New Dinosaur Tracks from the Lower Barremian of Portugal (Areia do Mastro Formation, Cape Espichel)

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Abstract
We present a new tracksite with multiple dinosaur tracks from the lowermost Barremian (Lower Cretaceous) of the Cape Espichel (Sesimbra, Portugal). The tracks are localized on three beds on the top carbonate beds of the Area do Mastro Formation. Those bioclastic, nodular limestones were deposited in a very shallow subtidal-intertidal, restricted lagoon environment. The track surfaces are very dinoturbated, with a substantial number of tracks. Several tracks assign to sauropods, ornithopods and theropods dinosaurs were recorded. Due to heavy bioturbation and the preservation conditions, it is not possible to define trackways; some preliminary work done on the tracks could disclose some behaviours of their producers. Several species of carnivore and herbivore dinosaurs crossed that large area at different times. Herbivores may have used the lagoon margin as passage between feeding spots, while carnivores frequented the area to hunt in groups or individually.

Keywords
Trampled Surface, Dinosaurs, Locomotion Behavior, Lower Cretaceous, Cape Espichel, Portugal, Iberia
1. Introduction

The very first palaeontological investigations on Cape Espichel took place in the second half of the 19th century. The Portuguese Geological Survey (Sauvage, 1897-1898) reported dinosaur and crocodile teeth from the Papo-Seco Formation, at Boca do Chapim site. Later, Lapparent and Zbyszewski (1957) reported turtle remains and crocodile teeth and bones, as well as dinosaurian remains. Fragments of jaws found at Boca do Chapim by Sauvage (1897-1898) were identified as being from a crocodile (Suchosaurus girardi); they were later analysed by E. Buffetaut and classified as the spinosaurid Baryonyx, based on similarities with the holotype of Baryonyx walkeri from the English Barremian (Buffetaut, 2007). In 2011, O. Mateus and colleagues reported skull and postcranial bones attributed to Baryonyx walkeri (Mateus et al., 2011). In scope of the palaeontological research carried out by the Centro Português de Geo-História e Pré-História (CPGP) in the last 20 years new data on the vertebrate faunas of Cape Espichel has been reported: At Boca do Chapim site, a preliminary analysis of newly discovered material showed several bones of an ornithopod dinosaur (Figueiredo, 2010, 2014); At Praia do Areia do Mastro site, vertebrate bone fragments and teeth of fish (cf. Lepidotus sp.), crocodiles (cf. Anteophtalmosuchus sp.), turtles, pterosaurs (Ornithocheiridae indet. and Ctenochasmatoidea indet.), dinosaurs (Baryonyx sp, Iguanodonts and Sauropoda indet.) were described by Figueiredo et al. (2015, 2016); At Praia do Guincho site, a natural cast of an ornithopod dinosaur track was reported (Figueiredo et al., 2017). In addition to this ichnological finding, in the area of Cape Espichel dinosaur tracks have been reported at several sites, in Upper Jurassic and Lower Cretaceous formations: Praia do Cavalo showed theropod tracks; a trackway of large sauropod is protected at Pedreira do Avelino Natural Monument; from another protected site, Pedra da Mua, trackways of sauropods and theropods were described (Lockley et al., 1994; Santos, 2003, 2008). These three sites are comprised in the Upper Jurassic; Lagosteirios site (Hauterivian, Lower Cretaceous) shows trackways and tracks of theropods and ornithopods (Antunes, 1976, 1990; Carvalho & Santos, 1993; Santos, 2003, 2008).

