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A new record of a possible ornithopod footprint from the Lower Cretaceous of Cabo Espichel (Sesimbra, Portugal)

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KEY WORDS - Dinosaur Ichnology, Theropods, Ornithopods, Photogrammetry, Barremian.

ABSTRACT - We present a new dinosaur footprint from Praia do Guincho, Portugal. Praia do Guincho is a seaside locality, situated 2 km north of Cabo Espichel. A loose cast of a tridactyl dinosaur footprint was discovered during fieldwork in 2011. The cliff where the footprint was found is composed of limestones, marls, sandstones and conglomerates that were deposited in shallow marine, lagoon and estuarine environments. The succession belongs to the Papo-Seco Formation (Lower Cretaceous-Barremian). The remains of several groups of vertebrates, including dinosaurs, have been reported in this formation. This paper provides a trackmaker study consisting of a visual analysis under different light angles and photogrammetric 3D modelling. The specimen has a digit III longer than II and IV. However, a substantial part of the shape of digit III is sediment, giving a flawed impression that it belongs to the footprint itself. The photogrammetric modelling revealed that digit III is shorter and more rounded than it appeared to be in the first place and the morphology of the cast (large plantar surface, similar length and width rounded heel, with elongate, narrow digits) matches with the features of the pes of ornithopods and with the characteristics described as belonging to ornithopod dinosaurs.

RIASSUNTO - [Nuova scoperta di una impronta di probabile Ornitopode del Cretaceo Inferiore di Cabo Espichel (Sesimbra, Portogallo)] *- In questo articolo viene descritta una nuova impronta di dinosauro proveniente da Praia do Guincho, una località marina situata circa a 2 Km a nord di Cabo Espichel. Durante la campagna del 2011, è stato scoperto un calco naturale isolato di un'impronta tridattila di dinosauro. La falesia dove è stata trovata l'impronta è composta da calcari, marne, sabbie e conglomerati, depositatisi in ambiente marino poco profondo, estuarino e lagunare. La successione appartiene alla Formazione di Papo-Seco (Cretaceo Inferiore-Barremiano). In questa formazione sono stati segnalati i resti di vari gruppi di vertebrati, inclusi dinosauri. Questo articolo mira ad identificare l'autore della traccia attraverso lo studio visuale (secondo differenti angoli di illuminazione) e la modellazione fotogrammetrica 3D. Infatti, una parte sostanziale del dito III è composta da sedimento, dando la falsa impressione di appartenere all'impronta stessa. Il dito III sembra pertanto più lungo delle dita II e IV, ma la modellazione fotogrammetrica ha dimostrato come il dito III sia più corto ed arrotondato di quanto appaia. La morfologia dell'impronta (grande superficie plantare, tallone arrotondato con lunghezza e larghezza simili, con le dita allungate e strette) corrisponde alle caratteristiche delle zampe dei dinosauri ornitopodi. Sulla base di confronti morfometrici, riteniamo quindi che l'impronta sia stata prodotta da un ornitopode.*

INTRODUCTION

The first palaeontological investigations on Cabo Espichel took place in the 19th century (Sauvage, 1897-1898). The Portuguese geological survey reported dinosaur and crocodile teeth from the Papo-Seco Formation at Boca do Chapim (Sauvage, 1897-1898). Later, Lapparent & Zbyszewski (1957) described turtle remains and crocodile teeth and bones, as well as dinosaurian teeth and bones in the same formation. Among the latter are two tooth fragments classified as carnosauria incertae sedis (Galton, 1994). Some herbivorous dinosaur remains were also reported. A purported *Iguanodon* tooth from Boca do Chapim (MGIGM.10), displayed in the collections of the Museu Geológico do LNEG (Lisbon), was identified as a cf. *Pelorosaurus* tooth (Figueiredo, 2000). Fragments of jaws found at Boca do Chapim by Sauvage (1897-1898) were identified as being from a crocodile (*Suchosaurus Girardi* Sauvage, 1897-1898); they were later analysed and attributed to the spinosaurid *Baryonyx*, based on similarities with the holotype of *Baryonyx walkeri* Charig & Milner, 1986 from the English Barremian (Buffetaut, 2007). Mateus et al. (2011) published skull and postcranial bones which they attributed to *Baryonyx walkeri* in the location dubiously identified as Praia das Aguncheiras (Mateus et al., 2011), whose topography matches that of Praia do Guincho.

