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Paleoenvironmental Approach on the Lower Cretaceous Sequences of Areia do Mastro (Cabo Espichel, Southern Portugal)

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Abstract: This palaeontological study focuses on the sedimentology and palaeofauna of Areia do Mastro locale in Cabo Espichel (Sesimbra, south of Lisbon). Two main geological formations are identified in Areia do Mastro: the Areia do Mastro Formation and the Papo-Seco Formation. We report herein the fossilized vertebrate and invertebrate remains from the basal deposits (marls, sands and gravels) of Papo-Seco Formation assigned to Lower Barremian (Lower Cretaceous). The sedimentological analysis and identified palaeofauna indicated a changing environment with important biological and ecological aspects. Extensive periods of sea level fluctuations and subsequent transgressive marine episodes had as a result the continental infralittoral internal platform to be gradually replaced by a lagoon, as revealed from the fossil remains embodied in the sediments during the formation of the afore mentioned sedimentary sequences.

Key words: Paleo-environment, dinosaurs, Barremian, invertebrates, vertebrates.

1. Introduction

The Early or Lower Cretaceous (145 Ma to 100.5 Ma) [1] is divided into the Berriasian, Valanginian, Hauteriviaa, Barremian, Aptian and Albian ages, from the oldest to the most recent. The layers of Areia do Mastro site present in this study belong to Barremian (129.5 Ma to 125 Ma) [1, 2].

Lower Cretaceous was marked by a great diversity in fauna and flora as a result of continuous rising high temperatures and continental fragmentation. During that period, dinosaurs showed a much higher diversity and a greater expansion within their phylogenetic tree than previously [3, 4]. Ornithopod groups replaced sauropods among herbivores. This change would be related to modifications in flora, with the emergence of the first flowering plants, which also contributed to alterations in biodiversity globally. Following those changes, there were also new species of insects that would develop close ecological relationships with the new plants [3, 4]. Oceans' warming brought about an abundance of sponges, ammonoid cephalopod mollusks, echinoderms, crustaceans and reefs consisting mainly of rudist bivalves. Brachiopods declined in diversity. The neogastropoda (modern gastropod mollusks) emerged in the Cretaceous. Among the tetrapods, turtles, crocodiles, lizards and anuran amphibians flourished. New groups of birds appeared, and within pterosaurs some giant species developed [3]. Some of this fauna is present in the fossil registration in Area do Mastro site: mollusks, turtles, crocodiles, pterosaurs and dinosaurs [5-7].

The very first palaeontological investigations in Cabo Espichel took place in the 19th century [5-9] and

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dinosaur and crocodile teeth were discovered at Boca do Chapim [10]. Later, Lapparent and Zbyszewski [11] reported turtles, crocodiles and dinosaur remains. New discoveries have followed in Papo-Seco Formation ever since. In 2011 it was published skull and other postcranial material that were attributed to *Baryonyx walkeri* [12]. Furthermore, the palaeontological investigations carried out by CPGP: Centro Português de Geo-História e Pré-História (Portuguese Centre of Geo-History and Prehistory) since 1998, produced new reports. These include several bones of an ornithopod dinosaur that were discovered in Boca do Chapim [8, 9, 11, 13-15]. Moreover, vertebrate bone fragments and teeth from crocodylomorphs, pterosaurs, turtles and dinosaurs were found in Areia do Mastro [5-9].

This study is based on a work already published by Figueiredo, et al. [9] within which the palaeoenvironmental context was described. The aim is to describe the environmental changes as seen within the stratigraphic sequence of the Areia do Mastro chiefly through the analysis of the sedimentary facies and the associated fauna.

2. Materials

This study was based on a collection of several vertebrate and invertebrate fossils collected from Areia do Mastro (Fig. 1). That collection is currently part of the palaeontological collection of CPGP. Those fossils are the product of surveys that were held between 1998 and 2019 at the cliffs of Areias do Mastro (Fig. 1) and of excavations of seven clay layers in the lower part of those cliffs between 2004-2009 and 2016-2019.

3. Results and Discussion

3.1 Geologic Setting

The fossiliferous stratigraphic level examined herein belongs to the FrmAM (Areia do Mastro Formation) and FrmPS (Papo Seco Formation) (Lower Barremian -127.5 Ma) [2]. It is located near Sesimbra, in the south west of the Setúbal Peninsula, at about 40 km south of Lisbon (Portugal) (Fig. 2).

Fig. 1 The Areia do Mastro site.