Trace fossils are useful for palaeontologists because they enable to know more about the activity of ancient organisms. For example, the study of dinosaur tracks has contributed significantly to the understanding of dinosaur behaviour, because they record locomotion gaits and speed, besides daily activities in environments in which the trackmakers lived. Dinosaur herding or other behaviours such as locomotion styles, feet biomechanics and speed calculations have been inferred from several tracksites worldwide (e.g. Castanera et al., 2011; Lockley et al., 1994; Myers & Fiorillo, 2009; Ostrom, 1972). In fact, palaeontologists have learned much more about dinosaur behaviour from trace fossils than from their body fossils’ functional anatomy. The purpose of this paper is to present new dinosaur tracks from Lower Cretaceous of Portugal and to discuss some preliminary data about the dinosaur behaviour represented by those tracks in successive trampled surfaces.
2. Geological, Stratigraphical and Paleoenvironmental Settings

The area of the new dinosaur tracksite is located between Boca do Chapim and Praia do Areia do Mastro sites. Those localities are situated at the coastal cliffs, about 2 km to the north of Cape Espichel (Figure 1), in the municipality of Sesimbra, SW of Setubal Peninsula, about 40 km south of Lisbon (Portugal, western Iberia).

The studied Lower Cretaceous sedimentary beds at Boca do Chapim and Praia do Areia do Mastro sites belong to the Lusitanian Basin, located on the Western Portuguese Margin and extending onshore from Aveiro to Sines (Figure 1). In the Lusitanian Basin, some Lower Cretaceous sedimentary successions present some ichnofossiliferous sites, which include dinosaur tracks.

The new tracksite is distributed in three limestone beds which outcrop at the upper part of the rocky beach, adjacent to a cliff about 60 m high. The cliff exposes a Lower Cretaceous (Barremian) sedimentary succession which includes limestones, marls, sandstones and thin conglomerate levels, deposited in shallow marine, lagoon and estuary environments. Three lithostratigraphic units were defined (from the bottom to top) (Figure 1 and Figure 2): the Areia do Mastro Formation, ascribed to the uppermost Hauterivian to lowermost Barremian; the Papo-Seco Formation, considered lower Barremian; and the Boca do Chapim Formation, dated as middle Barremian (e.g., Rey, 1972; Manupella et al., 1999; Aillud, 2001; Dinis et al., 2008; Rey et al., 2003; Figueiredo et al., 2020) (Figure 2).

**Figure 1.** Location of the Boca do Chapim and Praia do Areia do Mastro sites and stratigraphy: A—Location of Portugal in the world; B—Distribution of the Mesozoic rocks in Portugal (Lusitanian Basin and Algarve Basin); C—Distribution of Mesozoic formations in Lisbon and Setúbal peninsulas; D—Distribution and age of the Cretaceous formations in the area of Cape Espichel (J—Jurassic; C—Cretaceous; M-P—Miocene and Pliocene; Q—Quaternary).
The Areia do Mastro Formation comprises brackish-water estuarine sandstones and silty marls to marine carbonates (Rey, 1972, 1992; Manupella et al., 1999; Rey et al., 2003). The marine beds correspond to marly bioclastic limestones with a fauna consisting of invertebrates (echinoids, naticid gastropods and bivalves), dasycladacean alga and orbitolinid foraminifera (Rey, 1972, 1992; Manupella et al., 1999; Aillud, 2001), which document shallow marine and restricted lagoon environments.

The dinosaur tracks were found in three top beds of the Areia do Mastro Formation, which can be attributed to the lowermost Barremian (Rey, 1972; Manupella et al., 1999; Rey et al., 2003); remains of marine turtles and abundant large naticid gastropods were also found. The dinosaur trampled beds consist of bluish-grey limestones showing a nodular texture due to a high invertebrate bioturbation (mainly *Thalassinoides suevicus*) typical of an intertidal to subtidal lagoon environment (Neto de Carvalho et al., 2007), and that suggests that the dinosaurs crossed an intertidal environment (Figueiredo et al., 2017, 2020).

The penultimate bed of the Areia do Mastro Formation, which is 60 cm thick, consists of a sandy-limestone, with a macrofossiliferous content composed of fragments of turtle shell, fish teeth and internal moulds of naticid gastropods. The last beds of the Areia do Mastro Formation is a 2.1 m thick clay-limestone with fragments of bivalve shells, internal moulds of gastropods and rare fragments of turtle carapaces. The upper part of this bed shows convolute bedding (a probable palaeoseismites). Both beds are light grey in colour and very bioturbated, not only by dinosaurs (tracks), but also by worms and crustaceans (Figure 3). These beds are comprised between a bed of sandy-limestone below and a bed of yellow dolomitic sandstone, the latter already belonging to the Papo-Seco Formation.

