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New ornithopod footprints from the Areia do Mastro Formation (Lower Cretaceous), Espichel Cape (Portugal, Western Iberia) and their context in the Iberian ichnological ornithopod record

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ABSTRACT

Two new ornithopod natural casts are reported from the Praia do Areia do Mastro site, at Espichel Cape (near Sesimbra), western central mainland Portugal (western Iberia). In this Tracksite two geological formations occur: Areia do Mastro Formation and Papo-Seco Formation (lower Barremian). This locality (Praia do Areia do Mastro) occurs in a sedimentary succession comprising limestones, marls, sands and conglomerates, interpreted as marine, lagoonal and estuarine deposits. In the Papo-Seco Formation have yielded fossil remains of dinosaurs (teeth and bones) and other vertebrates (Figueiredo et al., 2015, 2016). The ichnological record is composed by two footprints, one of them incomplete, preserved as natural casts in convex hiporelief. They are tridactyl, mesaxonic and wider than long. The digit impressions are short, wide and have a blunt edge. The footprints present a round and wide posterior surface and have one pad impression in each digit and a wide and subrounded metatarsophalangeal pad impression. Based on the commented features, they are assigned herein to *Caririchnium* isp. This ichnogenus is present in other Lower Cretaceous sites in the Iberian Peninsula and is also present in other Barremian tracksites of Portugal. In Spain, *Caririchnium* tracks are typical of continental settings, while in Portugal they were mainly found in estuarine paleoenvironments. This contribution enhances the knowledge of the Early Cretaceous ornithopod diversity and distribution in the Iberian Peninsula.

1. Introduction

Worldwide, large ornithopod tracks are very abundant in the Cretaceous sedimentary record. They have been found in Europe, Asia, North America, South America, Africa and Australia (see Díaz-Martínez et al., 2015, and references therein). More than 40 ichnotaxa based on large ornithopod tracks were defined but the validity of many of them was questioned because they were poorly preserved tracks and without diagnostic features, with an inadequate diagnosis, or on the basis of temporal and/or geographical criteria (Sarjeant et al., 1998; Lockley et al., 2003; Romero-Molina et al., 2003). Recently, the ichnofamily Iguanodontipodidae were proposed to group the large iguanodontian tracks characterized mainly by mesaxonic, tridactyl and subsymmetrical pes tracks that are as wide as (or wider than) long and have one pad impression

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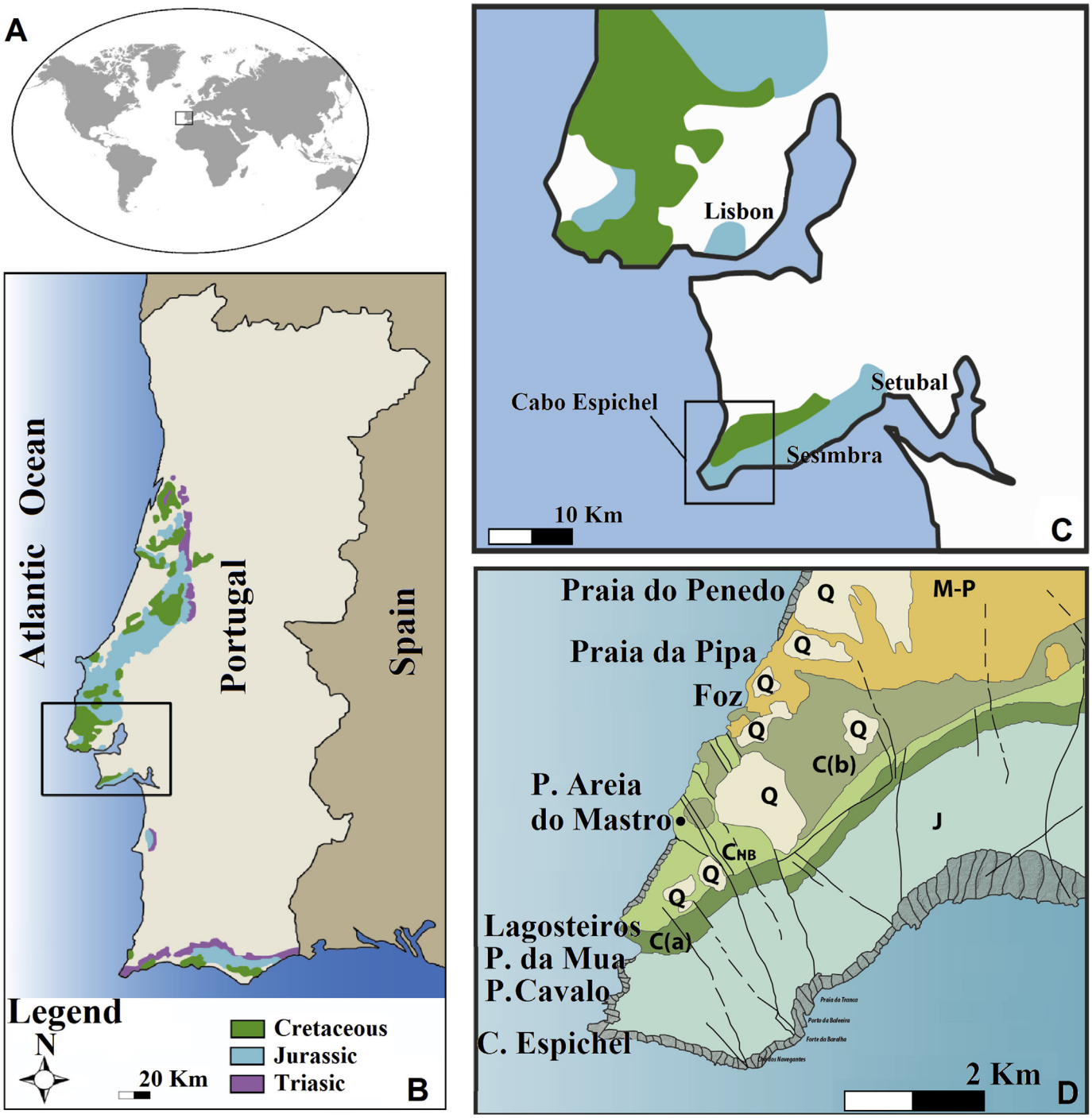

Fig. 1. Location and geology of the Espichel Cape area and the studied site. Adapted from Figueiredo et al. (2015, 2017). A - Location of Portugal; B – Location of Lisbon and Setubal peninsulas in Portugal; C – Location of Espichel Cape, Lisbon and Setubal peninsulas; D – Location of Praia do Areia do Mastro site in the Espichel Cape area. Key: J – Jurassic; C(a) – Cretaceous (Berriasian and Valanginian); Chb – Cretaceous (Hauterivian and Barremian); C(b) – Cretaceous (Aptian and Albian); M–P – Miocene and Pliocene; Q – Quaternary.

in each digit and one in the heel (Lockley et al., 2014; Díaz-Martínez et al., 2015).

In the Iberian Peninsula, several ichnofossil sites found in the Lower Cretaceous, have provided large ornithopod tracks, most of them in Spain (see Casanovas et al., 1993a, 1993b; Castanera et al., 2013; Díaz-Martínez et al., 2015; Pérez-Lorente, 2015 and references therein). In Portugal, the oldest large ornithopod tracks ever found are from Upper Jurassic sedimentary levels (Santos et al., 2000; Mateus and Milàn, 2008; Castanera et al., 2020). From the Lower Cretaceous successions, there are several sites with large ornithopod tracks: Espichel Cape, in Lagosteiros and from Papo-Seco Formation, in Praia do Guincho (Antunes, 1976, 1990; Galopim de Carvalho and Santos, 1992; Santos, 2003; Santos, 2008; Figueiredo et al., 2017), Algarve (Santos et al., 2000, 2013), Óbidos (Mateus and Antunes, 2003) and Sintra (Madeira and Dias, 1983; Santos, 2003, 2008).

Vertebrate fossils from the Espichel Cape are known since the 19th century. Dinosaur, crocodyliforms, turtles and pterosaurs have

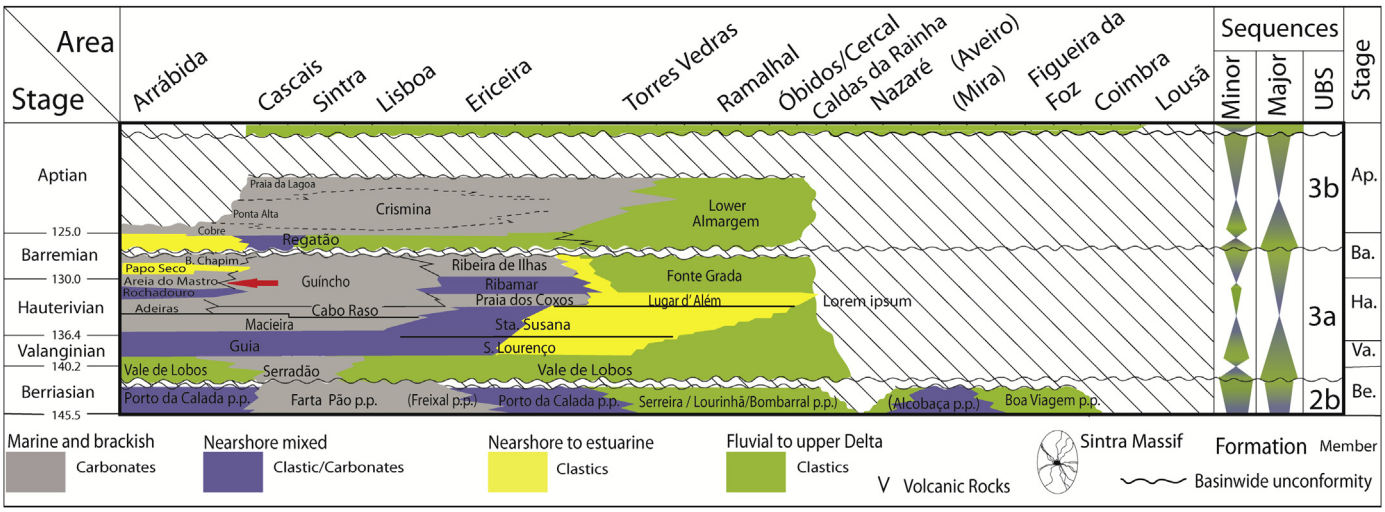

Fig. 2. Synthetic lithostratigraphic chart of the Lower Cretaceous of the western Portuguese margin (modified from Dinis et al., 2008). Triangles: blue - transgressive phase; green regressive phase. UBS: unconformity bounded sequences after Cunha and Pena dos Reis (1995). The studied site is in the Arrábida sector. The red arrow points out the Areia do Mastro Formation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

