


Fig. 2. Lithostratigraphic scheme for the Lower Cretaceous of the Algarve Basin. 1. Fluvial siliciclastic deposits; 2. Lagoon carbonated deposits; 3. Marine carbonated deposits; 4. Marine conglomerates; 5. Stratigraphic hiatus (adapted from Terrinha et al., 2013). *Stratigraphic interval assigned to the Arrifes section in this study. The Arrifes section is included in no. 3 of the key: marine carbonated deposits and is correlated to the Salema Formation.

this fossil group as the primary biostratigraphic tool. The age determinations of these strata have been assessed mainly through micropaleontological studies, but palynological studies are scarce (e.g., Berthou and Leereveld, 1990; Heimhofer et al., 2003, 2007). The most relevant micropaleontological (foraminifera-based) and stratigraphic studies were by Rey (1972, 1979a, 1979b, 1983, 1984, 1986), Ramalho (1971), Rey and Ramalho (1974), and Ramalho and Rey (1981). Berthou and Leereveld (1986, 1990) were first to study to use dinoflagellate cysts to the Berriasian to Albian deposits in the Algarve Basin, as well as the Lusitanian Basin of western-central Portugal (Fig. 1). More recently, Hochuli et al. (2006) and Heimhofer et al. (2007) presented palynological studies focused on the Luz and Porto de Mós formations with assemblages correlative of the lower Aptian and lower Albian, respectively.

The Arrifes section has not been assigned formal stratigraphic units (Figs. 2, 3). However, using lithologies and presumed stratigraphic positions, Rey and Ramalho (1974) correlated the section to an informal stratigraphic unit, named as "Marls, Limestones and Dolostones with *Chofatella decipiens*". Later, Berthou et al. (1983) recorded the presence of the foraminifer *Orbitulina* (*Mesorbitolina*) *parva* and assigned a late Aptian age for this section. Likewise, Correia (1989) described the Arrifes section (named as Arrifão in the later work) and recorded the foraminifer *Orbitulina* (*Mesorbitolina*) *parva* in a bed located ca. 30 m above the base of the section. Accordingly, Correia (1989) considered the entire section as Aptian in age. The latter author also interpreted the sedimentary succession at the Arrifes section as a transgressive megasequence, with subsidence and deep-water sedimentary environments increasing upsection.

Rey (2006) formalised the Lower Cretaceous stratigraphic units of Western Algarve and divided the "Marls, Limestones and Dolostones with *Chofatella decipiens*" unit, into two new stratigraphic units, from base to top: the Salema Formation (upper Hauterivian to lower Barremian), and the Barrancão Formation (upper Barremian to lower Aptian). According to Rey (2006), the two formations are separated by an angular unconformity due to intra-Barremian tectonism. In the correlation charts proposed for the entire Lower Cretaceous strata of the Algarve Basin (Rey, 2006, 2009), only the Barrancão Formation was recognised in Central Algarve, emphasising an extensive sedimentary hiatus between early Valanginian to late Barremian time in this sector. In Eastern Algarve, the Barrancão Formation correlates with the "Wealdian Facies" beds (Fig. 2).

Despite these advances in the regional Mesozoic stratigraphy, the Arrifes section is still challenging to correlate to formal stratigraphic units. Discussion of the section's stratigraphy has increased since Santos et al. (2013, 2016) recognised the similarity between dinosaur track sites there and those in the Lower Cretaceous Salema Formation at the type locality of Salema Beach (Western Algarve) suggesting that two sedimentary sections are correlative (Santos et al., 2013).

3. Materials and methods

The Arrifes section crops out along the coastal cliffs west of Albufeira (Fig. 1) where it was logged and systematically sampled for palynology and palynofacies purposes. The base of the stratigraphic sequence is at N37°04′43.12″; W8°16′11.10″ and the top at N37°04′35.33″; W8°16′35.54″. The entire section has a total thickness of 194 m, and consists of mainly of marls, limestones, marly limestones, minor sandstones and conglomerates.

Forty-eight (48) samples of marls and marly limestones of approximately 50 g of weight each were prepared for palynological and palynofacies study at the University of Algarve (UALG). All samples were processed according to palynological standard procedures (Wood et al., 1996), using hydrochloric and hydrofluoric acids to remove the inorganic components (carbonate and silicate minerals, respectively). Residues were sieved using a 15 μm screen, and those used for palynological identification were stained with safranin–O to enhance the morphological features. Residues used for palynology and palynofacies were mounted on microscope slides using Entelan®, a commercial resin-based mounting medium. Of the total samples processed, 17 were considered productive for palynological analysis. Of these 17, five samples proved to be very poor, with badly preserved palynomorphs, with many of which were unidentifiable (samples P0002.1, P0028.1, P071.1, P0108.1, P158.1, Tables S1 and S2).

All palynological slides were examined, qualitatively and quantitatively, under a Nikon Eclipse Ci transmitted light microscope. For quantitative analysis, a total of 250 palynomorphs were counted for each sample and are evaluated in the following categories: rare (<1–5%), common (6–10%), frequent (11–20%), abundant (21–40%), and superabundant (>40%). In addition, to determine major taxonomic variation, the Peridianales to Gonyaulacales value (P:G) ratio and sporomorphs to dinoflagellate cyst ratio (SP:D) were employed to explore paleoenvironmental changes and estimate the relative terrigenous influence throughout the succession. The overall counts and all taxa per sample are listed in Table S1 (*supplementary material*). Certain taxa have been summed under a group names, for environmental and ecological purposes, adapted and following the work Carvalho et al. (2016). In their work they stablished four dinoflagellate cyst communities (in upper Aptian strata from Sergipe Basin, Brazil) distinguished using cluster analysis to identify ecological similarities between palynomorph + communities from different paleoenvironments and palaeoceanographic settings. For simplicity, we adapted the community names to the following groups: *Oligosphaeridium* group (*Oligosphaeridium* + *Systematophora*), *Cyclonephelium* group (*Cyclonephelium* + *Exochosphaeridium* + *Pseudoceratium* + *Odontochitina*), *Spiniferites* group (*Spiniferites* + *Florentinia* + *Trichodinium*), *Subtilisphaera* group (*Subtilisphaera* + *Cribroperidinium*).

The results are plotted in diagram Tilia 2.6.1 software (Grimm, 1991) and subdivided into three assemblages based on stratigraphical key dinoflagellate cyst taxa. A constrained cluster analysis using the total sum of squares (CONISS: Grimm, 1987; Gill et al., 1993) was performed to detail the palaeoenvironment conditions.

Stratigraphically relevant taxa are presented and illustrated from Figures 8 to 10. In total, 91 genera and 50 species were identified. The nomenclature of dinoflagellate cyst species and suprageneric classification follows Fensome et al. (1993, 2008), and the descriptive morphological terminology follows Williams et al. (2017a, 2017b, 2019 and references therein). The dinoflagellate cyst biozonation follows Leereveld (1997) and Habib (1975, 1977), established for southern Europe's Lower Cretaceous Tethyan province. The sporomorph classification follows Trincão (1990), detailing the spore-pollen content in the Lower Cretaceous for the Portuguese Basins.

The recovery of organic matter for all 48 samples facilitated palynofacies analysis (Table S2), which was used to determine the nature of the depositional environments. During this analysis, the identification and general description of the palynological components were as follows: 1) phytoclasts; 2) terrigenous palynomorphs—spores and pollen grains; 3) marine palynomorphs—organic-walled dinoflagellate cysts, prasinophytes and foraminiferal linings; and 4) amorphous organic matter (AOM). The size, shape, and state of preservation of organic matter was considered.

This classification scheme is an adaptation of that of Tyson (1993, 1995). The description of the dispersed sedimentary