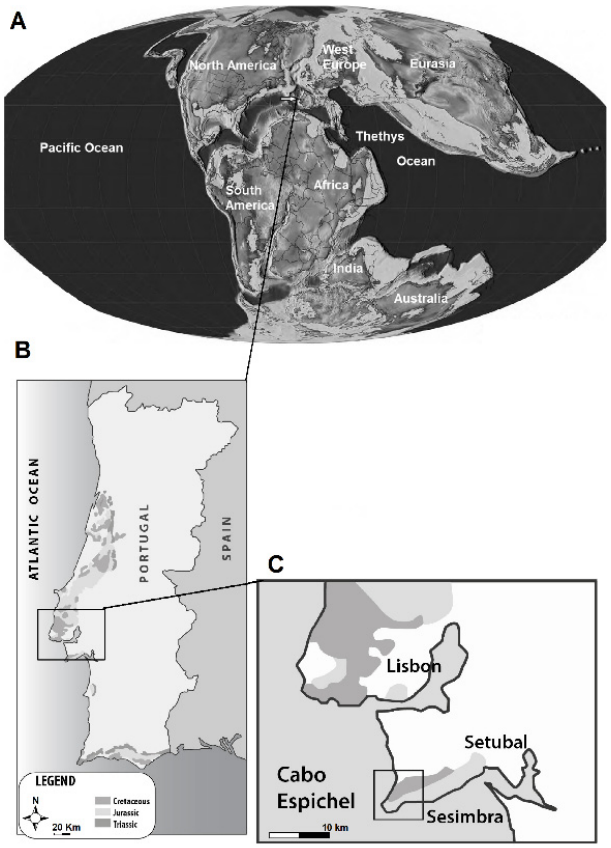

Fig. 2 Early Cretaceous palaeogeographic world map. A: Palaeogeographical location of Portugal during Barremian ~127.5 Ma; B: the Mesozoic sediments of Portugal; C: Lisbon and Setúbal Peninsulas and their associated Mesozoic sediments. Sources: Refs. [4-6, 16, 17].

The studied site, with coordinates 38°24′50.8″ N, 9°13′20.8″ W, is in a small beach (Areia do Mastro, about 1.5 km north of Cabo Espichel) at the coastal cliffs of the Cabo Espichel anticline. This formation lies between the Areia do Mastro Formation and the Boca do Chapim Formation [2]. In this site, only two

layers of the upper limit of FrmAM occur, however the FrmPS, with a thickness of 18 m, preserves its entire sedimentary sequence (Fig. 2). The FrmAM is attributed to the Upper Hauterivian-Lower Barremian and it is a predominantly carbonaceous unit [2, 16, 17]. A sedimentological study took place in the Papo-Seco Formation's lowest exposed layers and revealed the occurrence of two main continental facies and an interbedded transitional one, all in horizontal association without any visible unconformity [6].

3.2 Palaeofaunal Diversity

Broadly, the unearthed fossilized material includes various sizes of marine gastropod mollusks and bivalve shells and further fossilized wood fragments. Fossilized remains of fish teeth and bones and other vertebrate fragments such as those of turtles and dinosaurs were also found. During the field work, invertebrate remains and bivalves of the genus *Nipponomaia* were the most frequent finds. The published vertebrate fossils included mainly fish teeth (*Lepidotes*); crocodyliforms teeth (Cf. *Anteophthalmosuchus* sp.); turtles shells and bones; pterosaurs teeth (*Ornitocheiridae* and *Ctenochasmatoidea*) and teeth and bones of dinosaurs (*Baryonyx*, ornithopods and sauropods) (Fig. 3) [5-7].