been reported in the Papo-Seco Formation (Sauvage, 1897; Lapparent and Zbyszewski, 1957; Galton, 1994; Crespo, 2001; Mateus and Antunes, 2003; Buffetaut, 2007; Figueiredo, 2010, 2014; Mateus et al., 2011; Figueiredo et al., 2015, 2016, 2017). In the scope of the palaeontological investigations carried out by the Centro Português de Geo-História e Pré-História (CPGP), vertebrate fossils have been described at the Espichel Cape, from the Papo-Seco Formation: in the Boca do Chapim site, a preliminary analysis of the material discovered showed several bones of an ornithopod dinosaur (Figueiredo, 2010, 2014); in the Praia do Areia do Mastro site, vertebrate bone fragments and teeth belonging to a diverse fauna, including dinosaurs (*Baryonyx* sp., *Mantellisaurus* sp. Iguanodontoidea indet. and Sauropoda indet.), have been reported (Figueiredo et al., 2015, 2016).

At Espichel Cape, dinosaur tracks are known in the Praia do Cavalo and Pedra da Mua sites, which are located in the cliffs beneath the Espichel Cape Sanctuary (Tithonian, Espichel Formation) and in the Lagosteiros site, which is situated on top of a cliff to the north of Lagosteiros Bay (Berriasian; Porto da Calada Formation) (Antunes, 1976; Rey, 1992; Manupella et al., 1999; Santos, 2008). In Praia do Cavalo, a trackway of a large theropod was recognized by Dantas et al. (1994). The Pedra da Mua tracksite reveals at least eight levels with 38 sauropod trackways and 2 theropod trackways (Lockley et al., 1994). At Lagosteiros, two track levels with dinosaur footprints are known (Antunes, 1976; Santos, 2003, 2008). In a Berriasian clastic sequence that overlies the Upper Jurassic (Tithonian) limestones at Lagosteiros Bay, north of Espichel Cape (Sesimbra), two levels with dinosaurs footprints were found: Lagosteiros A - a track level with bipedal dinosaur tracks of a probable theropod (Santos, 2003); and Lagosteiros B - with several tridactyl impressions, a short track related to theropods, and a long sequence of poorly preserved subcircular footprints, with similar size and depth, attributed to a bipedal animal, probably an ornithopod (Antunes, 1976; Galopim de Carvalho and Santos, 1992; Santos et al., 1992). There is also a curious long impression that was interpreted as the tail mark of a dinosaur by Antunes (1976). At Praia do Guincho site (north of Areia do Mastro site), a natural cast of a footprint of an ornithopod dinosaur from Papo-Seco Formation (Barremian) was reported by Figueiredo et al. (2017). In the Boca do Chapim and Praia da Areia do Mastro sites, on the Areia do Mastro Formation, a new set of dinosaur footprints was described, including ornithopod dinosaurs (Figueiredo et al., 2021).

In the Barremian formations of Portugal, dinosaur remains (bones and teeth) have only been found in the Papo-Seco Formation (Lapparent and Zbyszewski, 1957; Mateus et al., 2011; Figueiredo et al., 2015). But dinosaur tracks are not as rare in these areas: four ichnofossil sites contain Barremian ornithopod footprints, which have been described as belonging to the ichnogenus *Iguanodontipus* (Madeira and Dias, 1983; Santos et al., 2000; Mateus and Antunes, 2003; Santos, 2003, 2008, Santos et al., 2013; Figueiredo et al., 2017).

The purpose of this study is to describe two new ornithopod natural casts from Areia do Mastro Formation at the Espichel Cape, which were found by the CPGP team at the Areia do Mastro site (Fig. 1). And discuss their ichnotaxonomical and paleobiological implications within the large ornithopod tracks record from the Iberian Península.

2. Geographical and geological context

The study area is located in the central-western mainland Portugal. The Prai do Areia do Mastro ichnofossil site is in the Espichel Cape area, about 40 km south of Lisbon, in the SW of the Setúbal Peninsula, nearside Sesimbra, with the latitude: 38°16′13″N; and longitude: 9°12′34″W (Fig. 1).

The study area is in the westernmost sector of Iberian Peninsula, focusing the Cretaceous sedimentary record of the Lusitanian Basin (e.g., Wilson et al., 1989). The ichnofossil site is located at the lower portion of the NW coastal cliffs on the Espichel Cape anticline, which mainly comprise Mesozoic (Jurassic and Cretaceous) sedimentary rocks (Fig. 1). At the palaeontological site of Areia do Mastro, only the two upper layers of the Areia do Mastro Formation and the lower part of the Papo-Seco Formation are exposed (Figs. 2, 3).

The Areia do Mastro Formation is mainly assigned to the upper Hauterivian, but the uppermost part of this formation is lower Barremian (Manupella et al., 1999; Aillud, 2001; Figueiredo et al., 2020). The analysed dinosaur tracks were found in a set of fallen blocks from the uppermost layers of the Areia do Mastro Formation (Fig. 3), where was described others dinosaur footprints (Figueiredo et al., 2021). Therefore, they are attributed to the lower Barremian. The upper part of this formation is composed of bioturbated calcareous silty layers with ostreidae remains (Manupella et al., 1999) and also a fauna consisting of marine invertebrates (echinoids, gastropods, bivalves) and foraminifera (Manupella

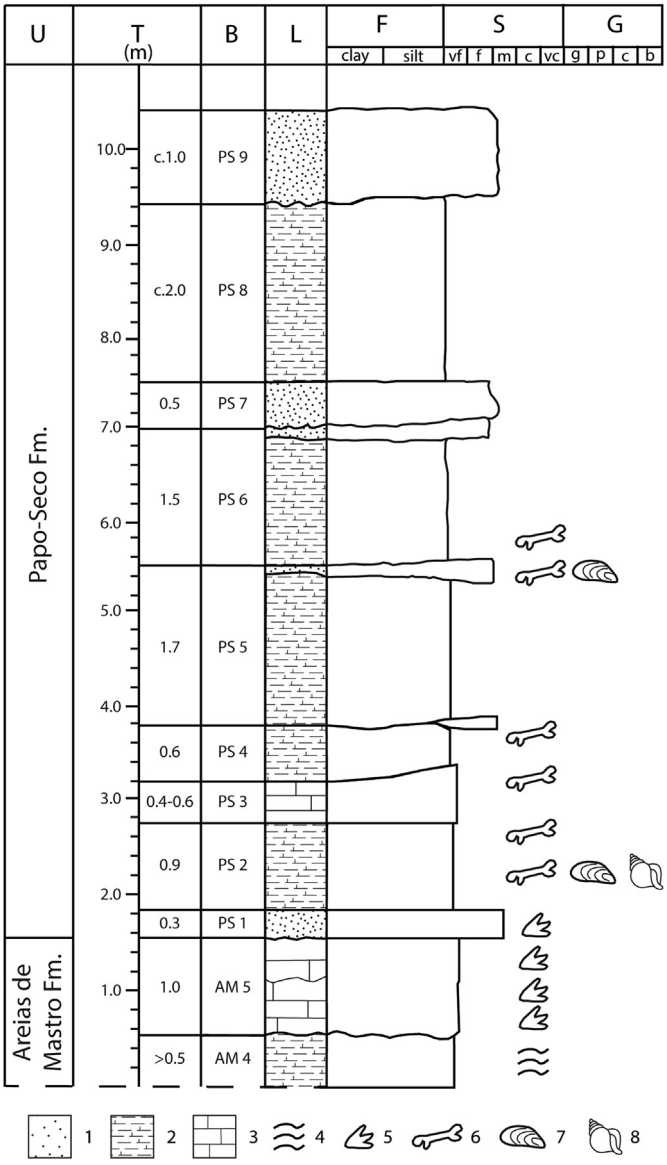

Fig. 3. The stratigraphic column of the Areia do Mastro site: 1 – sandstones;2 – marls; 3 – limestones; 4 – lamination; 5 and 6 – vertebrate fossils (5 – footprints; 6 – bones and teeth); 7 – bivalves; 8 – gastropods. Codes: U – lithostratigraphic unit; T – thickness; B – bed reference; L – Lithology; F – fines; S – sand; G – gravel.

et al., 1999; Aillud, 2001; Rey et al., 2003; Dinis et al., 2016). Sedimentological and palaeontological features of the Areia do Mastro deposits are interpreted as indicating a depositional environment of a marine internal platform. At the cliffs of the Praia do Areia do Mastro beach, the uppermost part of this lithostratigraphic unit comprises a sedimentary succession of marls, lignites and sands, in which dinosaur footprints – but also the fossils of Naticidae gastropods, bivalves and turtles – were found; these characteristics point to a lagoon/estuary type environment (Figueiredo et al., 2020). From a palaeoecological point of view, the composition of the facies suggests that the ornithopod tracks in Areias do Mastro were produced in a marginal-marine environment. The studied tracks are fallen casts and were found in the sector of the beach where the Areia do Mastro Formation crops out. From the lower to uppermost portion of the exposed succession of the Papo-Seco Formation, the layers consist of grey marls, grey carbonate silts and lenses of fine sands, with fossils of gastropods and bivalves and dinosaurs footprints (Figueiredo et al., 2021) (Fig. 3). The tracks, that are also made of silty limestone, are from the layer AM 5 (Fig. 3).