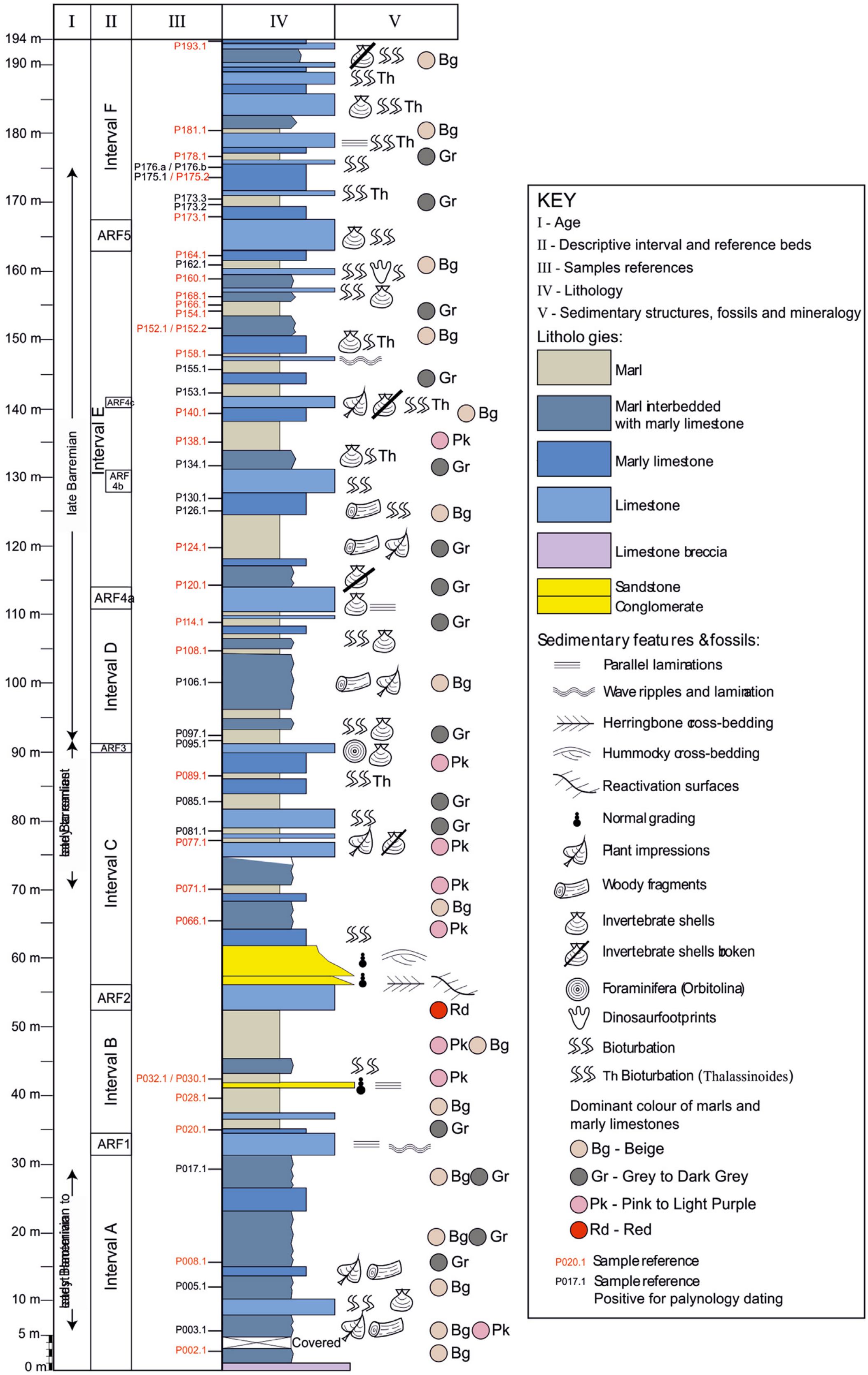
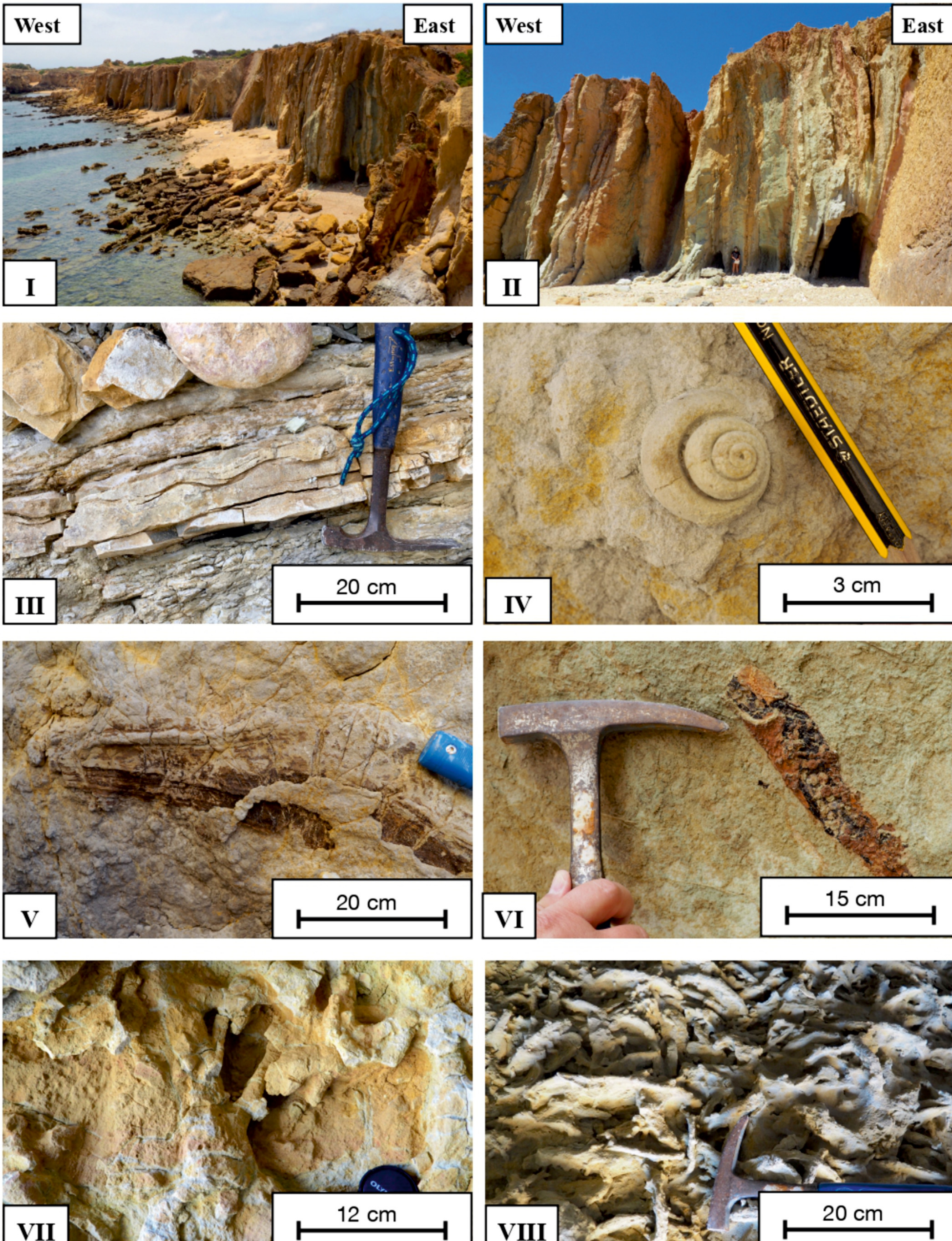


Fig. 3. Stratigraphic log of Arrifes succession, with the position of the studied samples, the age of the sequence, the lithologic intervals, reference beds, interpretation of the depositional settings in the carbonate ramp and sea level changes. Sample labels in black yielded palynomorphs used for palynostratigraphic dating, and sample labels in red characters were non-productive for palynostratigraphy and used only for palynofacies analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)


West
East
I
West
East
II
20 cm
III
3 cm
IV
20 cm
V
15 cm
VI
12 cm
VII
20 cm
VIII

organic matter components is summarised in Table S3 (Supplementary material).

The quantitative palynofacies approach involved a count of 250 organic particles per slide, performed using an Olympus BX51 microscope equipped with a digital camera (Olympus XC-50) and a metal halide lamp fluorescence unit XCite Series 120Q with violet and Blue þ12 filter block that yields a wavelength band of 390−490 nm. This system was allowed to stabilise for 15 min prior to any observation using fluorescence.

Palynological and palynofacies samples and residues are housed at University of Algarve, while all the palynological slides are housed in the Palynological Collection of National Energy and Geology Laboratory, Portugal.

4. Lithological descriptions and paleoenvironmental interpretations

The sedimentary succession at Arrifes consists mainly of shallow subtidal to intertidal carbonates and marls. The vertical organisation of the different lithologies and the palynological and palynofacies results were integrated when interpreting the sedimentary environments (see Section 7 (Discussion)). To facilitate lithological description and understanding of the depositional environments and their evolution, the Arrifes sequence has been divided into six descriptive intervals from A to F (Fig. 3). The boundaries between the intervals correspond to reference beds (ARF1 to ARF5) consisting of compacted micritic or bioclastic limestones. Due to the contrast in hardness between the reference beds and the interbedded marls and marly limestones, the basal units stand out on the cliff faces due to differential erosion through waves action, making them easy to recognise.

Interval A (0 m to the base of bed ARF1) begins with an ill-sorted monomictic breccia bed formed by limestone clasts, exhibiting an orange to pale red colour. The limestone clasts vary significantly in size from sand to pebble grade, are angular to subrounded, and show a clast-supported texture. This grainstones bed is slightly dolomitised, chaotic and nongraded, with a thickness over 2 m. It is partly eroded and unconformably covered by subhorizontal Miocene bioclastic limestones, making its original thickness impossible to assess. The origin of this breccia is likely due to subaerial exposure and karstification processes before the deposition of the Miocene limestones and thus its nature does not reflect an original sedimentary feature. Above the limestone breccia bed and up to the base of reference bed ARF1 is a ca. 32 m thick succession, consisting mainly of marls and marly limestones interbedded with a 2 m thick bioclastic limestone. The marls − marly limestone couplets contain broken shell fragments, plant impressions, small wood debris and bioturbation. The sediment becomes increasingly darker and marl dominated towards the top of the interval. The interbedded bioclastic limestone in this last interval shows bioturbation.

Interval B (from the base of bed ARF1 to the top of bed ARF2) starts with reference bed ARF1, which consists of ca. 4 m thick limestone showing wave and parallel laminations. Marls and marly limestones dominate the interval between reference beds ARF1 and ARF2, showing red and purple colouration with smears and spots of green to beige. Some beds show discrete carbonate nodules. Sedimentary structures and fossils are scarce, apart from *Thalassinoides* burrows. The dominant red colouration and the mottled appearance in this interval indicate redox reactions in the sediments, likely related to regular exposure to subaerial conditions. Near the middle part of this interval occurs an 80 cm thick sandstone bed showing normal grading, wave, and parallel laminations. The reference bed ARF2 consists of 3.9 m thick light-grey limestone. In the top part of this limestone bed contains khaki-brown nodules of iron oxides and calcite.

Interval C (from the top of bed ARF2 to the top of bed ARF3) begins with a ca. 5.7 m thick interval consisting of amalgamated buff quartz sandstone and conglomerate beds with calcite cement. The conglomerates (granule to pebble size) at the base of this interval sit on an erosive surface, are clast supported and are positioned at the base of normal graded beds. The clasts of the conglomerates are well-to sub-rounded. The sandstones are coarse-to fine-grained and show normal grading. The beds are amalgamated and have erosive bases. Tidal current structures (reactivation surfaces and herringbone cross-stratification) are dominant. Wave cross-laminae, hummocky-cross stratification (HCS), and parallel laminations were also observed at the top of this clastic interval. The fine-grained sandstone beds show moderate bioturbation.

The sequence above the last clastic interval up to the base of reference bed ARF3, is ca. 28 m thick, at the base it comprises marls and marly limestones couplets, in the middle it is dominated by bioturbated bioclastic limestones, and in its upper it consists of marls and heavily bioturbated marly limestones (Fig. 4.VIII). The lower marl beds are reddish with oxidation patches, and the beds become greyer towards the upper part of interval C. The thinly bedded marls interbedded with the limestones yield plant remains, and *Thalassinoides* burrows are common in the marly limestones in the upper part of the interval. The reference bed ARF3, which occurs towards the middle part of the Arrifes sequence, is easily recognised. It consists of a 1.2 m thick limestone, whose last 30 cm are made up almost entirely of benthic foraminifera tests (*Orbitolina*).