In view of the palaeontological investigations carried out by the Centro Português de Geo-História e Pré-História (CPGP), new data were later reported. In Boca do Chapim, a preliminary analysis of the discovered material showed several bones of an ornithopod dinosaur (Figueiredo, 2010, 2014). Discoveries of vertebrate bone fragments and teeth from fishes (cf. *Lepidotus* sp.), crocodylomorphs (cf. *Anteophtalmosuchus* sp.), pterosaurs (Ornithocheiridae indet. and Ctenochasmatoidea indet.) and dinosaurs

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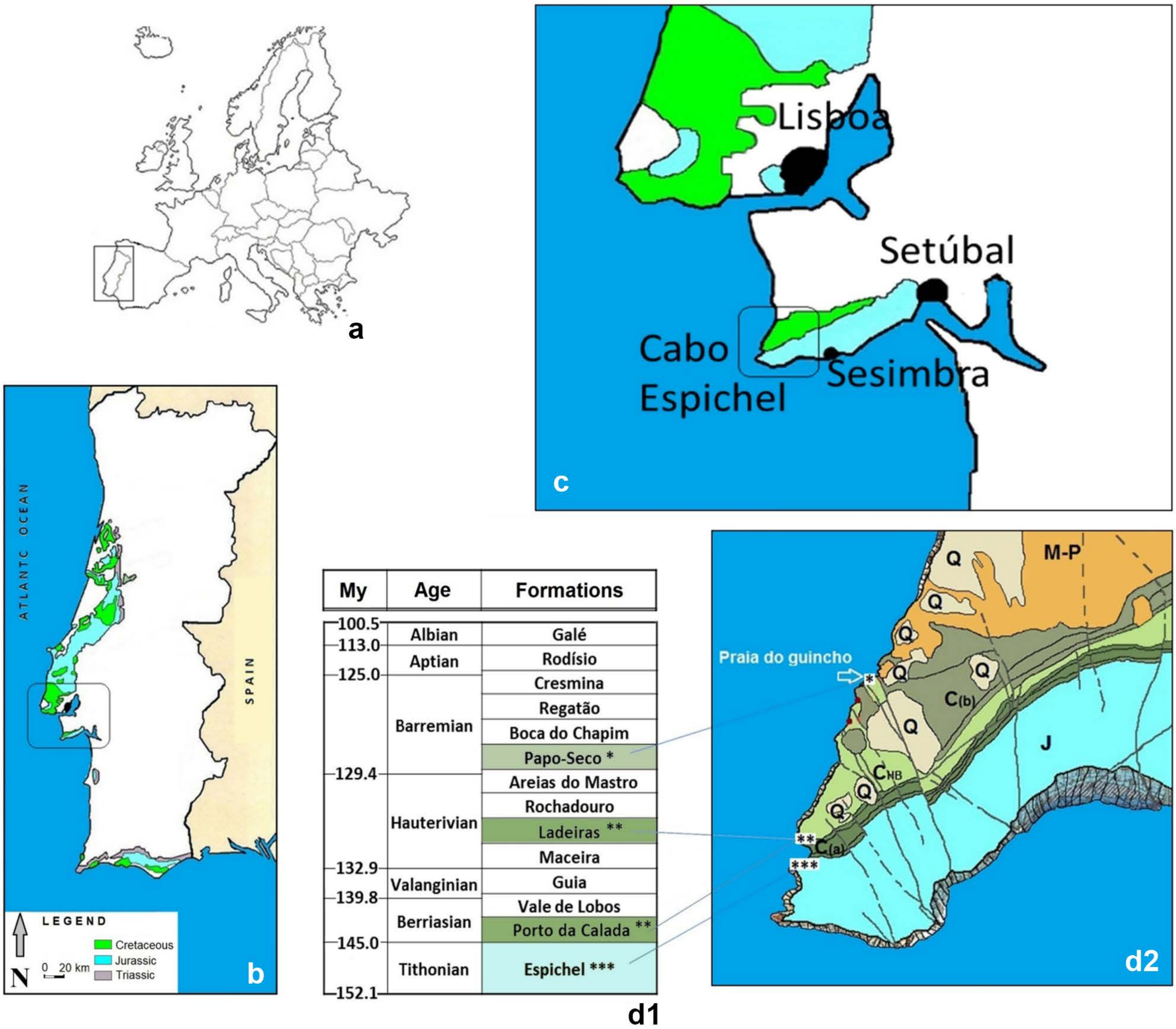