3. Materials and methods

This study is based on two natural casts preserved as convex hyporeliefs (CPGP.01.19.6 and CPGP.01.19.14) housed at the palaeontological collection of the CPGP. These footprint casts resulted from a prospection carried out along the cliffs at the Areia do Mastro site, in 2019. Lithologically, the casts are composed of siliciclastic limestone, with fine-grained, quartz-rich sediments. These two natural casts were found near the sea, on the coast, and are the result of sea erosion of layers located at the cliff base, which drop the casts from their place on the layer. CPGP.1.19.6 is incomplete: digit IV has been lost due to the action of the sea. CPGP.1.19.14 is complete.

In the Laboratório de Arqueozoologia e Paleontologia (LAP) of the CPGP, the casts were visually analysed at different angles of light and on a 3D model, enabling a more detailed analysis. The 3D model used in this study (Fig. 4) was generated and modelled with the *3D Scanner Pro* application. The footprints were measured and studied through a comparison, analysis of the main characteristics, and biometric analysis. Various morphometric parameters of these footprint casts were therefore calculated for comparison following the method of Moratalla et al. (1988) and Mateus and Milàn (2008). The measurements used herein are based on the length of the vertices that are identified by acronyms (Fig. 4) adapted from Moratalla et al. (1988) and Romilio and Salisbury (2011, 2014), and subsequent calculation of ratios between the different parameters. Resulting data for the studied footprints is shown in Fig. 5. The construction of the stratigraphic column followed the usual conventions (e.g., Nichols, 1999; Miall, 2016).

A study was done to calculate the size of the producers of these footprint casts. This study was based on others that estimated the size of producers of footprints attributed to ornithopods. Alexander (1976) calculated the approximate hip height (sum of the femur, tarsus and metatarsus III) by multiplying foot length by 4. Another method was suggested by Sanz et al. (1984) based on a statistical analysis of the skeletal remains of ornithopods using the formula $h = 3.91FL + 10.94$ (h = hip height; FL = foot length). Moreover, Thulborn and Wade (1984) and Thulborn (1990) proposed morphometric and allometric equations for different kind of dinosaurs: small theropods (FL < 25 cm): $h = 4.5FL$; large theropods (FL > 25 cm): $h = 4.9FL$; small ornithopods (FL < 25 cm): $h = 4.8FL$; large ornithopods (FL > 25 cm): $h = 5.9FL$; small dinosaurs in general (FL < 25 cm): $h = 4.6FL$; large dinosaurs in general (FL > 25 cm): $h = 5.7FL$ (Fig. 5).

4. Description

The two natural casts are tridactyl, sub-symmetric and mesaxonic. They are wider than long, present a rounded and wide posterior surface, and short and wide digit impressions (Fig. 6A–D). CPGP.1.19.6 track corresponds to a right pes and preserves only the digit II and III impressions. It is 38.4 cm long, and a width of 42.1 cm is estimated. The digit impressions have a blunt distal edge and semicircular pad impressions. The divarication angle between II and III is 41°. The posterior area shows a broad and semicircular metatarsophalangeal pad impression, which has a width greater than the width of the digit III pad impression. CPGP.1.19.14. is a right pes track and is almost as long as it is wide (36.3 cm and 37.2 cm, respectively). The digit impressions are formed by ovoid pad impressions and have blunt distal edges (the digit III end is narrower than that of CPGP.1.19.6). The metatarsophalangeal pad impression is ovoid in shape, large, and is wider than the width of the digit III

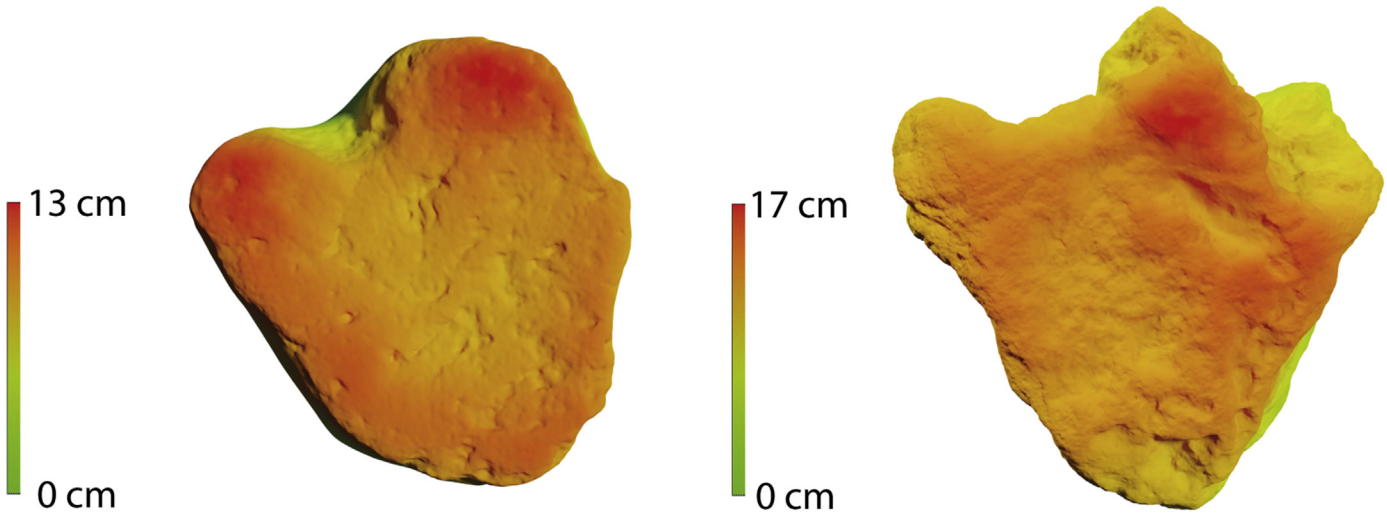

Fig. 4. False color depth map of the photogrammetric digital model (Left: CPGP.1.19.6; right: CPGP.1.19.14). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

pad impression (Fig. 6E–F). Other measures following the proposal of Moratalla et al. (1988) are included in Fig. 5. The divarication angle between digit II and III (35°) is smaller than between digit III and IV (30°) (Fig. 6G–H).

5. Discussion

5.1. Ichnotaxonomy

Although the Praia do Areia do Mastro footprints are not well preserved (sensu Marchetti et al., 2019) the general morphology is consistent with those included within the large ornithopod tracks: generally, they are wider than long or have equal width and length, with short and broad digits, high angle of divarication between digits II–III and III–IV, and the posterior end is rounded and symmetrical (Thulborn and Wade, 1984; Moratalla et al., 1988; Mateus and Milàn, 2008; Figueiredo et al., 2017). These biomorphic descriptions match the morphometric data obtained by Thulborn and Wade (1984) and Moratalla et al. (1988), supporting the idea that the Areia do Mastro site tracks correspond to a large ornithopod trackmaker (see below).

These tracks present diagnostic features of the ichnofamily Iguanodontipodidae Vialov, 1988 as described by Lockley et al. (2014) and Díaz-Martínez et al. (2015): they are mesaxonic, wide or wider than long (Fig. 4); a sub-symmetrical tridactyl shape; one pad impression in each digit and one in the "heel" (visible only in digits II and III, the IV digit is not well-preserved in CPGP.1.19.14 and not preserved at all in CPGP.1.19.6; Fig. 5); and wide posterior surface. The ichnogenera *Iguanodontipus*, *Amblydactylus*, *Caririchnium* and *Hadrosauropodus* were included generally in this ichnofamily. Díaz-Martínez et al. (2015) suggested that the size and shape of the metatarsophalangeal pad and the digit impressions are valuable ichnotaxobases to differ among these ichnotaxa. Thereby, *Iguanodontipus* that is characterized by a small, rounded heel and elongate and narrow digit impressions, *Caririchnium* presents large and rounded heel with short and wide digit impressions, and *Hadrosauropodus* has large and bilobed "heel" and short and wide digit impressions. These authors considered that *Amblydactylus gethingi* is a *nomen dubium* and included the ichnospecies *Amblydactylus kortmeyeri* within *Caririchnium*.

The main features of the Areia do Mastro footprints (i.e., large and rounded posterior surface, large metatarsophalangeal pad impression, approximately as wide as it is long, Fig. 5) allow us to classify them within *Caririchnium* (*sensu* Leonardi, 1984, 1979 and Díaz-Martínez et al., 2015) In CPGP.1.19.14, the distal part of the heel pad impression is clearly subtriangular (Fig. 5E–F), as occurs in ichnospecies *C. magnificum, C. kortmeyeri, C. lotus, C. yeondongensis* and *C. liucixini* (Leonardi, 1984; Currie and Sarjeant, 1979; Xing et al., 2007; Kim et al., 2016); in CPGP.1.19.6, the heel pad impression is not very evident. The preservation of the Areia do Mastro footprints allow us to assign them within the *Caririchnium* ichnogenus, but not to discriminate among their ichnospecies.