Interval D (from the top of bed ARF3 to the top of bed ARF4a) is 20 m thick and is dominated by laminated, grey to dark-grey marls interbedded with marly limestones showing (Fig. 4.II). These beds are rich in shell fragments, especially of bivalves and gastropods. *Thalassinoides* burrows occur throughout. Plant impressions and woody fragments appear in marls and marly limestone beds near the middle of this interval (Fig. 4.V).

Interval E (from the top of bed ARF4a to the bed ARF5) is ca. 52 m thick and is formed by three small intervals, each with a the basal bioclastic limestones (reference beds ARF4a, b and c) and ending at the top with marly limestones. The marls and marly limestones are rich in *Thalassinoides* burrows, shell fragments and often unbroken shells of bivalves and gastropods (Fig. 4.IV). Plant impressions and woody fragments are also common in the latter lithologies. Dinosaur footprints near the top of the third sedimentary cycle were described by Santos et al. (2013, 2016). The dominant colour of the marls and marly limestones is dark grey and beige, but red to purple marls grade upward to grey marls in the first of the sedimentary cycles. The reference bed ARF5 comprises a ca. 5 m thick amalgamated buff bioclastic limestone beds with bioturbation and rare unidirectional cross-bedding.

Interval F (from the top of bed ARF5 to the top of the section) is dominated by bioclastic limestones and marly limestones with subordinated marls. The marls and marly limestones are beige in

Fig. 4. I − The general view of the sea cliffs at Arrifes showing vertical bedding and continuous exposure of the sequence from descriptive lithologic intervals C to F, the younging of the sequence is towards West. II − The general aspect of Interval D shows marls interbedded with marly limestones. The thicker bed to the right is reference bed ARF3 (Scale − the person in the centre of the picture is ca. 1.75 m in height). III − Wave ripples between samples P155.1 and P158.1 in Interval E. IV − Internal mould of marine gastropod in Interval E. V − Plant impression of a leaf near sample P106.1 in Interval D. VI − Woody fragment near sample P003.1 in Interval A. VII − *Thalassinoides* trace fossils in Interval F. VIII − Heavily bioturbated limestone bed in Interval C.

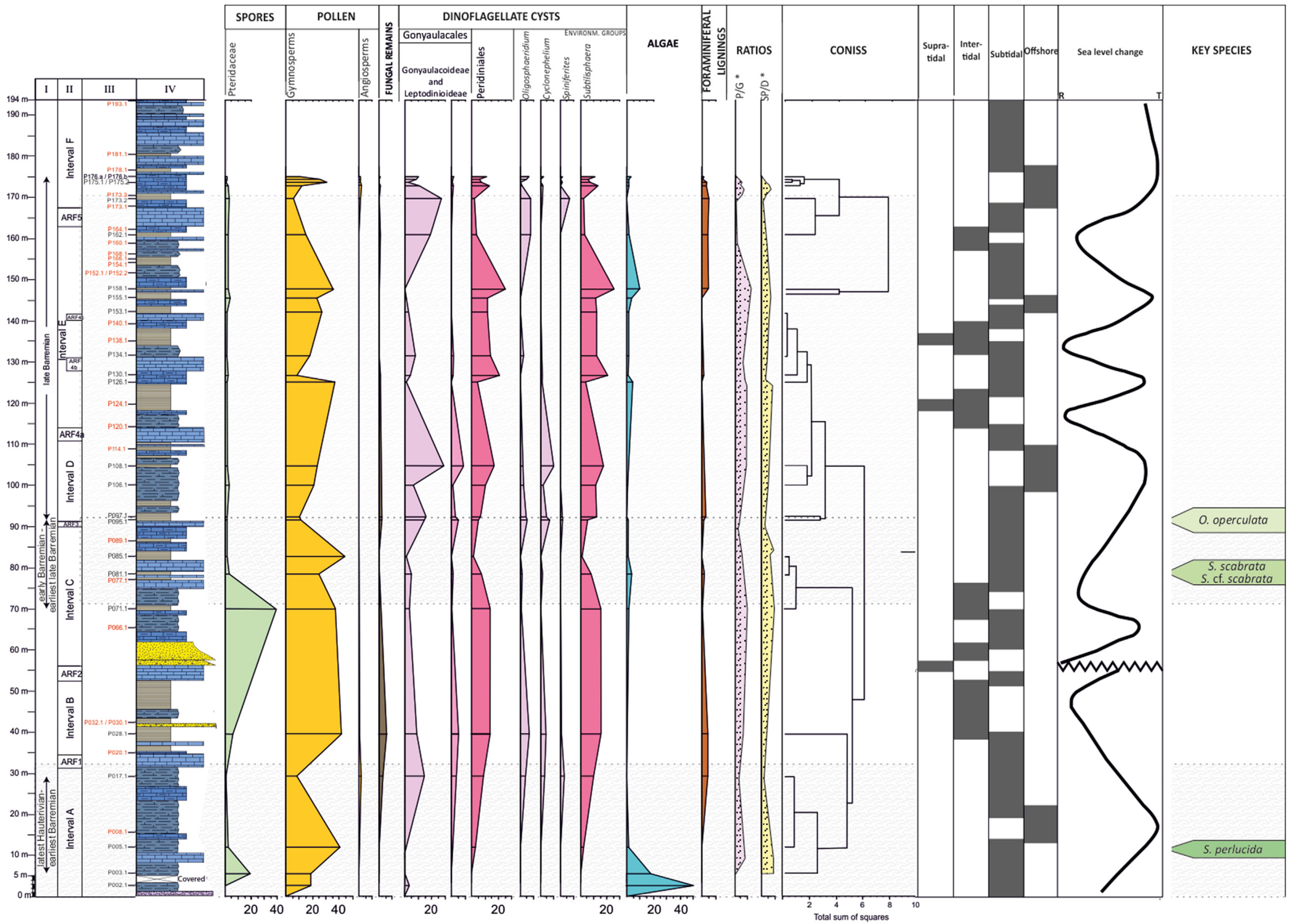


Fig. 5. Relative abundances of the different palynomorph and lithofacies groups used for palynostratigraphic and paleoenvironmental interpretations. Black samples – productive samples. Red samples – non-productive samples. P/G* and SP/D* with scale exaggerated by a factor of 20. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

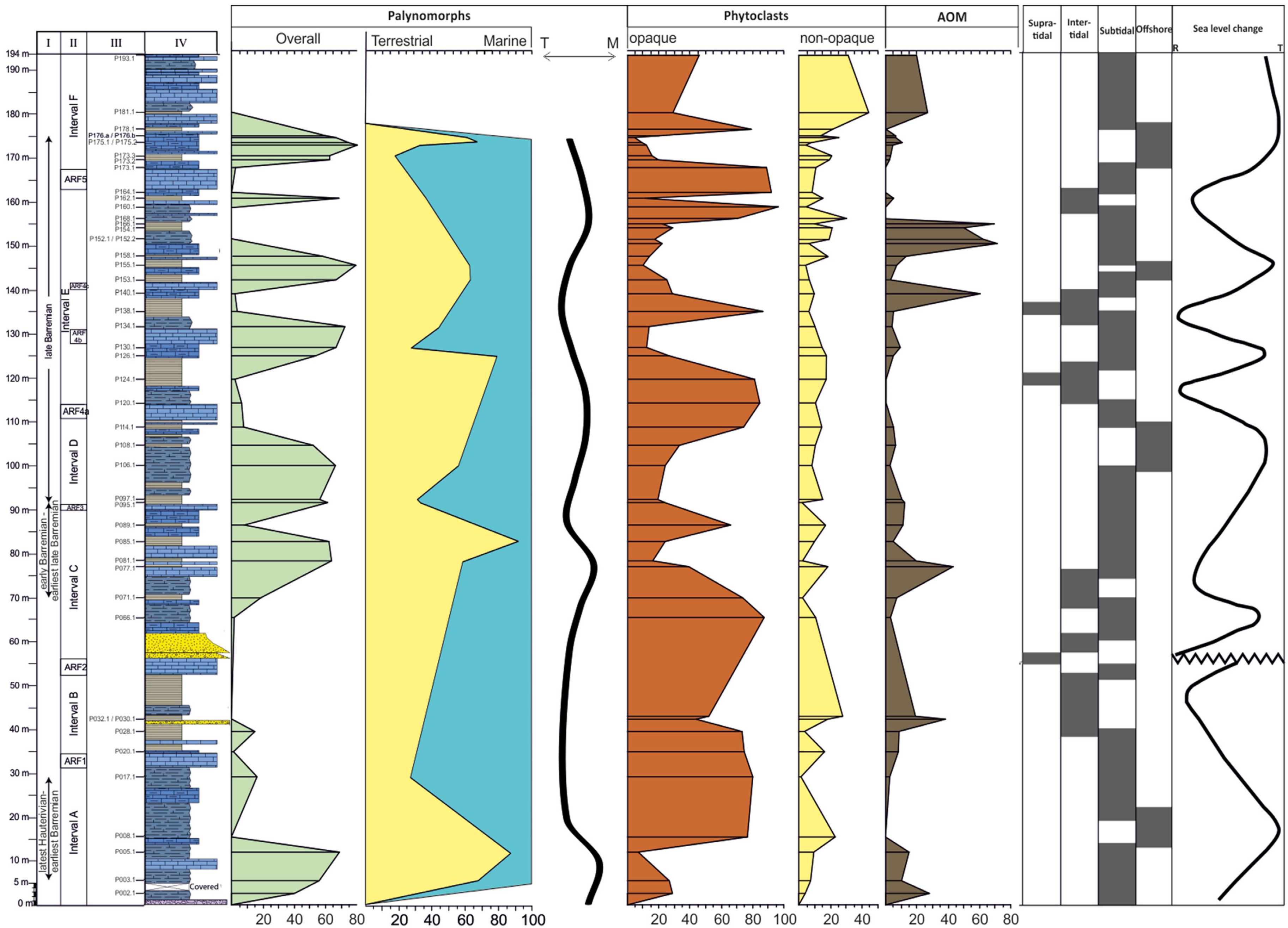


Fig. 6. Relative abundances of the different palynofacies categories and lithofacies groups used for paleoenvironmental interpretations.