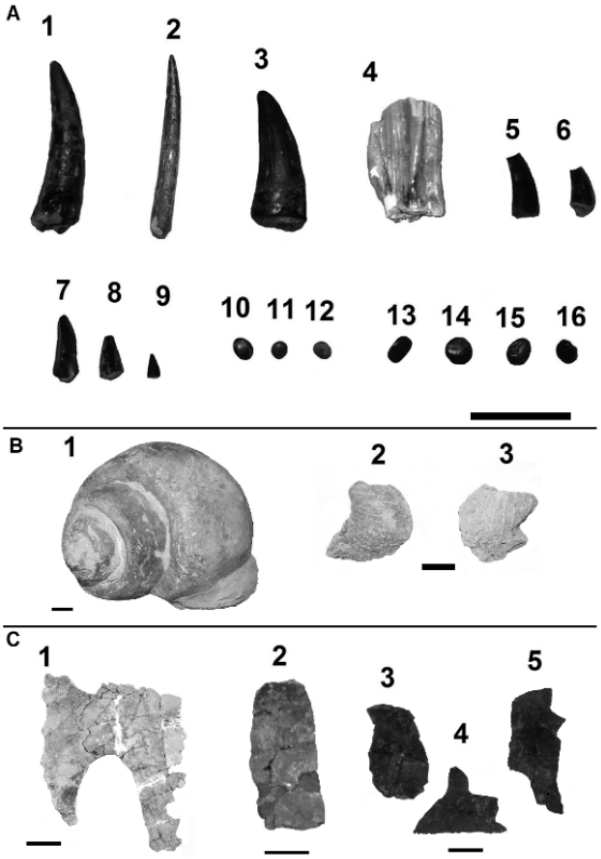

Fig. 3 A-Tetrapod Teeth remains (1: Ornithocheiridae; 2: Ctenochasmatoidea; 3: Baryonyx; 4: cf. *Mantellisaurus*; 5-9: *Anteophthalmosuchus* sp; 10-16: cf. *Lepidotes* sp.); B-1: Naticidae: predatory sea snails, marine gastropod molluskmolluskmollusks; 2 and 3: Bivalves *Nipponomaia*; C-Turtles remains (1: plastron; 2-5 costal plate) (adapted and modified from Refs. [4-6]).

3.3 Paleoecology

In Lower Cretaceous, the climate was generally warmer and more humid than today, probably because of very active volcanism associated with unusually high rates of seafloor spreading. The polar regions were free of continental ice sheets, their land instead covered by forest. Dinosaurs roamed Antarctica, even with its long winter night. Flowering plants (angiosperms) arose close to the beginning of the Cretaceous and became more abundant as the period progressed [17].

The layers in the base of Areias de Mastro's cliff, belong to the top of the FrmAM and are attributed to the Lower Barremian. The sedimentation of this unit was carried out in an environment of an infralittoral internal platform and presents a fauna consisting of marine invertebrates (echinoids, gastropods and bivalves) and foraminifera, which supports this palaeoenvironmental interpretation [2, 16]. In addition to these invertebrates, we also identified the remains of turtles, which persist throughout FrmPS [7]. The layers of the upper boundary of the formation are composed of clayey limestones, where remains of turtles and a very intense dinoturbation (bioturbation caused by the movements of dinosaurs) were found. These remains of turtle and dinoturbation layers are under study by an international team of paleontologists, geologists and GIS (Geographic Informatic Systems) specialists and coordinated by the

first author of this paper (Silvério Domingues Figueiredo). The FrmPS (Lower Barremian) consists of marls, rich in bivalves, green silty clays, with lignite and gypsum inclusions, presenting occasional intercalations of sandstones with horizontal stratification [2]. In the middle of the sequence limestones' intercalations continue. At the upper limit of the formation, the marls are covered by silty limestones [2]. Those sediments were formed in a depositional environment of a lagoon type [2], probably interrupted, in the middle and at the top, by episodic transgressions.

The analysis of this sedimentary sequence suggests that the environment changed from an infralittoral internal platform (in the top of FrmAM), to a lagoon or estuarine type environment. Essentially that replacement was developed gradually by transgressive episodes, resulting from extended periods of sea level rise tautochronous with the formation of this sedimentary sequence. The palaeofauna found sustains the environmental observations for this sequence (Fig. 4). In the carbonaceous layers, fossils of marine invertebrates are predominant, however, remains of marine vertebrates, such as turtle and fish remains, may still occur. In marsh plains and estuarine ecosystems, the remains of vertebrates in general are common [17]. These may include remains of saltwater marine vertebrates (turtles and fish), remains of semiaquatic vertebrates living in freshwater and brackish wetlands (crocodiles, fish and pterosaurs) and other terrestrial vertebrates, such as dinosaurs, which could, occasionally, frequent these environments.