5.2. Distribution of Caririchnium in the Iberian Peninsula

The ichnofamily Iguanodontipodidae is mainly related to large ornithopod tracks found in Cretaceous formations of Europe, Asia, and North and South America (Díaz-Martínez et al., 2015, 2016). These authors recognized three ichnogenera belonging to the Early Cretaceous Iguanodontipodidae: *Caririchnium* (Berriasian–Albian), *Iguanodontipus* (Berriasian–Valanginian) and *Hadrosauropodus* (Aptian–Albian to uppermost Cretaceous). In Europe, *Caririchnium* has been identified in the Valanginian–middle Albian, with a good record in the Barremian–Aptian, so there is hardly any overlap with the Berriasian–Valanginian record of *Iguanodontipus*; meanwhile, *Hadrosauropodus* is only known in the Maastrichtian (Díaz-Martínez et al., 2015).

Caririchnium was first defined in South America (Leonardi, 1984) and has been later identified in Europe (Díaz-Martínez 2013; Lockwood et al., 2014), North America (Currie, 1995) and Asia (Xing et al., 2013). According to Díaz-Martínez et al. (2015), *Caririchnium* tracks are known in Europe in several sites from the Iberian Peninsula (Spain and Portugal), England and Switzerland. More precisely, *Caririchnium* tracks are present in the Hauterivian–Barremian Salema Formation of Portugal (Santos et al., 2013; Díaz-Martínez et al., 2015); the basal Valanginian–lower Aptian Urbion Group, and the basal Barremian–middle Albian Enciso Group of La Rioja (Díaz-Martínez, 2013); the Barremian Camarillas and Mirambel formations of Teruel (Cobos and Gascó, 2012; Castanera et al., 2016); the Barremian–Aptian Abejar Formation of Burgos (Torcida et al., 2003; Torcida, 2006), all in Spain; also in the Barremian Wessex Formation of England (Lockwood et al., 2014); and in the Aptian Schrattenkalk Formation of Switzerland (Meyer and Thüring, 2003). Some of the Iberian tracks were previously described as "ornithopod footprints"

Measurements (cm)	CPGP.1.19.6	CPGP.1.19.14
L; L3	38,4	36,3
W	42,1*	37,2
R L/W	0,91*	0,97
L2		37,5
BL2		12
WM2		16
Wb2		12
K	28	33
M	30	32
BL3	14,5	13,5
WM3	10,5	10
Wb3	18,4	15,5
L4	37	37
BL4	10,5	12
WM 4	10,5	10
Wb4	14	11,5

Measurements - Heel (cm)	CPGP.1.19.6	CPGP.1.19.14
HL	20,1	27,3
HW	22,2	27,1
HW/ Wb3	21,9/14,5	27,1/13,5

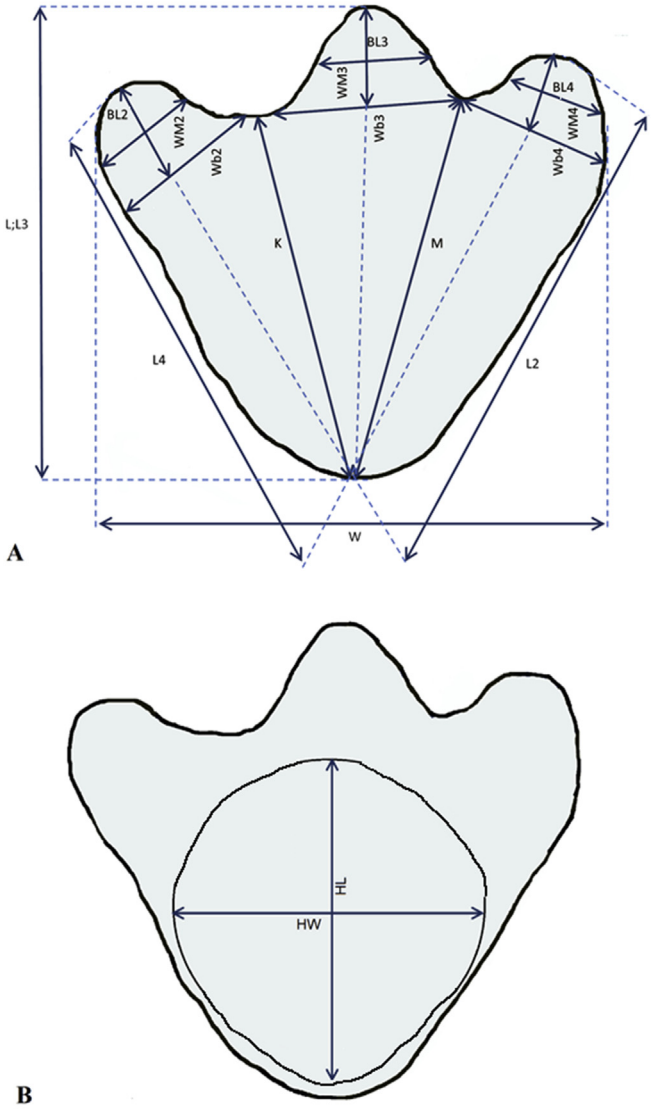

Fig. 5. Left: Measurements of the morphometric parameters. Right: A - outline and morphometric analysis (adapted from Moratalla et al., 1988 and Figueiredo et al., 2017); B - morphometric analysis of the heel of footprints CPGP.1.19.6 and CPGP.1.19.14. Dimensions and angles. Keys: BL2 to BL4 - digit lengths; HL - heel length; HW - heel width; K and M: interdigital (hypex) lengths; L - length; L2 to L4 - length of digits 2 to 4; W - width; Wb2 to Wb4 - proximal basal digit lengths; Wm2 to WM4 - middle digit widths; *estimate measurements.

or referred to ichnotaxa such as *Iguanodonipus* or *Brachyguanodonipus* (see Díaz-Martínez et al., 2015).

Of the four recognized ichnospecies of *Caririchnium* by Díaz-Martínez et al. (2015), *C. magnificum*, *C. billsarjeanti* and *C. lotus* would be present in the European record, and two of them - the ichnospecies types *C. magnificum* and *C. lotus* - would be in the Iberian record (i.e., in the Enciso Group of La Rioja; see Díaz-Martínez, 2013; see also Casanovas et al., 1989, 1993a, b, 1995a, b; Moratalla, 1993; Moratalla et al., 2003; Pérez-Lorente, 2003; Jiménez-Vela and Pérez-Lorente, 2005–2006; Razzolini et al., 2016). Other recently published ichnospecies of *Caririchnium* (*C. yeondongensis* and *C. liucixini*) were recorded in Asia (Xing et al., 2016; Kim et al., 2016).

The Barremian age of the Areia do Mastro Formation is consistent with the temporal distribution of *Caririchnium* in Europe, i.e., Barremian–middle Albian (see Díaz-Martínez et al., 2015: fig. 10B). This finding increases the distribution of *Caririchnium* tracks in a formation where they were not known so far. Moreover, it confirms the presence of this ichnogenus in Portugal at that age.

5.2.1. Caririchnium *record in Portugal*

In addition to the footprints described in this work, six Lower Cretaceous track sites with large ornithopod footprints have been described in Portugal, including formations from the Algarve and Lusitanian basins (Table 1). In Praia Santa, Praia de Salema, Praia do Guincho and Praia Grande, the footprints were originally attributed to the ichnogenus *Iguanodontipus* (Santos, 2003; Santos et al., 2013; Figueiredo et al., 2017), they could be assigned to *Caririchnium* as the tracks exhibit typical features of this ichnotaxon, as the pes tracks are large, tridactyl, with short, wide digits (Díaz-Martínez et al., 2015). In the case of Olhos de Água, Mateus and Antunes (2003) considered that the morphotype 1 was produced by an "iguanodontid trackmaker" that could be *Iguanodontipus* or *Caririchnium*. Based on figures 4 and 5B of Mateus and Antunes (2003),