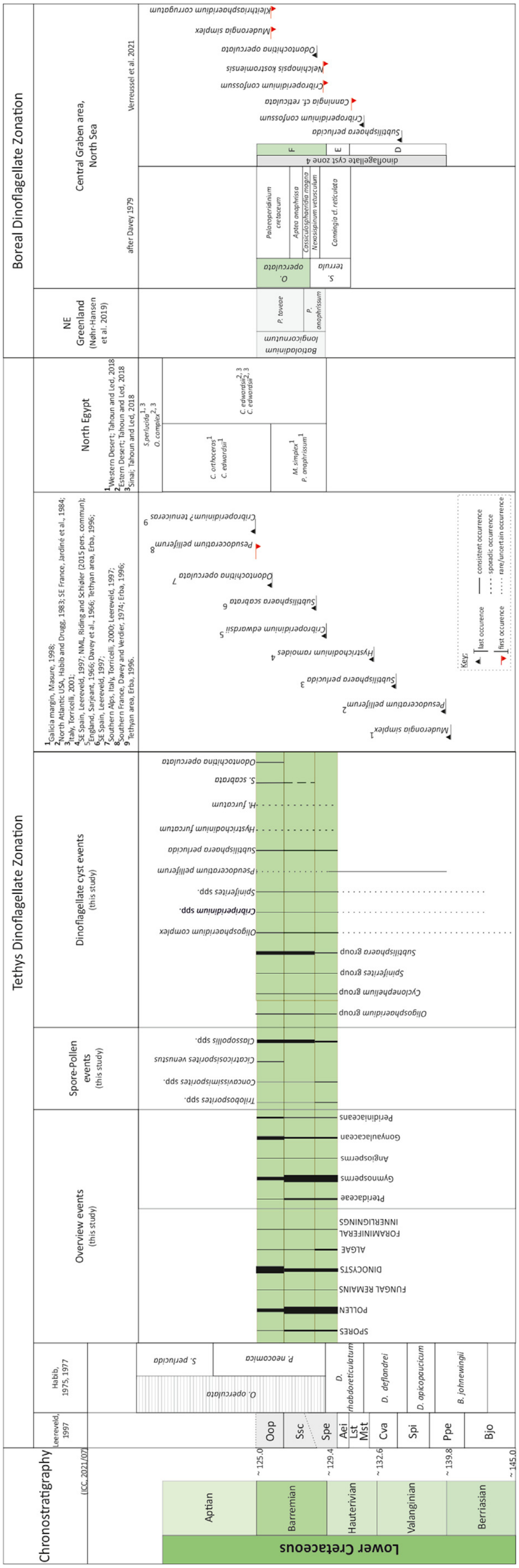


Fig. 7. Biozonal scheme and ranges of relevant stratigraphic taxa recovered in the Arrifes section (Algarve Basin) for the Lower Cretaceous, and interregional correlation with European and northern Africa dinoflagellate zonations and events, particularly during the Barremian stage.

colour. In this interval, the sedimentary cyclicity observed in the previous descriptive interval was more challenging to recognise, but the sedimentary features are similar. *Thalassinoides* burrows occur throughout the interval (Fig. 4.VII).

5. Palynostratigraphy

Palynomorphs from the Lower Cretaceous strata of the Arrifes section (Algarve, Portugal) were studied, and three different assemblages are described in this section. In general, the palynomorphs are well preserved. The assemblages are mainly composed of sporomorphs, dinoflagellate cysts, foraminiferal linings, and algae in different proportions. The relative abundance of dinoflagellate cysts generally increases upwards in the stratigraphic sequence in favour of sporomorphs (Table S1).

Quantitative and qualitative analyses of palynomorphs were performed based on selected species' first occurrence and taxa abundance. These assemblages are described below in stratigraphic order (oldest to youngest). More detailed information regarding the content of each assemblage is available in Table S1 and Fig. 5.

5.1. **Assemblage A** *(from P003.1 to P017.1 samples)*

Well-preserved specimens characterise this assemblage, with sporomorph dominance (ca. 61%) over dinoflagellate cysts (ca. 23%). The spores are better preserved than other palynomorphs and are a consistent component in this assemblage, averaging ca. 14% and reaching a maximum value of 32% in sample P003.1.

Gymnosperm pollen are represented mainly by frequent *Classopollis* and rare *Podocarpidites*. The frequent pteridophytes spores, represented by *Deltoidospora* sp., and *Concavissimisporites* sp., and *Trilobosporites* sp., is especially abundant in the lowermost sample (P003.1, ca. 32%), and steadily decreases towards the top of the Interval A (P017.1 sample). The reverse trend is observed in the dinoflagellate cysts, which increases to the top of this assemblage interval, specifically comprising an assemblage with Gonyaulacales including species of *Oligosphaeridium* (e.g., *O. complex, O. pulcherrimum*), as well as *Pseudoceratium* (ca. 8%). The *Subtilisphaera* species, particularly *Subtilisphaera perlucida*, characterises the Peridianales dinoflagellate cysts, reaching ca. 19%.

The average value for the P:G ratio in Interval A is about 0.36, reaching a maximum of 0.78 in sample P005.1 (Table S1, Fig. 5), whereas the SP:D ratio averages 0.73 and decreases steadily towards the top, from 0.99 to 0.28.

5.2. **Assemblage B** *(from P028.1 to P085.1 samples)*

In this assemblage, gymnosperm pollens are represented mainly by abundant *Classopollis*, which dominates over other palynomorphs (ca. 40%). The gymnosperm *Perinopollenites* sp. increases towards the top, from rare to abundant (2–23%). Common to frequent *Podocarpidites* sp., and rare to common *Callialasporites* (*C. dampieri, C. trilobatus, Callialasporites* spp.) also occur. The spore group (ca. 5%) is represented by rare pteridophyte spores such as *Deltoidospora* sp., *Cicatricosisporites* spp., *Densoisporites* sp., and *Patellasporites tavaredensis*.

The dinoflagellate cyst group represents about 14% of the assemblage, with Peridiniales cysts being more common (ca. 9%) and rare Gonyaulacales cysts (including rare ceratiacean cysts). The *Subtilisphaera* species are the most abundant, with the common