Fig. 1 - a) European geographical map with the localization of Portugal. b) Geologic Map with the Mesozoic Formation of Portugal. c) The Mesozoic of Lisbon and Setúbal peninsulas. d) Geology and chronological contexts of the geological formations of the Cabo Espichel and Praia do Guincho sequences: d1) chronological scale; d2 geological map with the locality of Praia do Guincho (white arrow). The dating of the Cretaceous ages is according to the International Chronostratigraphic Chart (2017). After Figueiredo et al. (2015, 2016).

(*Baryonyx* sp., Iguanodontoidea indet., Iguanodonts and Sauropoda indet.) were made in Areia do Mastro (Figueiredo et al., 2015, 2016). In 2011, a dinosaur footprint natural cast (convex hyporelief), was found in the cliffs of Praia do Guincho (north of Cabo Espichel). It was an isolated discovery, detached from its source layer. It is the first discovery of a dinosaur footprint from the Barremian in the Lusitanian Basin.

In Cabo Espichel dinosaur tracks are also known. Namely, they are reported from Praia do Cavalo and Pedra da Mua localized in the cliff beneath the Sanctuary of Cabo Espichel (Tithonian; Espichel Formation) and Lagosteiros localized on the top of the cliff north of Lagosteiros bay (Berriasian; Porto da Calada Formation) (Rey, 1992; Manupella et al., 1999). In Praia do Cavalo a trackway of a large theropod was recognized (Dantas et al., 1994). The Pedra da Mua track site reveals at least eight levels with 38 sauropod trackways and two theropod trackways (Lockley et al., 1994). In one of the Pedra da Mua track levels, seven parallel juvenile sauropod trackways were recognized. The footprints have similar sizes and depths and show the same travel direction. The analysis of these parallel trackways revealed that their producers were travelling at similar speeds (Lockley et al., 1994). Three other trackways of larger animals progressing in the same direction were also found (Lockley et al., 1994). This record represents the evidence of sauropod gregarious behaviour and an interesting example of the juvenile sauropod behaviour (Galopim de Carvalho & Santos, 1992, 1993; Lockley et al., 1994). In Lagosteiros two track levels with dinosaur footprints are known (Santos, 2003). In a Berriasian clastic sequence that overlies the Upper Jurassic (Tithonian) limestones in Lagosteiros Bay, north of Cabo Espichel (Sesimbra), one track level (Lagosteiros A) was discovered by José Luís d'Orey in 1996 with bipedal dinosaur tracks of a probable theropod (Santos, 2003). In 1971 another track level was discovered and attributed to the Hauterivian (Lagosteiros B) by Miguel Telles Antunes (Antunes, 1976). It has several disperse tridactyl impressions and a short trackway related to theropods. The most interesting feature of this site is a long sequence of poorly preserved subcircular footprints, with similar size and depth, attributed to a bipedal animal, probably an ornithopod (Galopim de Carvalho & Santos, 1992, 1993; Santos et al., 1992). There is also a curious long impression that was interpreted as the tail mark of a dinosaur by Antunes (1976).

The differentiation among morphotypes of dinosaurian tridactyl tracks is one of the most intricate problems of palaeoichnology (Moratalla et al., 1997). The advancement in computer science and palaeoichnological application of computers are leading to more accurate ichnotaxonomical attributions. Three-dimensional digital modelling constitutes an objective approach, especially when compared to classical methods (Bates et al., 2008; Petti et al., 2008; Remondino et al., 2010). Morphometric proportions are here used to discriminate the trackmaker of the analysed specimen following the procedures of Moratalla et al. (1988).