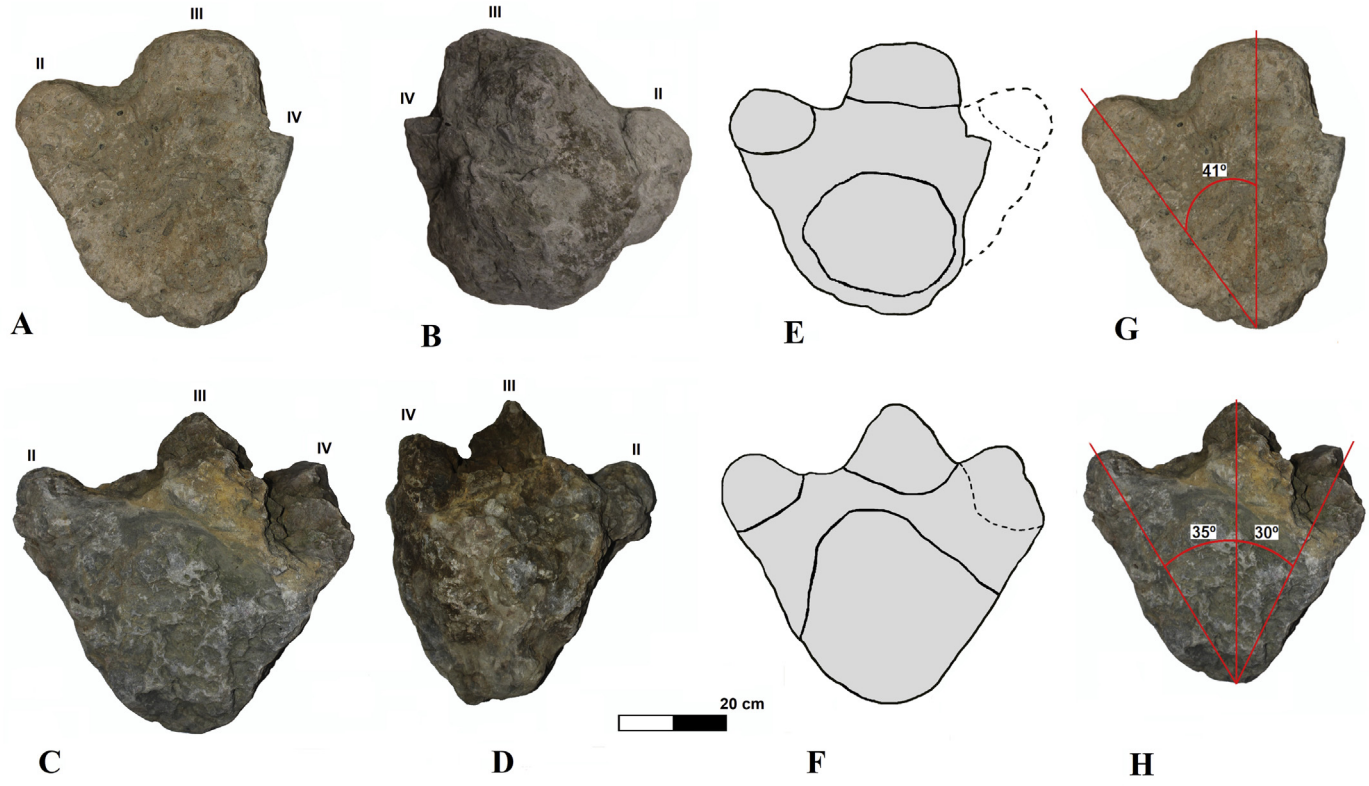

Fig. 6. A–D: Photographs of natural casts CPGP.1.19.6 (A and B) and CPGP.1.19.14 (C and D): A and C, top view; B and D, base view; E–F: drawing (top view) of CPGP.1.19.6 (E) and CPGP.1.19.14 (F), showing the estimate form of the IV digit and its digit pad of CPGP.1.19.6, in E, and the pad impressions identified in the natural casts; G–H: Angle of divarication between digits II–III and III–IV of natural casts CPGP.1.19.6 (A) and CPGP.1.19.14 (B). Scale: 20 cm.

the tracks are similar to those of *Caririchnium* in having both wide heel and digit impressions. It should be noted that there are five trackways assigned to morphotype 1 and manus prints are visible in one of them (Mateus and Antunes 2003).

In Lagosteiros, the footprints are almost subcircular in shape and do not reveal any morphological feature, therefore, they cannot be assigned to a precise ichnotaxon. In the other track sites, several footprints exhibit morphological features: in Praia de Salema, the footprints are tridactyl and mesaxonic, are as long as they are wide, and present short toes with rounded distal ends and symmetrical heel impressions (Santos et al., 2013). In Praia Santa, there is an isolated tridactyl and mesaxonic footprint, with rounded distal ends. Its length is equal to its width, and it has a symmetrical and U-shaped heel impression. There are also four tridactyl and mesaxonic footprints with rounded digits. These footprints are longer than they are wide, rotated inward, and they have a symmetrical impression mark with two indentations (Santos et al., 2013). In Praia do Guincho, there is an isolated cast of a tridactyl footprint with length similar to its width. It has a digitigrade and rounded morphology. It has short and round digits, with blunt tips. The heel area has a wide and rounded form (Figueiredo et al., 2017). The ornithopod footprints of Praia Grande are wide with short and

Table 1
Portuguese Lower Cretaceous track sites with large ornithopod footprints.

Tracksite	Localization	Geologic Unit	Stage	Stratigraphic Unit	Ichnotaxon	Ichnotaxonomic reinterpretation	References
Olhos de Água	Óbidos	Lusitanian Basin	Aptian–Albian	Complexo gresoso de Olhos Amarelos e Pousio da Galeota	*Iguanodontipus* isp/ *Caririchnium* isp	*Caririchnium* isp	Mateus and Antunes, 2003
Praia Grande	Sintra	Lusitanian Basin	lower Aptian	Camadas de Almargem	*Iguanodontipus* isp	*Caririchnium* isp	Madeira and Dias, 1983; Santos, 2003, 2008
Praia Santa	Vila do Bispo	Algarve Basin	lower Barremian	Salema Formation	*Iguanodontipus* isp	*Iguanodontipus* isp *Caririchnium isp*	Santos et al., 2000; Santos, 2013
Praia de Salema	Vila do Bispo	Algarve Basin	lower Barremian	Salema Formation	*Iguanodontipus* isp	*Caririchnium* isp	Santos et al., 2000; Santos, 2013
Praia do Guincho	Sesimbra/Cabo Espichel	Lusitanian Basin	lower Barremian	Papo-Seco Formation	*Iguanodontipus* isp	*Caririchnium* isp	Figueiredo et al., 2017
Areia do Mastro	Sesimbra/Cabo Espichel	Lusitanian Basin	lower Barremian	Areia do Mastro Formation	*Caririchnium* isp	*Caririchnium* isp	This study
Lagosteiros	Sesimbra/Cabo Espichel	Lusitanian Basin	Hauterivian	Ladeiras Formation	Ornithopoda ind.	Undetermined	Antunes, 1976; Santos el al., 1992; Santos, 2003

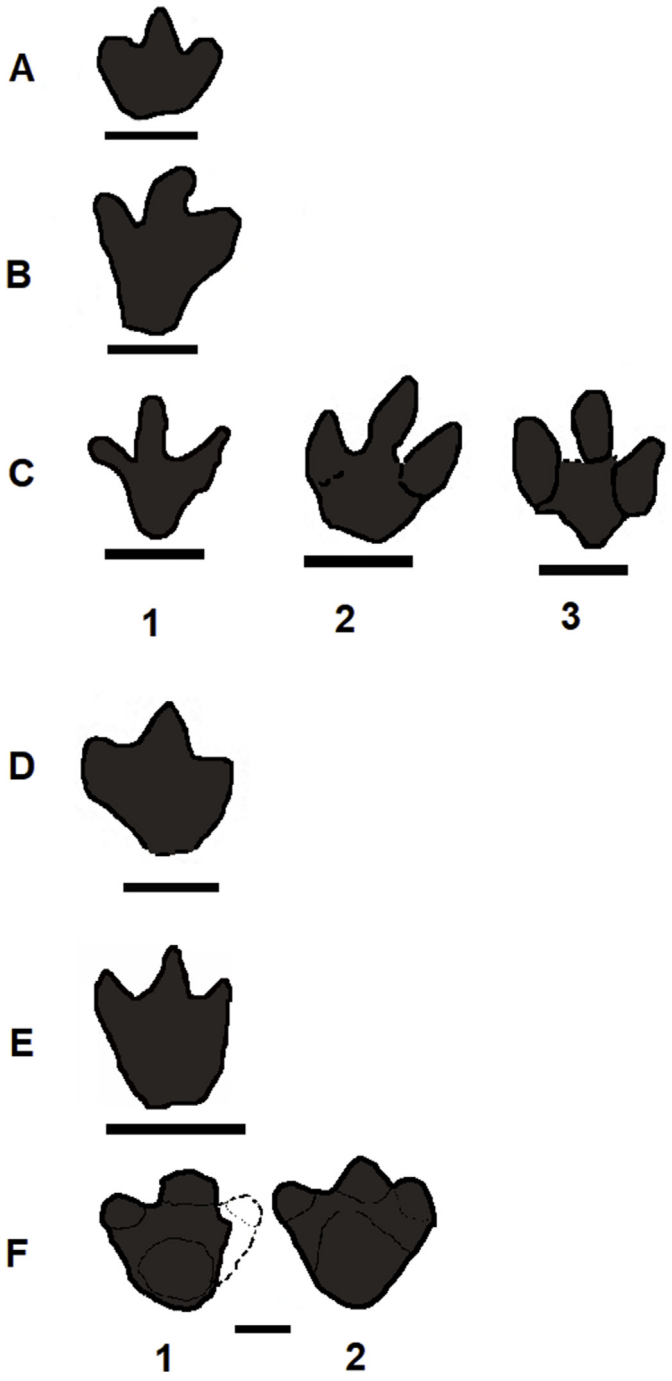

Fig. 7. Footprints of Lower Cretaceous Portuguese ichnofossil sites: A: Olhos de Água (redrawn from Mateus and Antunes, 2003); B – Praia Grande (redrawn from Santos, 2008); C – Praia Santa: 1 – Isolated footprint from level 1 (SAN1-1); 2 – footprint from trackway 1 (SAN2 -T1), level 2; 3 – footprint from trackway 2 (SAN2 -T2), level 2 (redrawn from Santos et al., 2013); D – Praia de Salema (redrawn from Santos et al., 2013); E – Praia do Guincho (redrawn from Figueiredo et al., 2017); F – Areia do Mastro: 1 – CPGP.1.19.6; 2 – CPGP.1.19.14.

round digits and a U-shaped heel mark (Madeira and Dias, 1983). In Olhos de Água, the footprints have a large size, with wide and round digit marks, length similar to their width, and the "heel" print is curved (Mateus and Antunes, 2003).