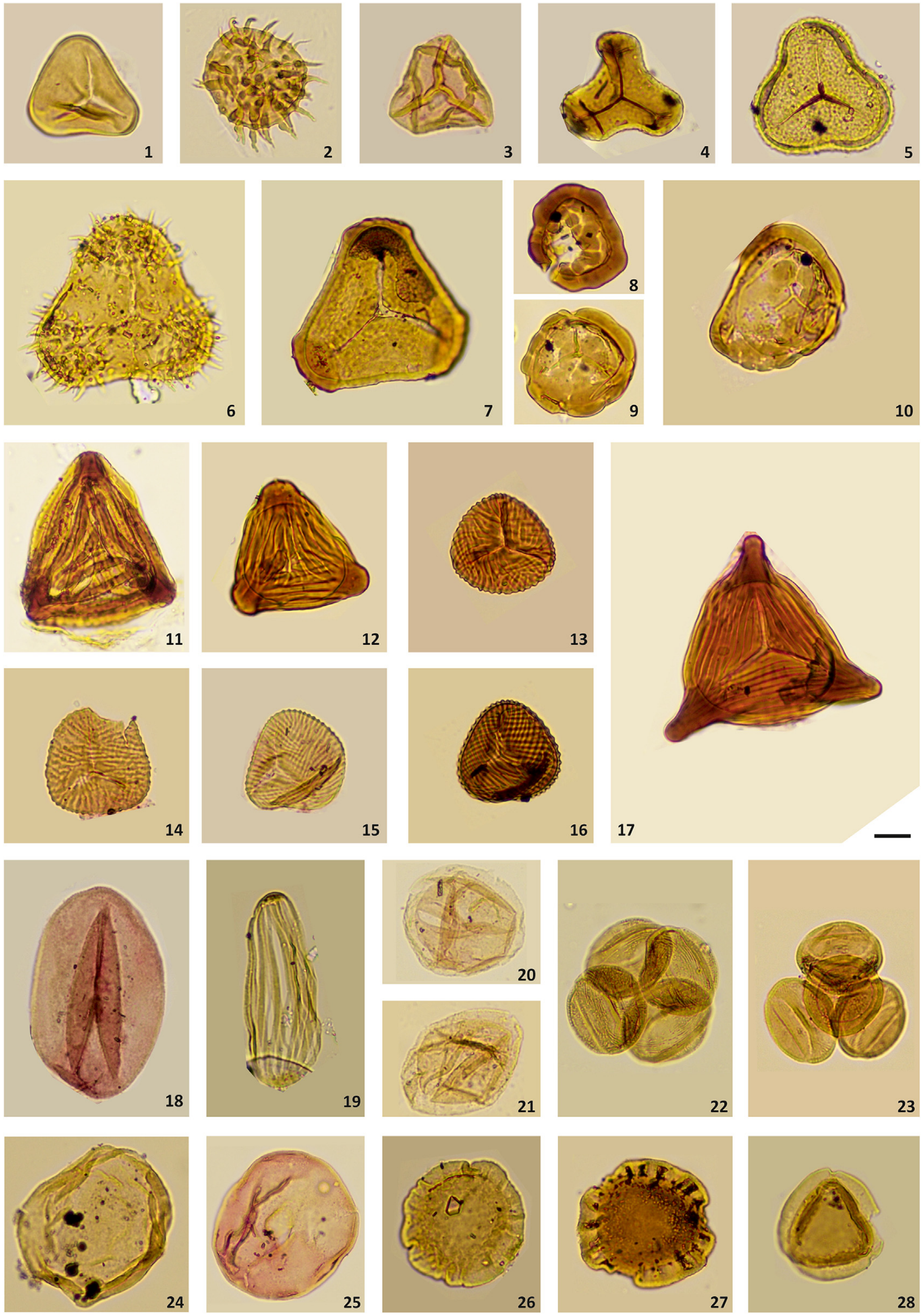


Fig. 8. Selected spore and pollen taxa recovered in the Arrifes section. The species name is followed by sample number, slide number, archive image number, and microscope coordinates. Scale bar = 10 μm. **1.** *Deltoidospora australis* (Couper, 1953) Pocock, 1970; P175.1 sample, s1_23 slide, 986/405. **2.** *Echinatisporis varispinosus* Srivastava, 1975; P005.1 sample, s1_26 slide, 1134/386. **3.***Cibotiumspora* sp.; P155.1 sample, s1_15 slide, 1028/444. **4.** *Cibotiumspora jurienensis* (Balme, 1957) Filatoff, 1975P003.1 sample, 1_46 slide, 991/400. **5.** *Concavissimisporites verrucosus* Delcourt and Sprumont, 1955; P003.1 sample, 1_65 slide, 1130/341. **6.** *Pilosisporites verus* Delcourt and Sprumont, 1955; P003.1 sample, 1_131 slide, 1125/130. **7.** *Trilobosporites arcensis* Trincão et al., 1990; P003.1 sample, 1_124 slide, 1050/218. **8**–**10.** *Patellasporites tavaredensis* Groot and Groot, 1962; 8. P106.1 sample, s1_7 slide, 983/482. **9.** P162.1 sample, 1_1 slide, 1056//424. **10.** P162.1 sample, s2_10 slide, 1087/307. **11.** *Costatoperforosporites* sp.; P003.1 sample, 1_130 slide, 1120/168. **12.** *Plicatella* sp.; P003.1 sample, 1_142 slide, 1064/107. **13**–**16.** *Cicatricosisporites venustus* Deak, 1963; **13.** P176 1/2A sample, s1_90 slide, 1050/273. **14.** P155.1 sample, s2_8 slide, 1040/454. **15.** P155.1 sample, s2_16 slide, 1038/440. **16.** P26.1 sample, 1_68 slide, 987/323. **17.** *Appendicisporites* sp.; P155.1 sample, s2_9 slide, 1041/153. **18.** *Monosulcites* sp., P134.1 sample, s1_166 slide, 1088/358. **19.** *Ephedripites* sp.; P003.1 sample, 1_145 slide, 1110/98. **20**–**21.** *Perinopollenites elatoides* Couper, 1958; **20.** P134.1 sample, s1_134 slide, 1008/378. **21.** P85.1 sample, s1_18 slide, 1117/498. **22.** *Classopollis* sp.; P005.1 sample, 1_18 slide, 994/415. **23.** *Classopollis* sp.; P153.1 sample, 1_6 slide, 1047/410. **24**–**25.** *Araucariacites australis* Cookson, 1947; **24.** P81.1 sample, s1_67 slide, 982/350. **25.** P176 1/2A sample, s1_2 slide, 1054/467. **26**–**27.** *Callialasporites dampieri* (Balme, 1957) Dev, 1961; **26.** P003.1 sample, 1_137 slide, 1075/113. **27.** P003.1 sample, 2_59 slide, 1050/177. **28.** *Callialasporites trilobatus* (Balme, 1957) Dev, 1961; P003.1 sample, 1_104 slide, 1088/261.

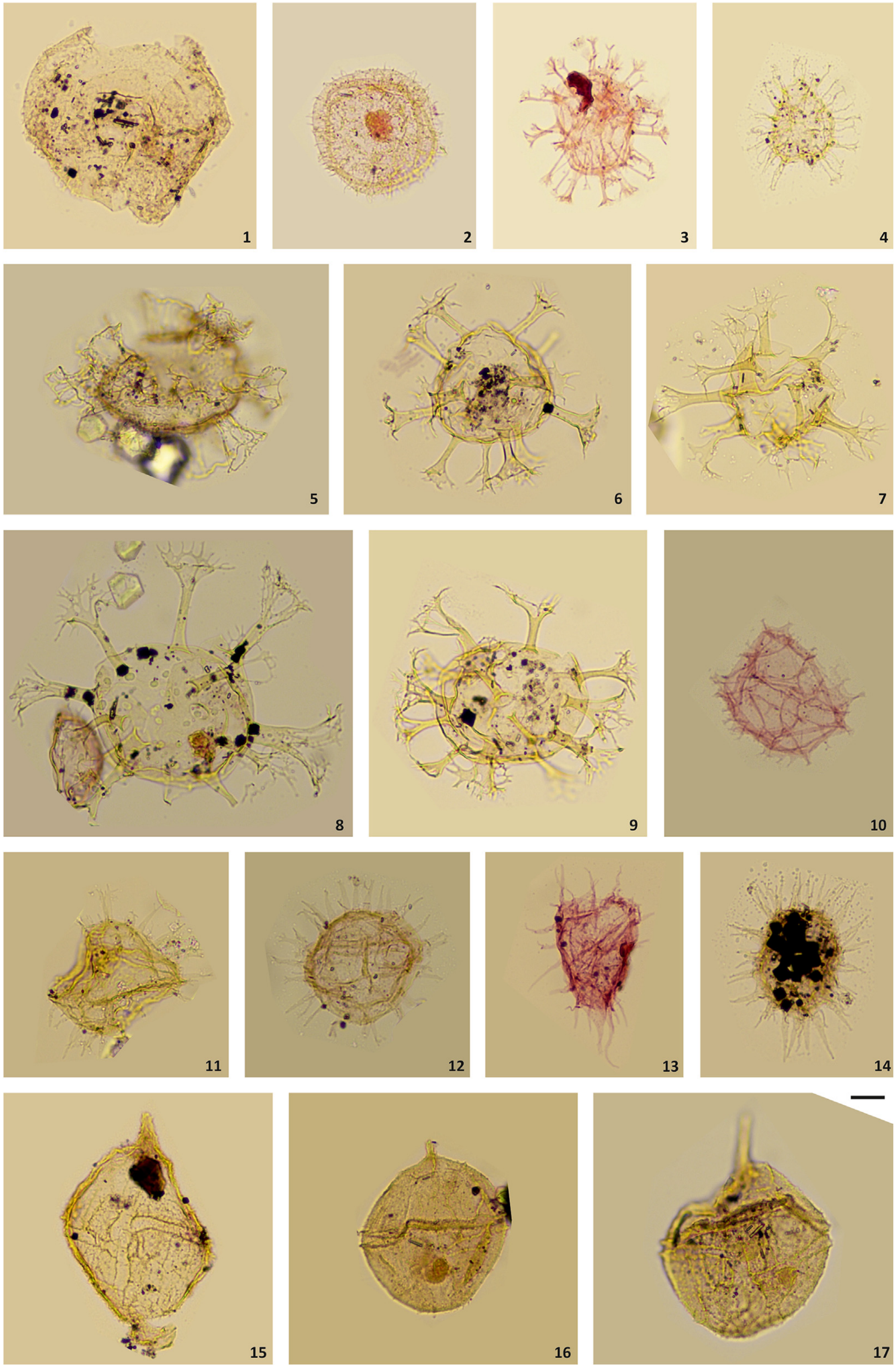


Fig. 9. Selected Gonyaulacales recovered in the Arrifes section. The species name is followed by sample number, slide number, archive image number, and microscope coordinates. Scale bar = 10 µm. 1. *Tenua* sp.; P176 1/2B sample, 1_61 slide, 1043/364. **2.** *Cometodinium habibii* Monteil, 1992a; P176 1/2B sample, 1_97 slide, 1110/382. **3.** *Kiokansium williamsii* Singh, 1983; P134.1 sample, s1_37 slide, 1114/420. **4.** *Kiokansium unituberculatum* (Tasch in Tasch et al., 1964) Stover and Evitt, 1978; P17.1 sample, s1_83 slide, 1068/416. **5.** *Hystrichosphaerina schindewolfii* Alberti, 1961; P95.1 sample, s1_12 slide, 985/498. **6–7.** *Oligosphaeridium complex* Davey and Williams, 1966; **6.** P17.1 sample, s1_111 slide, 958/408. **7.** P005.1 sample, s1_90 slide, 1035/391. **8** and **9.** *Oligosphaeridium pulcherrimum* (Deflandre and Cookson, 1955) Davey and Williams, 1966; **8.** P95.1 sample, s1_122 slide, 1091/423. **9.** P17.1 sample, s1_37 slide, 1064/455. **10.** *Spiniferites* sp.; P134.1 sample, s1_156 slide, 1070/366.**11–14.** *Hystrichodinium* spp. **11.** P005.1 sample, 1_121 slide, 1050/367. **12.** P175.1 sample, s1_1 slide, 1000/307. **13.** P176 1/2A sample, s1_15 slide, 980/448. **14.** P17.1 sample, s1_115 slide, 1055/396. **15–16.** *Cribroperidinium* sp. **15.**P81.1 sample, s1_45 slide, 1062/386. **16.** P26.1 sample, 1_22 slide, 950/412. **17.** *Cribroperidinium edwardsii* Davey, 1969; P17.1 sample, s1_144 slide, 940/383.

Subtilisphaera perlucida and *Subtilisphaera* spp. identified, including the first rare occurrences of *Subtilisphaera scabrata*. The Gonyaulacales cysts are more common in sample P081.1, including rare *Cribroperidinium* spp., and *Oligosphaeridium* spp.

The P/G ratio averages 0.65, reaches its maximum value in the lowermost sample (P026.1) of this assemblage and decreases towards the top of the interval (Table S1; Fig. 5). The SP/D ratio averages 0.85, reaching the maximum value (0.96) in the uppermost sample (P085.1).

5.3. **Assemblage C** *(from P095.1 to P176.1/2B samples)*

Dinoflagellate cysts dominate Assemblage C, with a most significant increase in Gonyaulacales cysts (ca. 22.46%). The *Cribroperidinium* genus is abundant in the lower part of the interval. At the same time, the numbers of the *Kiokansium* spp. and *Oligosphaeridium* spp. (including *O. complex* and *O. pulcherrimum*), are more consistent throughout this assemblage. Remarkably, P173.2 is the only sample that contains *Trichodinium* (including *T. castanea*). The rare, ceratiacean cyst assigned to *Odontochitina* forms (including *O. operculata*) occur sporadically in the upper part of the assemblage (from sample P095.1 upwards). In contrast, *Pseudoceratium* (including *P. pelliferum* and *P. securigerum*) only occurs at the base of this assemblage. The number of *Subtilisphaera* species oscillates throughout this assemblage, reaching a maximum in sample P130.1 (ca. 52%) and a minimum in sample P173.2 (ca. 4%). The presence of foraminiferal linings is almost constant throughout this assemblage (averaging ca. 4%) (Table S1, Fig. 5).