3. Materials and Methods

This study consists in the analysis of three big sets of dinosaur tracks found in three different limestone beds located at the top of the Areia do Mastro Formation. Most of the work was carried out in the field, comprising the measurements, GIS location and orientation of each track. More detailed observations of sediment samples and the analysis of the data collected in the field were done in the laboratory.
Figure 3. Stratigraphic column of the transition of the upper beds of the Areia do Mastro Formation to the first bed of the Papo-Seco Formation. L1, L2, L3—indication of the trampled surfaces, presented in this work.

4. Ichnological Description of the Tracksite

During the paleontological field work done in 2019, three trampled beds were identified at Praia do Areia do Mastro site, and at the base of the cliffs between Praia do Areia do Mastro and Boca do Chapim sites. The tracks presented in this work are located at the top of the last two beds of the Areia do Mastro Formation (Figure 3) and, in addition to these tracks, others were identified in the last beds of the Areia do Mastro Formation, but not studied. During the year 2020, field work was done to survey these tracks at these very dinoturbated stratigraphic surfaces. A total of 614 tracks were identified in an area summing about 1350 m² (Figure 4). Positive tracks and negative casts were found.

This set of tracks features a wide variety of producers. Tracks of three different groups of dinosaurs were identified (Figure 5): theropods (93 tracks); sauropods (324 tracks) and ornithopods (197 tracks). In terms of representation percentages, the carnivores are 15%, while herbivores are 85% (31% of ornithopods and 54% of sauropods) (Table 1). The ichnological record is not well preserved, because the intense dinoturbation and by the fact that tracks are exposed in very narrow outcrops at the coastal cliff exposed to an intensive wave erosion. Due to preservational conditions, was not possible to clearly define trackways so far, but it was possible to identify the orientation of each one of the tracks. It was found that the tracks had a very varied orientation. The size of the tracks is also...
**Figure 4.** Location of the beds studied with dinosaur tracks (modified from a Google Earth image).

**Figure 5.** Some of the dinosaur tracks identified in the 3 beds: A-D Bed 1 (L1): A and B: sauropod tracks (A = manus; B = pes); C: ornithopod track (pes); D: Theropod track. E-H Bed 2 (L2): E and F: theropod track; G: sauropod track (pes); H: ornithopod track (pes). I-M Bed 3 (L3): I-L sauropod track (pes), In I (3 tracks) is possible to observe the sedimentary deformation resulting from the pressure of the foot; M: ornithopod track (pes). Scale: A, B, F, J, L, M = 15 cm; C, D, E, G and H = 20 cm; I = 25 cm.
very varied and the morphological differences between some tracks of the same group of dinosaurs suggests that these were produced by individuals of different species and different ages. They may also show preservation variants in substrates originally with different consistencies.

5. Animal Behaviour

Dinosaur tracksites data provide useful complementary constraints on the problem of population density and behaviour of large predators (e.g., Lockley & Hunt, 1995) and other groups of dinosaurs. Dinosaurs gregarious behaviour based on ichnological evidence has been described in several parts of the world and in different ages. Several dinosaur tracksites, especially sauropod tracks, indicate that those animals often formed social groups: an example of this gregarious behaviour are the parallel trackways of sauropods at the Pedra da Mua, in Cape Espichel, dated from the Tithonian, or Las Cerradicas, from the Berriasian of Spain (Lockley et al., 1994; Castanera et al., 2011). On the other hand, some accumulations of dinosaur skeletons with numerous individuals of the same species suggest the existence of very large herds or group gathering (Moreno et al., 2011).