Most of the morphological features of the footprints of these Portuguese track sites suggest that they are closer to the ichnogenus *Caririchnium*. If so, this indicates that only the ichnogenus *Caririchnium* is present so far in the Lower Cretaceous ichnological record of Portugal. The length/width ratio is 0.91 in CPGP.1.19.6 (estimated) and 0.97 in CPGP.1.19.14 (Fig. 5). However, the length/width ratio of these casts is in the same pattern of *Iguanodontipus*; the footprints of Areia do Mastro are larger than the most *Iguanodontipus* footprints and present some features such as large and rounded heel, short and wide digits, and a quadripartite morphology consisting of impressions of three digits and a heel pad (Figs. 4, 5), which are anatomical characters consistent with the diagnosis of ichnogenus *Caririchnium*, following Leonardi (1984), Lockley et al. (2014) and Díaz-Martínez et al. (2015).

Except for some prints of Praia Santa (Fig. 7, C2 and especially C3) that are *Iguanodontipus*-like, other tracks appear to be similar to those of the ichnogenus *Caririchnium*. Pending a detailed review of the tracks and trackways of these Portuguese sites, it seems that *Caririchnium* is the most representative ichnogenus in the Lower Cretaceous ichnological record of Portugal.

5.3. Possible trackmaker

Tracks belonging to *Caririchnium* (and other ichnogenera of Iguanodontipodidae) can be assigned to iguanodontian ornithopods. Following Díaz-Martínez et al. (2015), a basal member of Ankylopollexia or a basal Styracosterna may have been the producer of the tracks. Several basal styracosternan taxa are represented by skeletal remains in the Barremian fossil record of the Iberian Peninsula, including species of *Iguanodon*, *Mantellisaurus*, *Morelladon* and *Delapparentia* (see Sanz et al., 1984; Ruiz-Omeñaca, 2011; Gasulla et al., 2015; Verdú et al., 2015, 2019, 2020 and references therein). The Barremian formations of Portugal have yielded osteological remains that have been referred to *Iguanodon* and *Mantellisaurus* (Lapparent and Zbyszewski, 1957; Crespo, 2001; Mateus and Antunes, 2003; Figueiredo et al., 2015), although part of this material is under review.

After we applied Alexander (1976) formula to the footprints under study, we concluded that the producer had a hindlimb with a hip height of 1.54 m, for the producer of CPGP.1.19.6, and 1.46 m for the producer of CPGP.1.19.14. The application of the formula suggested by Sanz et al. (1984) to footprints CPGP.1.19.6 and CPGP.1.19.14 resulted in slightly higher values: 1.61 m and 1.53, respectively. Applying the values of Thulborn and Wade (1984) and Thulborn (1990) for large ornithopods to the footprint casts, we estimate the total height of the limb (up to the acetabulum) at 2.27 m for CPGP.1.19.6 and 2.14 m for CPGP.1.19.14.

Among all the methods used above to estimate the hip height of the producers, resulting values vary between a minimum of 1.54 m/1.45 m and a maximum of 2.27 m/2.14 m. In contrast to the methods suggested by Thulborn and Wade (1984) and Thulborn (1990), those proposed by Alexander (1976) and Sanz et al. (1984) appear inaccurate, as they are too general and not attuned to the different groups of dinosaurs. Unfortunately, the finding with an isolated footprint prevents further considerations.

5.4. Palaeoenvironment

The palaeoenvironment where the natural casts were found constitutes a transgressive unit deposited in a valley previously excavated during a sea level drop. In other Portuguese ichnofossil sites with occurrence of *Caririchnium,* the footprints are in sediments deposited in marine/estuarine environments. On the other hand, *Caririchnium* tracks found in the Lower Cretaceous of Spain seem to represent continental environments (see Díaz-Martínez, 2013; Castanera et al., 2016). For instance, the Urbión Group consists of fluvial deposits interbedded with channels while the Enciso Group is a siliciclastic to carbonate mixed lacustrine system with occasional marine incursions (Clemente, 2010). On the other hand,

the Camarillas Formation is related to fluvial systems with of channels low sinuosity (Molina and Yébenes, 1987) and the Mirambel Formation to alluvial and shallow lacustrine deposits with a certain marine influence (lagoon deposits) (Castanera et al., 2016). Finally, the Abejar Formation is interpreted as a braided fluvial system (Clemente and Alonso, 1990).

Therefore, *Caririchnium* tracks would span a wide range of palaeoenvironments, mainly occurring in lowland, marshy and estuarine environments in the Iberian Peninsula.

6. Conclusions

The Areia do Mastro palaeontological site at Espichel Cape (near Sesimbra, Portugal) has yielded an important set of fossil remains, including vertebrate bones and footprints. These include fossils of actinopterygian fish, crocodyliforms, pterosaurs and dinosaurs. Most of the remains were collected in the basal layers of the Areia do Mastro Formation (lower Barremian). This work presents the first ichnological evidence from this site and from this lithostratigraphic unit. Two footprint casts were found near the seashore: they are the result of marine erosion of the cliff basal layers, which dropped the casts from its position on the layer. The sedimentology of the deposits indicates an infralittoral internal platform environment. The fossil association, consisting of marine invertebrates (echinoids, gastropods and bivalves), marine turtles and foraminifera, is consistent with the paleoenvironmental interpretation.

Dinosaur ichnofossils from the Areia do Mastro Formation are two large-sized, subsymmetric tridactyl pes natural casts, with a length similar to their width, but slightly wider. Based on the general shape (short and rounded digit impressions, rounded overall outline, high angle of divarication between digits) and size (maximum width around 40 cm), the tracks are considered to belong to large ornithopods. They share features with the ichnofamily Iguanodontipodidae: mesaxonic, tridactyl and subsymmetric pes tracks that are as wide as (or wider than) they are long and had one pad impression in each digit and one in the heel. The Areia do Mastro footprint casts are referred to the ichnogenus *Caririchnium* based on the following characters: large and rounded metatarsophalangeal pad impression that is wider than the maximum width of the proximal part of digit III impression; short, wide digit impressions. A review of large ornithopod tracks from the Lower Cretaceous (mainly Barremian) formations of the Algarve and Lusitanian basins suggests that *Caririchnium* is a representative ichnotaxon of the Iberian record and it is present in both continental and estuarine palaeoenvironments.

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References

Aillud, G.F., 2001. Palaeoecology, Palaeoenvironmental Analysis and their Application to Sequence Stratigraphy: Lower Cretaceous, Lusitanian Basin, Portugal. PHD Dissertation. University of Plymouth.

Alexander, R., 1976. Estimates of speeds of dinosaurs. Nature 261, 129–130.

Antunes, M.T., 1976. Dinossáurios eocretácicos de Lagosteiros. Ciências da Terra (UNL) 1, 1–35.

Antunes, M.T., 1990. Dinossáurios em Sesimbra e Zambujal: episódios de há cerca de 140 milhões de anos. Sesimbra Cultural 12–14, 0.

Buffetaut, E., 2007. The spinosaurid dinosaur Baryonyx (Saurischia, Theropoda) in the Early Cretaceous of Portugal. Geological Magazine 144, 1021–1025. https://doi.org/10.1017/S0016756807003883.

Casanovas, M.L., Fernández, A., Pérez-Lorente, F., Santafé, J.V., 1989. Huellas de dinosaurio de La Rioja. Yacimientos de Valdecevillo, La Senoba y de la Virgen del Campo. Ciencias de la Tierra 12, 1–190.

Casanovas, M.L., Ezquerra, R., Fernández, A., Pérez-Lorente, F., Santafé Llopis, J.V., et al., 1993a. Icnitas de dinosaurios. Yacimientos de Navalsaz, Las Mortajeras, Peñaportillo, Malvaciervo y la Era del Peladillo 2, (La Rioja, España). Zubía Monográfico 5, 9–133. https://doi.org/10.1093/jisesa/ieu138.

Casanovas, M.L., Ezquerra, R., Fernández, A., Pérez-Lorente, F., Santaté, J.V., et al., 1993b. Tracks of a herd of webbed Ornithopoda and other footprints found in the same site (Igea, La Rioja, Spain). Revue de Paléobiologie 7, 29–36.

Casanovas, M.L., Ezquerra, R., Fernández, A., Pérez-Lorente, F., Santafé, J.V., et al., 1995a. Huellas de dinosaurio en el yacimiento de Soto 3 (La Rioja, España). Ciencias de la Tierra 18, 27–28.

Casanovas, M.L., Ezquerra, R., Fernández, A., Montero, D., Pérez-Lorente, F., et al., 1995b. El yacimiento de La Canal (Munilla, La Rioja. España). La variación de la velocidad en función del tamaño del pie de los ornitópodos. Zubía 13, 55–81. https://doi.org/10.1093/jisesa/ieu138. PMID: 25527586.

Castanera, D., Pascual, C., Razzolini, N.L., Vila, B., Barco, J.L., Canudo, J.I., 2013. Discriminating between medium-Sized tridactyl trackmakers: Tracking ornithopod tracks in the base of the Cretaceous (Berriasian, Spain). PLos One 8 (11), e81830. https://doi.org/10.1371/journal.pone.0081830.

Castanera, D., Díaz-Martínez, I., Moreno-Azanza, M., Canudo, J.I., Gasca, J.M., 2016. An Overview of the Lower Cretaceous Dinosaur Tracksites from the Mirambel Formation in the Iberian Range (NE Spain). New Mexico Museum of Natural History and Science Bulletin 71, 64–74.