6. Palynofacies

The different palynofacies groups have significant oscillations throughout the section (Fig. 6; Table S2). The palynofacies groups and subgroups presented bellow follow the attributions and adapted schemes of Tyson (1993, 1995). The Opaque Phytoclasts subgroup is abundant to superabundant in most studied samples, particularly in the following intervals: i) from sample P008.1 to sample P071.1; ii) from sample P114.1 to sample P124.1; and iii) from sample P166.1 to sample P173.1. An increase in the relative abundance of the Non-Opaque Phytoclasts subgroup occurs at the top of the Arrifes section in Interval F, from 180.9 m to the end of the section. The relative abundances below that interval oscillate between frequent to abundant. A similar trend is recognised for the AOM group; however, some abundance events are worth noting in samples P140.1, P152.1, P152.2, P154.1 and P166.1 (Fig. 6; Table S2).

The Palynomorph group, which includes spores and pollen, and dinoflagellate cysts, and other algae, presents the biggest amplitude range in the relative abundances of the palynomorphs throughout the section. This group's relative abundance commonly ranges from rare to superabundant, showing the highest relative abundances towards the top of the section: P134.1, P158, P160.1, P175.1, and P175.2. Low abundance intervals were recorded from samples P032.1 to P066.1,P152.1 to P160.1, P164.1 to P173.1, and P181.1 to P193.1 (Fig. 5; Table S2).

7. Discussion

7.1. Age

The assemblages identified in the present research are assigned to the Lower Cretaceous, specifically the uppermost Hauterivian to upper Barremian. The age is based on correlation with the southern European standard biostratigraphic zonation established on the first occurrences of key dinoflagellate cysts calibrated against the standard ammonite zones, as proposed by Leereveld (1995, 1997) for the Iberia Basin.

In the present study, three assemblages (A to C; Figs. 5 and 7) were identified, based on the distribution of stratigraphically significant dinoflagellate cyst taxa: i) Assemblage A, from the uppermost Hauterivian–lowermost Barremian, based on the first occurrence of *Subtilisphaera perlucida*; ii) Assemblage B, from lower to lowermost upper Barremian, based on the first occurrence (FO) of *Subtilisphaera scabrata*; and iii) Assemblage C, from upper Barremian upwards, based on the first occurrence of species of *Odontochitina*, in particular *O. operculata*.

Following Leereveld (1997), the occurrence of *Subtilisphaera perlucida* (Spe interval zone) indicates the uppermost Hauterivian to lowermost Barremian for this interval (Figs. 5 and 7). The *Subtilisphaera perlucida* Spe Interval Zone (uppermost Hauterivian – lowermost Barremian; Figs. 5 and 7) ranges from the last occurrence of *Aprobolocysta eilema* to the first occurrence of *Subtilisphaera scabrata*, the interval including the first occurrence of *Subtilisphaera perlucida*. In the section studied, the first occurrence of *Subtilisphaera perlucida* is observed in sample P005.1, without any evidence of the occurrence of other more recent *Subtilisphaera* species. Therefore, Assemblage A correlates well with the Spe Interval Zone of Leereveld (1997).

However, the chronostratigraphic assignments based on the first occurrence of *S. perlucida* are quite different in other Europe sites. For instance, Torricelli (2001) documents the presence of *S. perlucida* in the upper Valanginian (Italy, Vallone Rosmarino section). Likewise, Davey (1979) and Riding et al. (2010) used *S. perlucida* as key species for the upper Hauterivian in eastern England and the southern North Sea Basin. In southern France, the *S. perlucida* cyst ranges up into upper Aptian, and in southern England, its occurrence is most marked in the upper Aptian (Davey and Verdier, 1974).

In this study, the *Hystrichodinium ramoides* and *H. furcatum* are rare, but occur throughout the section. *H. ramoides* is recorded in upper Barremian deposits and is rare in the lower Barremian (Riding and Schiøler pers. commun). Nevertheless, Leereveld (1997) documented that *H. ramoides* is restricted to the lowermost Hauterivian in the Iberia Basin in Spain. Similar horizons were interpreted for *H. furcatum* in Portugal (Berthou and Leereveld, 1990; Riding and Schiøler, 2015 pers. commun). Accordingly, the sparse occurrences of these taxa in the Arrifes section suggest an age no younger than the late Barremian.

According to Leereveld (1997), the *Subtilisphaera scabrata* Ssc Interval Zone ranges from the first occurrence of *Subtilisphaera scabrata* to the first occurrence of *Odontochitina operculata* and is assigned to the lower Barremian to lowermost upper Barremian (Figs. 5 and 7). In this section, the first rare occurrence of *Subtilisphaera scabrata* (Sca interval zone of Leereveld, 1997) in the P081.1 sample indicates the lower to lowermost upper Barremian.

Leereveld (1997) defined the *Odontochitina operculata* Oop Interval Zone as ranging from the FO of *Odontochitina operculata* to the FO of *Cribroperidinium tenuiceras*. The FO of *Odontochitina operculata* is indicative of an age no older than the late Barremian (Costa and Davey, 1992; Leereveld, 1995, 1997) (Figs. 5 and 7). *Odontochitina* (including *O. operculata*) first occurs sporadically in the upper part of the Arrifes section, from sample P095.1 upwards. Additionally, the occurrence near sample P114.1 of the charophyte *Clavator grovesii* var. *jiuquanensis* also supports the upper Barremian assignment for this part of the Arrifes section (Jordi Pérez-Cano, pers. commun). This charophyte is the key species of the biozone named after it, and whose base is of late Barremian age (Pérez-Cano et al., 2022).

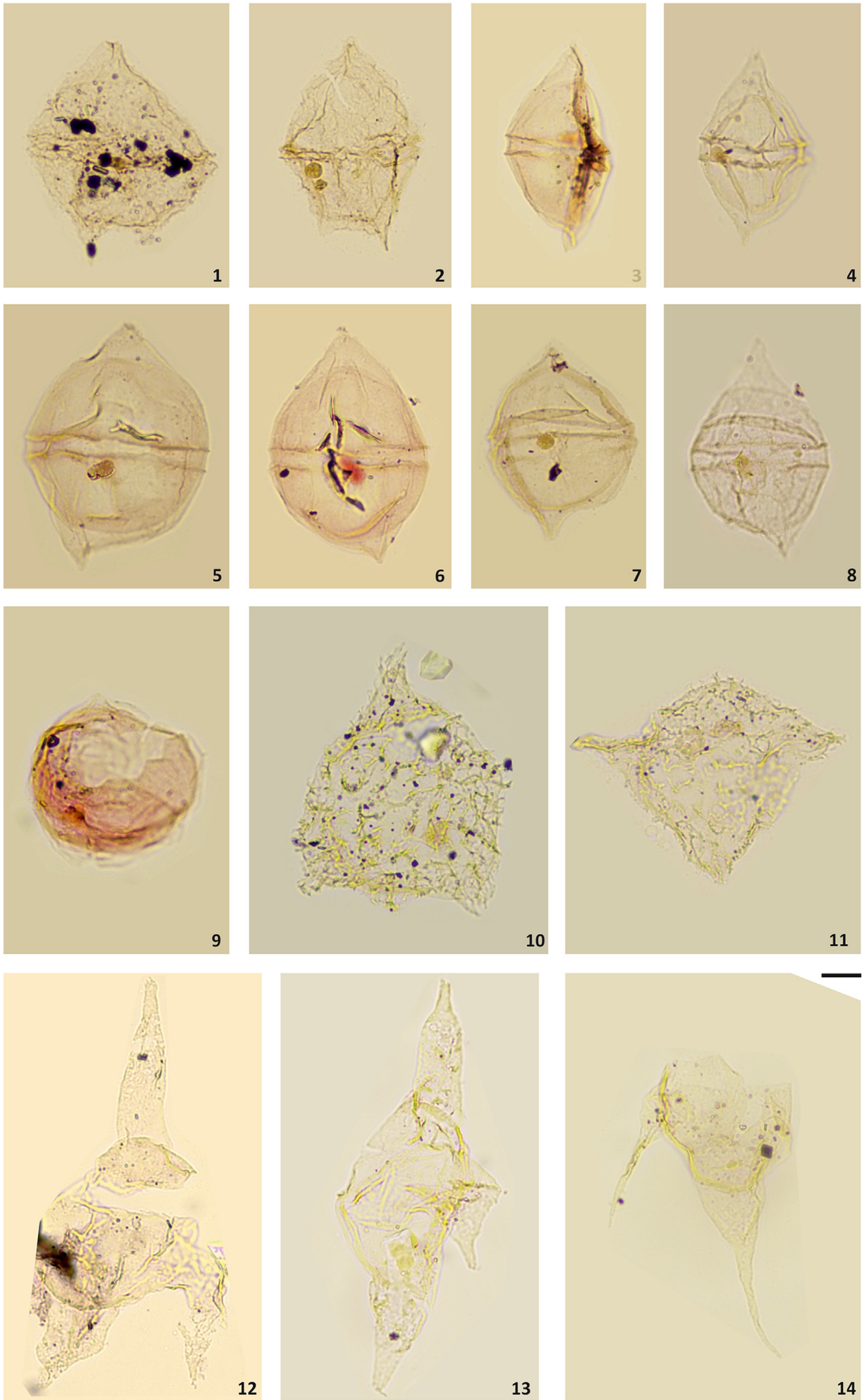


Fig. 10. Selected Peridianales (photomicrography 1–13) and Gonyaulacales (photomicrography 7–14) dinoflagellate taxa recovered in the Arrifes section. The species name is followed by sample number, slide number, archive image number, and microscope coordinates. Scale bar = 10 μm. **1–2. 1.** *Palaeoperidinium* sp.; **1.** P17.1 sample, s1_52 slide, 930/443. **2.** P17.1 sample, s1_102 slide, 1020/403. **3.** *Subtilisphaera perlucida* (Alberti, 1959b) Jain and Millepied, 1973; P134.1 sample, s1_71 slide, 960/410. **5–7.** *Subtilisphaera scabrata* Jain and Millepied, 1973; **5.** P134.1 sample, s1_17 slide, 1017/420. **6.** P134.1 sample, s1_11 slide, 988/420. **7.** P26.1 sample, 1_16 slide, 1014/420. **8.** *Subtilisphaera senegalensis* Jain and Millepied, 1973; P175.1 sample, s1_41 slide, 1016/387. **9.** *Ovoidinium diversum* Davey, 1979b; P130.1 sample, s1_110 slide, 960/412. **10.** *Pseudoceratium pelliferum* Gocht, 1957; P95.1 sample, s1_107 slide, 1006/429. **11.** *Phoberocysta* sp.; P17.1 sample, s1_114 slide, 1075/397. **12.** *Odontochitina* cf. *rhakodes* Bint, 1986; P175.1 sample, s1_14 slide, 1006/420. **13.** *Odontochitina ancala* Bint, 1986; P175.1 sample, s1_60 slide, 1090/320. **14.** *Odontochitina operculata* (Wetzel, 1933a) Deflandre and Cookson, 1955; P95.1 sample, s1_149 slide, 1100/400.