Trackways are the closest thing that we have to motion pictures of the behaviour of fossil animals (Paul, 2010). Tracks, especially when they occur in large numbers, can also give indications about behaviour of fossil vertebrates. Some of dinosaur tracks or trackways have shown that some groups of dinosaurs traveled in groups or herds. Such behaviour has been described from sauropod tracks, at Oxfordshire, from Middle Jurassic of England (Day et al., 2004), at Pedra da Mua (Cape Espichel), from the Upper Jurassic of Portugal (Lockley et al., 1994) and Las Cerradicas (Teruel province), from the Lower Cretaceous of Spain (Castanera et al., 2011), as previously referred; ornithopod trackways at Tereñes (Asturias) from Upper Jurassic of Spain (Pinuela et al., 2016), or hadrosaurid dinosaur trackways at Denali National Park, from the Upper Cretaceous of Alaska (Fiorillo et al., 2014). Some tracksites have also revealed that some herds protected their young by keeping them in the centers of migrating groups (i.e. Malkani, 2007; Diedrich, 2011; Romano et al., 2018; Farlow et al., 2012; Thulborn & Wide, 1989). Other trackways show that dinosaurs did not drag their tails when they walked, which confirms the type of posture evidenced in the ske-
letons of dinosaurs (Paul, 2010). The study of trackways can estimate dinosaur’s gait and speed and provide information about the way of locomotion of dinosaurs, by measuring the pace and stride, or determine the gregarious behaviour shown by some of these animals, when there are parallel trackways, approximately constant distances between those, same direction of movement, tracks with identical depth and preservation, as well an identical estimated speed (e.g., Ostrom, 1972; Lockley et al., 2002; Santos, 2003, 2008). In the case of the new tracksite described in this study, as it was not possible yet to identify trackways, the distance between eventual parallel trackways and speed estimation of the animals were not possible to measure; so, it is not possible to have conclusions about the form of displacement and gregarious behavior of dinosaurs that produced these tracks. In future, more detailed and in-depth studies of the data collected during the field work can give new insights about behavioural parameters. However, the data already analyzed, allow us to make some preliminary behavioural characterization of the dinosaurs that left these tracks.

6. Discussion

The presence of ornithopods, sauropods and theropods is documented in the body fossil record of Lower Cretaceous of Cape Espichel (Lapparent & Zbyszewski, 1957; Antunes, 1976; Mateus et al., 2011; Figueiredo et al., 2015, 2017). With specific regard to the occurrence of dinosaurs in the Barremian it is verified the occurrence of various remains of ornithopods, sauropods and theropods in the Papo-Seco Formation overlying the Areia do Mastro Formation, especially in basal beds of this formation and in the same sites of the tracks presented in this work. The ornithopod remains are comprised of bone elements and teeth of iguanodonts (Lapparent & Zbyszewski, 1957; Figueiredo, 2010, 2014; Figueiredo et al., 2015), and a track cast identified as Iguanodontipus (Figueiredo et al., 2017); the sauropods include a fragment of a caudal vertebra (Figueiredo et al., 2015) and the theropods are represented by bone elements and teeth of Baronyx and Megalosaurus (Lapparent & Zbyszewski, 1957; Buffetaut, 2007; Figueiredo, 2010, 2014; Figueiredo et al., 2015; Mateus et al., 2011). Theropod teeth were recently discovered by the CPGP team, but still unpublished.

In addition to the tracksite described in this work, seven Lower Cretaceous tracksites are known in Portugal. Ornithopod tracks were described in Praia Santa and Praia de Salema, at Vila do Bispo (Algarve basin); from Lusitanian basin, Lagosteirios and Praia do Guincho, at Sesimbra, Praia Grande, at Sintra and Olhos de Água, at Óbidos (Antunes, 1976; Madeira & Dias, 1983; Santos et al., 2003; Santos, 2008; Mateus & Antunes, 2003; Santos, 2008; Figueiredo et al., 2017). Theropod tracks were described at Praia de Salema (Vila do Bispo), at the Algarve Basin, and Lagosteirios (Sesimbra) and Praia Grande (Sintra) sites, at the Lusitanian Basin (Antunes, 1976; Madeira & Dias, 1983; Santos, 2008). Sauropod footprints were described at Praia Grande (Sintra) and Parede (Cascais), both in the Lusitanian Basin (Madeira & Dias, 1983; Santos, 2008; Santos et al., 2015).