Castanera, D., Silva, B.C., Santos, V.F., Malafaia, E., Belvedere, M., 2020. Tracking Late Jurassic ornithopods in the Lusitanian Basin of Portugal: Ichnotaxonomic implications. Acta Palaeontologica Polonica 65 (2), 399–412.

Clemente, P., 2010. Revisão da estratigrafia cretácea jurássica superior no oeste da Bacia de Cameros, norte da Espanha. Revista de la Sociedad Geológica de España 23 (3–4), 101–143.

Clemente, P., Alonso, A., 1990. Estratigrafia e sedimentologia das facções continentais do Cretáceo Inferior na borda sul da Bacia de Los Cameros. Estudos Geológicos 46 (3–4), 257–276.

Cobos, A., Gascó, F., 2012. Presencia del icnogénero Iguanodontipus en el Cretácico Inferior de la provincia de Teruel (España). Geogaceta 52, 185–188.

Crespo, E.G., 2001. Paleo-Herpetofauna de Portugal. Museu Bocage - M.N.H.N., Lisboa, p. 183.

Cunha, P.P., Pena dos Reis, R., 1995. Cretaceous sedimentary and tectonic evolution of the northern sector of the Lusitanian Basin. Cretaceous Research 16, 155–170. https://doi.org/10.1006/cres.1995.1013.

Currie, P.J., 1995. Ornithopod trackways from the Lower Cretaceous of Canada. In: Sarjeant, W.A.S. (Ed.), Vertebrate Fossils and the Evolution of Scientific Concepts. Gordon & Breach, Amsterdam, pp. 431–443.

Currie, P.J., Sarjeant, W.A.S., 1979. Lower Cretaceous dinosaur footprints from the Peace River Canyon, British Columbia, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology 28, 103–115.

Dantas, P., Santos, V.F., Lockley, M.G., Meyer, C.A., 1994. Footprint evidence for limping dinosaurs from the Upper Jurassic of Portugal. Gaia 10, 43–48.

Díaz-Martínez, I., 2013. Icnitas de dinosaurios bípedos de La Rioja (Cuenca de Cameros, Cretácico Inferior): icnotaxonomía y aplicación paleobiológica. PhD dissertation. Universidad de La Rioja, Logroño, Spain, p. 650.

Díaz-Martínez, I., Pereda-Suberbiola, X., Pérez-Lorente, F., Canudo, J.I., 2015. Ichnotaxonomic Review of Large Ornithopod Dinosaur Tracks: Temporal and Geographic Implications. PLos One 10 (2), e0115477. https://doi.org/10.1371/journal.Pone.0115477.

Díaz-Martínez, I., de Valais, S., Cónsole-Gonella, C., 2016. First evidence of Hadrosauropodus in Gondwana (Yacoraite Formation, Maastrichtian-Danian), northwestern Argentina. Journal of African Earth Sciences 122, 79–87.

Dinis, J., Rey, J., Cunha, P.P., Callapez, P., Pena dos Reis, R., 2008. Stratigraphy and allogenic controls of the western Portugal Cretaceous: an updated synthesis. Cretaceous Research 29, 772–780. https://doi.org/10.1016/j.cretres.2008.05.027.