7.2. Depositional environments interpretation

The Arrifes sequence was deposited on a gentle slope carbonate ramp. The coastline would have a rather dense vegetation cover, as evidenced by common plant fragments, wood remains, and terrestrial palynomorphs (spores and pollen) found throughout the section. Most deposition was on inner ramp dominated by tidal and wave processes and a mid to outer ramp below fairweather wave base and storm wave base, respectively. Due to the gentle slope, eustatic variations and progradation of the carbonate ramp environments gave rise to a cyclicity described below. The logging of the Arrifes section and the sedimentary features led to the identification of four depositional environments based on their position and depth in the carbonated ramp. Thus, with progressive increase in the ramp depth, supratidal, intertidal (inner ramp), subtidal (mid ramp) and offshore (outer ramp) zones are recognized.

The supratidal zone is characterised by the accumulation of marls and thin-bedded limestones with parallel laminations; their reddish to variegated colour, suggest oxidation due to prolonged subareal exposure. Invertebrate fossils, palynomorphs, ichnofossils, and remains of plants and woody fragments are rare. Diagenetic carbonate nodules are common. The lack of evaporite minerals in the sediments suggests that the shoreline was vegetated, neither warm or arid, and consisting of carbonate mud.

The intertidal depositional zone corresponds to a mud-dominated inner ramp. It is characterised by red to beige marls, marly limestones and bioclastic limestones. Trace fossils, broken invertebrate shells and wood fragments are common. Palynomorphs are rare and black phytoclasts dominate the palynofacies.

The subtidal depositional zone is that part of the mid-ramp below the fairweather wave base. It is characterised by the deposition of bioclastic limestones and marly limestones. Bioclastic limestone beds formed by invertebrate shells (bivalves and gastropods), benthic foraminifera, and trace fossils are common. The marly limestones and marls of this depositional zone show grey to beige colours. Marine (dinoflagellates) and terrestrial-derived palynomorphs (pollens and spores) are common in the marls.

The offshore depositional zone corresponds to the outer ramp below the storm wave base and consists of marls interbedded with thinly-bedded marly limestones. The sediments are grey to dark grey. Palynomorphs and amorphous organic matter are the two most common palynofacies groups, with abundant opaque phytoclasts. Invertebrate fauna and trace fossils are rare. The reduced number of carbonate beds of the outer ramp show sedimentary features that reflect wave action, and the absence of redeposited carbonate sediments by mass-flow processes suggests a consistently gentle slope carbonate ramp mainly dominated by tidal cycles.

The sandstone interval between ca. 55 and 60 m constitutes the only deposit not related to a carbonate-ramp depositional system. It may correspond to a short-lived episode of clastic input. The evolution of the depositional environments is shown in Fig. 3, in which the dominant ramp depositional zones are related to the different lithologies. The figure also shows an interpretation of sea-level changes during the latest Hauterivian to the late Barremian interval.

Interval A, at the base of the studied section, dates from the latest Hauterivian to the earliest Barremian and consists essentially of marly lithologies deposited in the subtidal and offshore zones of the carbonate ramp. The grey to beige colours of the marl beds indicate dysoxic to oxygenated seafloor conditions, and the plant and woody fragments suggest the proximity to a vegetated shoreline. A deepening trend occurs upsection towards the middle beds of Interval A, followed by a shallowing trend up to reference bed ARF1. The palynology and palynofacies assemblages correspond to deepening trend, with palynomorphs and AOM groups dominating the palynofacies. The significant occurrence of the *Subtilisphaera* group, as occurs from sample P017.1 upsection, is usually associated with restricted, low-salinity marine environments (Davey, 1970; Jain and Millepied, 1975a, 1975b; Piasecki, 1984; Harding, 1986; van Helmond et al., 2014) and suggests a nearshore deposition; this observation, concurs with the shallowing upward trend described for the upper part of Interval A, where the proximity of the shoreline and the consequent input of fresh water onto the carbonate ramp would have educed the average salinity. Owing to the abundance of *Subtilisphaera*, the Peridianales/Gonyaulacales (P/G) ratio is essentially controlled by this genus, and the peridinioids dominate practically through the entire interval A (Fig. 5, Table S1). In addition, presence of the gymnosperm pollen *Classopollis* points to nearshore deposition (Duane, 1997), and warm and dry conditions (e.g., Vakhrameyev, 1982). Dry paleoclimatic conditions are also indicated by the regular occurrence of araucaroid (*Araucariacites*) pollen throughout the interval A (Schrank and Mahmoud, 1998). However, some palynomorphs, such as pollen grains and Peridianales cysts, may deposit in a low energy distal settings (e.g., Tyson, 1993, 1995).

Interval B is dominated by reddish and variegated marls, and includes an layer composed of conglomerates and sandstone, evidencing a pulse of clastic sedimentary influx to the carbonate depositional system. The sedimentary structures and oxidation levels displayed in Interval B suggest deposition in shallow parts of the carbonate inner-ramp zones, with frequent subaerial exposure. Intervals A and B together may suggest an initial sea-level rise followed by a sea-level fall, the latter recorded through most of Interval B. The dominance of opaque phytoclasts in the palynofacies groups indicates oxidising conditions and supports the intertidal depositional conditions for most of this interval sediments.

At the base of interval C, dated from the early Barremian-earliest late Barremian, are conglomerate and sandstone layers with sedimentary structures that suggest episode of coastal deposition followed upsection by a deepening trend. The base is erosive, overlain by a deposit with well-rounded quartz clasts, suggesting beach deposition. The succeeding sandstone layers show bidirectional cross-bedding, surface reactivation and hummocky cross-stratification, recording intertidal to subtidal conditions dominated by tidal processes and occasionally storms. These layers mark an episode of clastic sediment influx into the carbonate deposition system, which was not repeated in the upsection of the Arrifes sequence. Marly limestones and marls on top of the sandstone beds indicate the return of carbonate deposition. The depositional environments of these carbonate beds range from intertidal to subtidal, and from ca. 68 m to the top of Interval C, subtidal mid-ramp conditions dominated. Despite the occurrence of marine palynomorphs (dinoflagellate cysts, marine algae and foraminiferal linings), sporomorphs dominate the interval. These mixed assemblages reinforce the interpretation of oscillation between intertidal and subtidal deposition. Interval C also shows a trend toward rising sea level towards the top of the interval, verified by the slight increase of Gonyaulacales cysts, particularly for the presence of more typical distally palynomorphs (specially *Oligosphaeridium*) (e.g., Harker et al., 1990; Omran et al., 1990; Wilpshaar and Leereveld, 1994; Li and Habib, 1996). The AOM group also increases toward the top of interval C, reinforcing evidence for a more distal deposition, mostly under anoxic conditions (Tyson, 1993, 1995; Mendonça Filho et al., 2012).

Interval D, dated as late Barremian, consists of marls and marly limestones, showing mainly depositional characteristics of subtidal and offshore zones. No cyclicity is apparent in this interval. However, considering the basal layers of the overlying Interval E, a trend toward lower sea-level trend occurs in this section. The marly beds outcropping at the base of Interval D yielded upper Barremian dinoflagellates cysts. Marine palynomorphs, such as dinoflagellate cysts and foraminiferal linings dominate the assemblages. The notable increase in chorate Gonyaulacales suggests a more stable environment of deposition in inner-neritic settings (mid to outer-ramp) and perhaps a short-term marine transgressive pulse.

Interval E comprises three sedimentary cycles that begin and end with bioclastic limestones (reference beds ARF4a, 4b and 4c). Between these beds are marls and marly limestones deposited mainly in the intertidal to subtidal zones. In the lowest cycle, the marls between reference layers ARF4a and ARF4b are reddish and variegated, suggesting supratidal to intertidal depositional conditions, thus marking a sea level fall. Over the subsequent two sedimentary cycles, depositional environments shifted rapidly between intertidal to subtidal and possibly offshore conditions. However, the sedimentary structures suggest offshore to subtidal depositional settings in the marls at the top of the ARD4c reference layer and dominant intertidal conditions at the top of Interval E.

Additionally, the *Subtilisphaera* group continues to be abundant during this interval, and terrestriallly-derived palynomorphs (in particular, pollen) continued to be present. These observations may indicate shallower settings. However, when associated with high Gonyaulacales ratios, they more likely result from a mixed marine environment with a higher terrestrial influx due to local sea-level fluctuations and the progradation of the carbonate ramp. The dinosaur footprints (at ca. 161 m) also confirm this environmental interpretation for the late Barremian. The footprint-bearing layer has been interpreted as the product of inter-tidal deposits. It is correlated to the abundant dinosaurian fauna that lived alongside the Early Cretaceous coastline of the Algarve Basin (Santos et al., 2013, 2016). Similar footprints were also recognised in the Barremian Salema Formation of cropping out at Salema beach (Western Algarve, Santos et al., 2013).