The tracks present in this work were found in a context of a carbonate tidal
area. The large number of tracks in three different beds, their general orientation and the diversity of represented dinosaur groups suggest the existence of a coastal area intensely crossed during thousands of years by different species of dinosaurs, mainly herbivores which probably used the area as a passage to different pasture zones. Parallel tracks were not identified but the large number of tracks with similar depth and orientation, mainly of sauropods, could suggest the passage of groups of animals at the same time. The superposition of tracks indicates successive crossing moments. The smaller number of carnivore tracks (Table 1) suggests that theropods could have used that area as a hunting ground. The inferred frequency seems that the large theropods (few tracks identified) may have been solitary hunters with exclusive territorial behaviour, while the small theropods, which left a greater number of tracks there, might have hunted in groups. However, it is difficult to relate observed trackways to grouping behaviour of carnivores. Indeed, the tracks investigated here do not display typical patterns of gregariousness such as those observed for herds of herbivore dinosaurs.

Myers & Fiorillo (2009) stated that sauropods could be segregated in small herds, according to age: the juveniles could live in groups, and adults chosen to live alone. The set of tracks presented in this work shows that the majority of the sauropod footprints belongs to adult individuals. More studies can reveal that the sauropods passed at the same time, or at different times. If the sauropod passed in this place at different times, the hypothesis of Myers and Fiorillo (2009) can reenforce the idea of the sauropods that make those tracks passed alone in the margin of the lagoon.

The fluctuations of sea level in the tidal carbonate environments, with low hydrodynamics, recorded by the dinoturbated stratigraphic surfaces at the top of the Areia do Mastro Formation, likely facilitated the preservation of the dinosaur tracks and probably provided a preferential habitat for these animals, if merely transitional. In other Portuguese ichnofossil sites with occurrence of dinosaur tracks, sediments were deposited in very shallow marine, estuarine or deltaic environments (Santos et al., 2015; Santos, 2003, 2008; Figueiredo et al., 2017).

7. Conclusion

The paleontological sites of Boca do Chapim and Praia do Areia do Mastro have yielded important vertebrate remains, including skeletal fossils of dinosaurs from the Papo-Seco Formation, and new sauropod, ornithopod and theropod trampled surfaces at the top beds of the Areia do Mastro Formation. From the Areia do Mastro formation only, a few dinosaurs remains were known before: two ornithopod track casts (Figueiredo et al., submitted work in 2020).

Those tracksites represents a great increase in paleontological record, in particular the dinosaurs remains of Areia do Mastro Formation and they are relevant as a good evidence of a diverse dinosaur fauna throughout the Lower Cre-
taceous in the Lusitanian Basin. By the large number of tracks identified (the tracksite with the largest number of dinosaur footprints) and data obtained, that may offer an important contribution to the knowledge of the dinosaurs of the Lower Cretaceous, especially about conclusions that may be provided about the social behaviours of these animals. In the heavily dinoturbated surfaces, most of the contemporaneous sauropod tracks belong to adults which may be evidence for gregarious behaviour as previously highlighted for juveniles (e.g., Myers & Fiorillo, 2009). Both large number of sauropod and ornithopod tracks in shallow subtidal-to-lower intertidal environments, found in three different beds, allow considering that these large herbivores used the coastal flats to move between pastures, possibly related with close by alluvial plains, during a large period, contributing for trampling the ground, and for a period that can be measured by thousands of years. Also, the relatively small theropod tracks outnumber the larger tracks of the same group, enabling to identify the predominance of small carnivores in the tidal environments of Cape Espichel during the lowermost Barremian, and possibly chasing for prey in groups.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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