Dinis, P.A., Dinis, J.L., Mendes, M.M., Rey, J., Pais, J., 2016. Geochemistry and mineralogy of the Lower Cretaceous of the Lusitanian Basin (western Portugal): Deciphering palaeoclimates from weathering indices and integrated vegetational data. Comptes Rendus Geoscience 348, 139–149.
Figueiredo, S.D., 2010. Breve Notícia sobre a Descoberta de um Novo Dinossáurio Ornitópode no Cabo Espichel. Boletim do Centro Português de Geo-História e Pré-História III (4), 7–15.
Figueiredo, S.D., 2014. Os Dinossáurios em Território Português: as espécies, as jazidas e os fósseis. Chiado Editora, Lisboa, p. 232.
Figueiredo, S.D., Rosina, P., Figuti, L., 2015. Dinosaurs and other vertebrates from the Papo-Seco Formation (Lower Cretaceous) of southern Portugal. Journal of Iberian Geology 41 (3), 301–314. https://doi.org/10.5209/rev_JIGE.2015.v41.n3.47828.
Figueiredo, S.D., Strantzali, I., Rosina, P., Gomes, M., 2016. New Data about the Paleo Environment of the Papo-Seco Formation (Lower Cretaceous) of Southern Portugal. Journal of Environmental Science and Engineering A 5, 463–470. https://doi.org/10.17265/2162-5298/2016.09.004.
Figueiredo, S.D., Dinis, P., Belo, J., Rosina, P., Strantzali, I., 2017. A new record of a possible ornithopod footprint from the Lower Cretaceous of Cabo Espichel (Sesimbra, Portugal). Bollettino della Società Paleontologica Italiana 56 (2), 217–231.
Figueiredo, S.D., Rosina, P., Strantzali, I., Antunes, V., Figueiredo, S., 2020. Paleo-environmental Changing Approach on the Lower Cretaceous Sequences of Areia do Mastro (Cabo Espichel, Southern Portugal). Journal of Environmental Science and Engineering A 9, 66–71. https://doi.org/10.17265/2162-5298/2020.02.003.
Figueiredo, S., Carvalho, C., Cunha, P., Carvalho, I., 2021. New Dinosaur Tracks from the Lower Barremian of Portugal (Areia do Mastro Formation, Cape Espichel). Journal of Geoscience and Environment Protection 9, 84–96. https://doi.org/10.4236/gep.2021.91007.
Galopim de Carvalho, A.M., Santos, V.F., 1992. Sesimbra, um pólo importante para o conhecimento da história dos dinossáurios em Portugal. Sesimbra Cultural 2, 6–9.
Galton, P.M., 1994. Notes on Dinosauria and Pterodactylia from the Cretaceous of Portugal. Neues Jahrbuch für Geologie und Paläontologie 194, 253–267.
Gasulla, J.M., Escaso, F., Narváez, I., Ortega, F., Sanz, J.L., 2015. A New Sail-Backed Styracosternan (Dinosauria: Ornithopoda) from the Early Cretaceous of Morella, Spain. PLos One 10 (12), e0144167. https://doi.org/10.1371/journal.pone.0144167.
Jiménez-Vela, A., Pérez-Lorente, F., 2005-2006. El corral del Totico. Dos nuevos yacimientos con pistas singulares. (Enciso, La Rioja, España). Zubia 18–19, 115–144.
Kim, J.Y., Lockley, M.G., Chun, H.Y., 2016. New dinosaur tracks from the Lower Cretaceous (Valanginian-Hauterivian) Saniri Formation of Yeongdong area, central Korea: Implications for quadrupedal ornithopod locomotion. Cretaceous Research 61, 5–16.
Lapparent, A.F., Zbyszewski, G., 1957. Les dinosauriens du Portugal. Memórias dos Serviços Geológicos de Portugal 2, 1–63.
Leonardi, G., 1979. Nota preliminar sobre seis pistas de dinosaurios Ornithischia da Bacia do Rio do Peixe, em Souse, Paraiba, Brasil. Anais da Academia Brasileira de Ciências 51, 501–516.
Leonardi, G., 1984. In: Erizzo (Ed.), Le impronte fossili dei dinosauri. Sulle Orme dei deinosauri, Venezia, pp. 161–186.
Lockley, M.G., Meyer, C.A., Santos, V.F., 1994. Trackway evidence of a herd of juvenile sauropods from the Late Jurassic of Portugal. Gaia 10, 27–35.
Lockley, M.G., Nadon, G., Currie, P.J., 2003. A diverse dinosaur-bird footprint assemblage from the Lance Formation, Upper Cretaceous, Eastern Wyoming: implications for ichnotaxonomy. Ichnos 11, 229–249.
Lockley, M.G., Xing, L., Lockwood, J.A.F., Pond, S., 2014. A review of large Cretaceous ornithopod tracks, with special reference to their ichnotaxonomy. Biological Journal of the Linnean Society 113, 721–736.
Lockwood, J.A.F., Lockley, M.G., Pond, S., 2014. A review of footprints from the Wessex Formation (Wealden Group, Lower Cretaceous) at Hanover Point, the Isle of Wight, southern England. Biological Journal of the Linnean Society 113, 707–720.
Madeira, J., Dias, R., 1983. Novas pistas de dinossáurios no Cretácico Inferior. Comunicações dos Serviços Geológicos de Portugal 69, 147–158.
Manupella, G., Antunes, M.T., Pais, J., Ramalho, M.M., Rey, J., 1999. Notícia Explicativa da Carta Geológica de Setúbal. Lisboa, p. 143.
Marchetti, L., Belvedere, M., Voigt, S., Klein, H., Castanera, D., Díaz-Martínez, I., et al., 2019. Defining the morphological quality of fossil footprints. Problems and principles of preservation in tetrapod ichnology with examples from the Palaeozoic to the present. Earth-Science Reviews 193, 109–145. https://doi.org/10.1016/j.earscirev.2019.04.008.
Mateus, O., Antunes, M.T., 2003. A new dinosaur tracksite in the Lower Cretaceous of Portugal. Ciências da Terra (UNL) 15, 253–262.
Mateus, O., Milàn, J., 2008. Ichnological evidence for giant ornithopod dinosaurs in the Upper Jurassic Lourinhã Formation, Portugal. Oryctos 8, 47–52.
Mateus, O., Araújo, R., Natário, C., Castanhinha, R., 2011. A new specimen of the theropod dinosaur Baryonyx from the early Cretaceous of Portugal and taxonomic validity of Suchosaurus. Zootaxa 2827, 54–68.
Meyer, C.A., Thüring, B., 2003. The first iguanodontid dinosaur tracks from the Swiss Alps (Schrattenkalk Formation, Aptian). Ichnos 10, 221–228.
Miall, A.D., 2016. Stratigraphy. A modern synthesis. Springer, London, p. 454. https://doi.org/10.1007/978-3-319-24304-7.
Molina, M.D., Yébenes, A., 1987. Sedimentação costeira e continental durante o Cretáceo Primitivo. Sinclinal de Galve, Teruel. Estudos geológicos 43 (Extra), 3–21.
Moratalla, J.J., Sanz, J.L., Jiménez, S., 1988. Multivariate analysis on Lower Cretaceous dinosaur footprints: discrimination between ornithopods and theropods. Geobios 21, 395–408.
Moratalla, J.J., 1993. Restos indirectos de dinosaurious del registro espanol: paleoichnologica de la Cuenca de Cameros (Jurasico superior-Cretacico inferior) y Paleoologia del Cretácico superior. Thesis doctoral. Faculdad de Ciencias Universidad Autónoma, Madrid, 729 pp.
Moratalla, J.J., Hernán, J., Jiménez, S., 2003. Los Cayos Dinosaur Tracksite: An Overview on the Lower Cretaceous Ichno-Diversity of the Cameros Basin (Cornago, La Rioja Province, Spain). Ichnos 10, 229–240.
Nichols, G., 1999. Sedimentology & Stratigraphy. Blackwell, Oxford, p. 355.
Pérez-Lorente, F., 2003. Icnitas de dinosaurios del Cretácico en España. In: Pérez-Lorente, F. (Ed.), Dinosaurios y otros reptiles mesozoicos de España, vol. 26. Instituto de Estudios Riojanos, pp. 49–108.
Pérez-Lorente, F., 2015. Dinosaur trackways and footprints of La Rioja. Indiana University Press, Indiana, p. 363.
Razzolini, N.L., Vila, B., Díaz-Martínez, I., Manning, P.L., Galobart, A., 2016. Pes shape variation in an ornithopod dinosaur trackway (Lower Cretaceous, NW Spain): new evidence of an antalgic gait in the fossil track record. Cretaceous Research 58, 125–134.
Rey, J., 1992. Les unités lithostratigraphiques du Crétacé inférieur de la région de Lisbonne. Comunicações dos Serviços Geológicos de Portugal 78, 103–124.
Rey, J., Graciansky, P.C., Jacquin, Th, 2003. Les séquences de dépôt dans le Crétacé inférieur du Bassin Lusitanien, vol. 90. Comunicações do Instituto Geológico e Mineiro, pp. 15–42.
Romero-Molina, M.M., Pérez-Lorente, F., Rivas Carrera, P., 2003. Análisis de la parataxonomía utilizada con las huellas de dinosaurio. In: Instituto de Estudios Riojanos, vol. 26. Dinosaurios y otros reptiles mesozoicos de España, pp. 13–32.
Romilio, A., Salisbury, S.W., 2011. A reassessment of large theropod dinosaur tracks from the mid-Cretaceous (late Albian/Cenomanian) Winton Formation of Lark Quarry, central-western Queensland, Australia: A case for mistaken identity. Cretaceous Research 32, 135–142.
Romilio, A., Salisbury, S.W., 2014. Large dinosaurian tracks from the Upper Cretaceous (Cenomanian/Turonian) portion of the Winton Formation, Lark Quarry, central-western Queensland, Australia: 3D photogrammetric analysis renders the 'stampede trigger' scenario unlikely. Cretaceous Research 51, 186–207.
Ruiz-Omeñaca, J.I., 2011. *Delapparentia turolensis* nov. gen. et sp., un nuevo iguanodontoideo (Ornithischia: Ornithopoda) en el Cretácico Inferior de Galve. Estudios Geologicos 67, 83–110. https://doi.org/10.3989/egeol.40276.124.
Santos, V.F., 2003. Pistas de dinossáurio no Jurássico e Cretácico de Portugal., Considerações Paleobiológicas e paleoecológicas. PhD Dissertation. Universidad Autónoma de Madrid, p. 365 (unpublished).
Santos, V.F., 2008. Pegadas de Dinossáurios de Portugal. Museu Nacional de História Natural, Lisboa, p. 124.
Santos, V.F., Moratalla, J.J., Dantas, P.M., Cachão, M.A., Silva, C.M., Coke, C.J., 1992. Pistas de dinossáurios do Cretácico superior da região de Lisboa (Portugal). Problemas de interpretação de uma pista de pegadas subcirculares. In: III Congr Geol España y VIII Congr Latinoamericano Geol. Salamanca. Actas 1, pp. 565–569.
Santos, V.F., Dantas, P., Moratalla, J.J., Terrinha, P., Coke, C., Agostinho, M., Galopim de Carvalho, A.M., 2000. Rastos de Iguanodontídeos no Cretácico da Bacia Algarvia, Portugal. In: Diez, J.B., Balbino, A.C. (Eds.), Libro de Resúmenes del I Congresso Ibérico de Paleontología/XVI Jornadas de la Sociedad Española de Paleontología, Évora, Portugal, 12 e 14 de Outubro de 2000, pp. 22–23.
Santos, V.F., Callapez, P.M., Rodrigues, N.P.C., 2013. Dinosaur footprints from the Lower Cretaceous of the Algarve Basin (Portugal): New data on the ornithopod palaeoecology and palaeobiogeography of the Iberian Peninsula. Cretaceous Research 40, 158–169.
Sanz, J.L., Casanovas, M.L., Santafé, J.V., 1984. Restos autopodiales de Iguanodon (Reptilia, Ornithopoda) del yacimiento de Santa Bárbara (Cretácico inferior, Galve, Provincia de Teruel, España). Estudios Geologicos 40, 251–257.
Sarjeant, W.A.S., Delair, J.B., Lockley, M.G., 1998. The footprints of Iguanodon: a history and taxonomic study. Ichnos 6, 183–200.
Sauvage, H.E., 1897. Vertébrés fossils du Portugal. Direction des Travaux Géologiques du Portugal, Lisboa, Lisboa, p. 46.
Thulborn, R.A., Wade, M.J., 1984. Dinosaur trackways in the Winton formation (Mid-Cretaceous) of Queensland. Memoirs of the Queensland Museum 21, 413–517.
Thulborn, T., 1990. Dinosaur Tracks. Chapman & Hall, London, p. 410.
Torcida, F., 2006. Restos directos de dinosaurios en Burgos (Sistema Ibérico): un balance provisional. In: Colectivo Arqueológico y Paleontológico de Salas. Actas de las III Jornadas Internacionales sobre Paleontología de Dinosaurios y su Entorno, Salas de los Infantes, Burgos, pp. 105–128.
Torcida, F., Montero, D., Huerta, P., Izquierdo, L.A., Pérez, G., et al., 2003. Rastro ornitópodo de andar cuadrúpedo con marca de cola. Cretácico inferior (Burgos, España). In: Pérez-Lorente, F., (coord.) (Eds.), Dinosaurios y otros reptiles mesozoicos en España, vol. 26. Ciencias de la Tierra, pp. 109–118.
Verdú, F.J., Royo-Torres, R., Cobos, A., Alcalá, L., 2015. Perinates of a new species of Iguanodon (Ornithischia: Ornithopoda) from the lower Barremian of Galve (Teruel, Spain). Cretaceous Research 56. https://doi.org/10.1016/j.cretres.2015.05.010 doi: 250e264.
Verdú, F.J., Cobos, A., Royo-Torres, R., Alcalá, L., 2019. Diversity of large ornithopod dinosaurs in the upper Hauterivian-lower Barremian (Lower Cretaceous) of Teruel (Spain): a morphometric approach. [Diversidad de grandes dinosaurios ornitópodos en el Hauteriviense superior-Barremiense inferior (Cretácico Inferior) de Teruel (España): una aproximación morfométrica]. Spanish Journal of Palaeontology 34 (2), 269–288.

Verdú, F.J., Royo-Torres, R., Cobos, A., Alcalá, L., 2020. Systematics and paleobiology of a new articulated axial specimen referred to Iguanodon cf. galvensis (Ornithopoda, Iguanodontoidea). Journal of Vertebrate Paleontology 40 (6). https://doi.org/10.1080/02724634.2021.1878202.

Vialov, O.S., 1988. On the Classification of Dinosaurian Traces. Vsesoyuznogo Paleontologicheskogo Obshchestva 31, 322–325.

Wilson, R.C.L., Hiscott, R.N., Willis, M.G., Gradstein, F.M., 1989. The Lusitanian basin of west-central Portugal: Mesozoic and Tertiary tectonic, stratigraphic, and subsidence history. In: Tankard, A.J., Balkwill, H. (Eds.), Extensional Tectonics and Stratigraphy of the North Atlantic margins, pp. 341–361.

Xing, L.D., Wang, F., Pan, S., Chen, W., 2007. The discovery of dinosaur footprints from the Middle Cretaceous Jiaguan Formation of Qijiang County, Chonqing City [in Chinese] Acta Geologica Sinica 81, 1591–1602.

Xing, L., Lockley, M.G., Piñuela, L., Zhang, J., Klein, H., et al., 2013. Pterosaur trackways from the Lower Cretaceous Jiaguan Formation (Barremian—Albian) of Qijiang, Southwest China. Palaeogeography, Palaeoclimatology, Palaeoecology 392, 177–185.