Finally, Interval F is dominated by bioclastic limestones and marly limestones with sedimentary structures suggesting sedimentation in the carbonate ramp's subtidal zones. Dark-grey marls at the base of this interval yielded dinoflagellates of late Barremian age. These sedimentary features may indicate the deepest depositional conditions of this interval, typifying the subtidal zone of the outer carbonate ramp. The dominant depositional settings from the dark-grey marls to the top of the logged sequence are of the subtidal part of the mid-ramp. The base of interval F coincides with a general dominance of the dinoflagellate cyst group in palynofacies analysis, with an increase of Gonyaulacales at the base of the interval. Together with the common to abundant non-opaque phytoclasts and AOM, the palynofacies components corroborate a more deep-water depositional setting, mostly under dysoxic-anoxic conditions. To the top of the sequence (from P176.1b upwards), the palynomorph group is absent, and the opaque phytoclasts and AOM groups dominate, highlighting possible anoxic conditions and distal depositional settings.

8. The Arrifes section in the context of the Cretaceous stratigraphy of the Algarve Basin

The Arrifes section is positioned in the Central Algarve following the lithostratigraphic scheme of Rey (1983) of the Lower Cretaceous of the Algarve Basin (Fig. 2). The correlation with other Algarve Lower Cretaceous stratigraphic units is very difficult to establish due to the absence of age control (in particular, palynostratigraphy).

The most reliable age assigned to the Arrifes section (from AR-9 level in Correia, 1989) is based on the orbitolinid *Mesorbitolina parva*, indicating a probable earliest Aptian age (Velic, 2007; Schroeder et al., 2010; Cherchi and Schroeder, 2013). The new palynostratigraphic data presented in this study suggests a latest Hauterivian–late Barremian age for the Arrifes section, thus equivalent to the Salema Formation (Rey et al., 2006) of Western Algarve Basin. The tidally influenced shallow-water carbonates of the Salema Formation further support this correlation (Rey and Ramalho, 1974; Rey, 2006; Dinis et al., 2020).

Furthermore, Santos et al. (2013, 2016) recognised the similarity between dinosaur tracksites of the Arrifes section and those of the Salema Formation, assigning a Lower Cretaceous age for these footprints. This evidence supports the possible correlation between the Arrifes section and the Salema Formation.

Based on the geological evidence described above and the latest Hauterivian – late Barremian age obtained, we argue that the Arrifes section is a temporal equivalent of the Salema and Barrancão formations described by Rey (2006) and (Santos et al., 2013). However, there are some differences, namely: i) the Arrifes section is considerably thicker (194 m) when compared to those described by Rey (2006) (ca. 30 m thick) and by Santos et al. (2013) (ca. 33.5 m thick). The carbonate depositional environments in the Arrifes section are predominantly of the mid to outer carbonate ramp, with subtidal conditions; ii) the outcrops of the Salema Formation at Ansa da Almádena (Rey, 2006) and Praia da Salema (Santos et al., 2013), consist mainly of carbonate and dolomitic lithologies that suggest depositional environments closer to the shoreline, where supratidal and intertidal (inner-ramp) conditions dominated. Lastly, the intra-Barremian unconformity described by Rey (2006) between the Salema and the Barrancão formations is not recognised in the Arrifes section. This unconformity is tentatively related to an immersion phase of the carbonate basin around the early and late Barremian boundary, followed by erosion and progradation of the carbonate shelf (Rey, 2006). In the Arrifes section, the clastic succession at the base of Interval C is interpreted as a period of emersion of the carbonate ramp due to sea level fall and the influx of clastic material. According to the age provided by the dinoflagellates, this arenitic succession is older than the late Barremian. Thus, the latter arenitic succession may be tentatively synchronous with the intra-Barremian unconformity defined by Rey (2006). However, as stressed above, no angular unconformity between the sandstones and the underlying layers was observed in the Arrifes section.

9. Palynological correlation between southern Europe, and southern Africa across the Hauterivian to Barremian interval

The most detailed Lower Cretaceous southern European dinoflagellates biozonal scheme was defined in the Iberia Basin (from the Rio Argos succession in Spain by Leereveld, 1995, 1997); this, was correlated to ammonite-controlled sections in Switzerland and southeastern France (Millioud, 1969; Davey and Verdier, 1974; Jardiné et al., 1984; Srivastava, 1984; Pourtoy, 1989; Londeix, 1990). More recently, this zonation was used in Italy (southern Alpes) (Torricelli, 2000) and in northern Africa (northern Egypt, Tahoun and Led, 2018; Fig. 7). This biozonation scheme has become standard in southern Europe and northern Africa. It includes the following key taxa for the Hauterivian–Barremian interval: *Cribroperidinium* spp., *Pseudoceratium pelliferum*, *Hystrichodinium ramoides*, *Subtilisphaera perlucida*, *Subtilisphaera scabrata*, *Odontochitina operculata* and *Cribroperidinium*? *tenuiceras* (the last species not being recorded in the Arrifes section). These taxa are widespread in this age interval in the Tethyan realm, of which is part.

These taxa are also known in northeastern European regions, such as: England (Erba, 1996), Galicia (Masure, 1988), North Sea (Davey, 1979 and Verreussel et al., 2021) and North-East Greenland (Nøhr-Hansen et al., 2019), emphasising the cosmopolitan nature of this assemblage. Nevertheless, the northestern European zonal schemes and dinoflagellate cyst events are based on other groups of taxa of boreal influence (for instance, *Aptea* spp., *Batioladinium* spp., *Canningia* spp., and *Nexosispinum* spp.).

Focussing on cosmopolitan and key species recorded in the Arrifes section, the occurrence of *Pseudoceratium pelliferum* (from sample P005.1 to sample P097.1) is notable; its abundance and that of *Pseudoceratium* sp. (from sample P017.1) show a marked decrease upsection, and disappear in the late Barremian. These features were also recognised by Erba (1996) and Davey and Verdier (1974), who established that the last occurrence of *P. pelliferum* is at the Barremian–Aptian boundary in Mediterranean regions of Tethys. Elsewhere, *Pseudoceratium pelliferum* is recognised in the Boreal North Sea, generally in older strata, with first (Habib and Drugg, 1983; Jardiné et al., 1984) and last occurrences during the late Berriasian (DSK2 Zone, Poulsen and Riding, 2003). Therefore, the last occurrence of *Pseudoceratium pelliferum* points to age no younger than the late Barremian in the Arrifes section.

Likewise, the first occurrence of *Cribroperidinium edwardsii* is used as a stratigraphic marker for the Barremian–Aptian boundary in Europe. It has been consistently recorded in the Barremian of England (Sarjeant, 1966; Davey et al., 1966) and occurs in the Aptian in Germany (Eisenack, 1958) and the Albian in Romania (Baltes, 1967). In northern Egypt, *C. edwardsii* is a key taxon for the early Barremian to the Aptian (Tahoun and Led, 2018). Accordingly, the occurrence of *C. edwardsii* (from P017.5 to P173.2) supports Barremian age, not excluding a younger age. Erba (1996) and Leereveld (1997) suggested that the first occurrence of *Cribroperidinium*? *tenuiceras* indicates proximity to the Barremian-Aptian boundary. The absence of this dinoflagellate cyst in the Arrifes section may support a pre-Aptian age.

The occurrence of the distinctly Tethyan genera *Cribroperidinium*, *Pseudoceratium*, and *Subtilisphaera* in the Arrifes section contrasts with the absence of boreal taxa. Thus, in the central Algarve Basin, the Barremian dinoflagellate cyst events indicate a strong Tethyan influence, resulting in a more restricted assemblage resembling those of southeastern Europe and northern Africa and less like those of northeastern Europe.

10. Conclusions

The Arrifes section is a 194 m thick stratigraphic succession consisting mainly of interbedded limestones, marly limestones, and marls. A gentle slope carbonate ramp depositional paleoenvironment is suggested for the studied sequences based on evidence from the sedimentology, palynology and palynofacies data. Mid to outer carbonate ramp zones characterised by subtidal conditions make the most of the carbonate facies of the Arrifes section. The vertical organisation of the carbonate ramp depositional settings allows the recognition of several sedimentary intervals related to sea-level changes and the progradation of the carbonate ramp.

The palynological study of the Arrifes section revealed well-preserved assemblages containing 24 spore genera (16 species), 13 pollen genera (6 species), 50 dinoflagellate cyst genera (29 species), and four algal genera. Based on dinoflagellate cysts, the section is assigned to the uppermost Hauterivian to upper Barremian, with three range intervals being recognised: i) uppermost Hauterivian–lowermost Barremian, based on the occurrence of *Subtilisphaera perlucida*; ii) lower to lowermost upper Barremian, based on the first occurrence of *Subtilisphaera scabrata*; and iii) upper Barremian, based on the first occurrence of species of *Odontochitina* such as *O. operculata*.

Overall, the sedimentological and palynological analysis of critical groups and ratios suggests an overall increase in the water column towards the top of the section. During the latest Hauterivian – earliest Barremian, after a mid to outer-ramp settings at the base of the section, a sea level fall is evident, culminating in the subaerial exposure of the carbonate ramp with influx of clastic sediments; the latter, corresponds to the sandstone beds at the base of Interval C. Above the uppermost sandstones beds, the section is of late Barremian age and is characterised by several sea-level change cycles. However, the general trend is an upsection increase in the depth of depositional setting to mid to outer-ramp zones.

The dinoflagellate cyst assemblages recovered in this section proved to be consistent but significantly less diverse than coeval assemblages elsewhere in southern Europe, with recognition of taxa widespread in the Tethyan realm (*Cribroperidinium* spp., *Pseudoceratium pelliferum*, *Hystrichodinium* spp., *Subtilisphaera perlucida*, *S. scabrata*, and *Odontochitina operculata*).

The new palynostratigraphic data suggest that the Arrifes section is older (latest Hauterivian to late Barremian in age) than previously considered (Aptian; Berthou et al., 1983). The section also appears to correlate with the Salema Formation lithostratigraphically and biostratigraphically, implying that a reinterpretation of the significant sedimentary hiatus between upper lower Valanginian to lower upper Barremian in the Algarve Basin is needed. These results and ongoing palynostratigraphic research will better characterise the Lower Cretaceous lithostratigraphic setting of the Algarve Basin.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cretres.2022.105433.