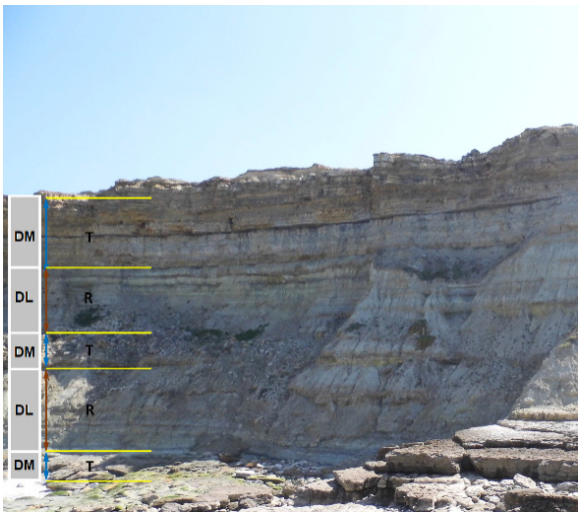

Fig. 4 Areias do Mastro stratigraphic sequence. DL: deltaic/lagoonar sequences; DM: deltaic/marine sequences. T: transgressive phase; R: regressive phase.

The studied layers (basal layers of FrmPS) were formed in an environment of shallow-marine features (lagoon, estuary). The sedimentological analysis and taxon identification suggested an evolution from a closed (estuary) to gradually a more open sea environment (pelagic) [5, 6].

3.4 Discussion

Previous sedimentary studies (combined mineralogical/palynological study by Ruffell and Batten, 1990) suggested that the Barremian paleoclimate was dominated by relative aridity, the fauna and features of the studied layers in Papo-Seco Formation, presenting an estuarine-lagoon type environment with aquatic or semiaquatic fauna, suggest a more humid paleoclimatic interpretation.

As in Kullberg, et al. [18], the western Iberian margin constitutes a passive margin during the late Berriasian-late Aptian, gradually creating full marine conditions southwards by the opening of the shelf to the Atlantic Ocean [20] with a rapid rise in relative sea-level [21, 22]. The vertebrate fauna found in Areia do Mastro is consistent with the fauna of the Lower Cretaceous. In general, the Lower Cretaceous environments are characterized by such fauna: crocodyliforms, turtles, pterosaurs, dinosaurs and *Lepidotes*. The invertebrates are also abundant, with the main fossil occurrence being that of gastropods (especially relatively big sized naticidae) and bivalves (*Nipponomaia*). Other invertebrates are mentioned from these geological formations in other studies [5-7, 14, 15].

Examination of the fossil specimens and sediment samples from a paleoenvironmental perspective, revealed that the basal layer was deposited in a lagoon

or estuarine like environment, whilst the upper layer was deposited in a costal one. The fossilized animal diversity is indicative of the following environments: invertebrate fossils, like *Eomiodon Cuneauos* indicates brackish environment of estuarine type; *Nipponomaia* is a fresh water mollusk of lacustrine floodplain environments, and *Naticids* (Fig. 4) live on sandy substrates at a great variety of depths depending on the species [6]. From the studied material, one species of fish, that of *Lepidotes*, is generally found in environments such as fresh-water lakes and shallow seas; and shared habitat with crocodiles and turtles. The remains of tetrapods (Fig. 3) suggest the following environments: Turtles [7]: represent semi-aquatic to marine environments; crocodiles [5]: represent semi-aquatic environments; pterosaurs: generally, are found in the littoral zone; and dinosaurs: in both terrestrial and the littoral zone. Specifically, *Anteophthalmosuchus* sp. [5] was a semi-aquatic crocodile and its remains are found in areas of open water environments but more broadly in freshwater wetlands and sub-environments such as marshes, swamps and swampy lakes or ponds, streams and rivers. Pterosaurs (*Ornithocheiridae* and *Ctenochasmatoidea*) [5], with dietary habits depended on fish-eating animals, preferred locations near sea and lagoons; *Baryonyx* [5, 10, 12, 22], for the same reasons, inhabited littoral or fluvial zones, lagoons, and estuarine environments as well [6].

4. Conclusion

In the Areia do Mastro stratigraphic distribution of the sedimentary facies, in the basal layers, reflects differences in the depositional style of the paleo-coastal system through time, probably as a function of episodic transgressive-regressive cycles, in shallow marine to a transitional (lagoon, reef, estuarine) and continental environments.

More specifically, it demonstrates an evolution from a lagoon-like (cat's-pond) environment, more closed, to a coastal marine environment. Between these two depositional phases, the increase in the sandy fraction indicates the opening of the lagoon and, possibly, an estuarine episode and agrees with description already provided.

Along the all stratigraphic sequence in Areia do Mastro site, the sedimentary facies and the fossil record in each layer show a predominance of continental environments, interrupted by transgressive episodes, as we can see in Fig. 4. The characteristics of the stratigraphic sequence and the studies on the sedimentary facies and on the fossil record suggest that the environments identified in Areia do Mastro are consistent with those that characterize the Lower Cretaceous.

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