GEOLOGICAL, STRATIGRAPHICAL AND SEDIMENTOLOGICAL CHARACTERIZATION

Praia do Guincho is a small beach about 2 km north of Cabo Espichel (coordinates: 38º27'00.27" N / 9º12'05.60" W), at the bottom of the coastal cliffs of the Cabo Espichel anticline. The cliff is about 60 m high and composed primarily of limestones, marls, sandstones and conglomerates that were deposited in marine, lagoon and estuarine environments. Although there are calcareous layers of the Boca do Chapim and Areias do Mastro formations, this costal sector mainly exposes the Papo-Seco Formation. It is located SW of Setubal Peninsula in the municipality of Sesimbra, about 40 km south of Lisbon.

The Papo-Seco Formation is placed between the Areia do Mastro Formation and Boca do Chapim Formation and is assigned to the Lower Barremian (Rey, 1972, 1992; Manupella et al., 1999) (Fig. 1). This formation, 18.5 meters thick, is characterized by marls and green silty clays containing lignite and gypsum, interbedded with sandstones presenting horizontal stratification (Rey, 1972; Manupella et al., 1999). The fauna retrieved from Papo-Seco Formation consists of dinosaur remains in the lower coarser-grained sandstone layers, and invertebrates (bivalves, gastropods, and ostracods) in the marl levels. The upper part of the formation is composed of calcareous silty layers with ostreid remains (Manupella et al., 1999). The sedimentological and palaeontological features point to an open estuarine environment at the base of Papo-Seco Formation, passing upwards to a lower-energy lagoonal setting, where several remains of marine and terrestrial vertebrates were recovered (Manupella et al., 1999; Figueiredo et al., 2015, 2016).

On the track site, the Papo-Seco Formation is comprised of a meter thick, white or grey, fine-grained silty sandstones, with gypsum and thin organic laminae. The organic laminae frequently highlight distinct erosive-based sets with cross-stratification and, sometimes, parallel stratification. These sediments are interbedded with up to three layers of trough cross-stratified, moderately sorted, medium to coarse feldspathic sandstones. In general, these coarser grained layers are less than 0.80 m thick, wedging out laterally into the fine-grained deposits. Channel-shaped beds of fining upward coarse to medium-grained sandstone with scattered pebbles occasionally occur. Cross stratification and the geometry of the channel-shape beds indicates a general W to SW direction of the palaeocurrents. This mostly siliciclastic interval passes upwards to mudstone-marl layers with carbonate nodules.

The siliciclastic Papo-Seco Formation is interpreted as a transgressive unit deposited in an incised valley after a local sea level drop (Rey, 1992; Rey et al., 2003; Dinis et al., 2008). It constitutes the lower part of a depositional sequence, the transgressive surface of which has been placed at the base of Papo-Seco Formation, whereas the maximum flooding is probably at the upper part of the succeeding, marl and calcareous, Boca do Chapim Formation (Fig. 2). The predominance of erosive based trough cross-stratification and the scarcity of mudstones indicate deposition associated with the migration of sinuous-crest dunes. The organic laminae reveal the presence of vegetated land surface adjacent to the channels and the occurrence of stagnant water bodies (Tibert & Gibling, 1999). A coastal setting is reinforced by the predominance of well-sorted fine to medium sand deposits and confirmed by the presence of echinoderm remains (Rey, 1972, 1992). The coarser grained units, which texturally resemble the tridactyl footprint sediment cast, probably represent deposition in distributary channels within the coastal plain. The thicker and coarser sandstone bed may be attributed to a larger channel.

MATERIAL AND METHODS

The studied material consists of a medium-sized tridactyl footprint (29.7 cm long in a block with a 35 cm maximum length) preserved as a natural cast (CPGP.3.11.1) (Fig. 3). The infilling of the actual print that forms the cast is composed of a coarse-grained, quartz-rich sediment. The sediment of the block is stratified, and represented by quartz-rich limestone, sandstones and marls, with small fragments of lignite. CPGP.3.11.1 is now in the permanent exhibition of the Museum of Centro Português de Geo-História e Pré-História (CPGP).

To establish the most likely originating stratigraphic bed, a sample of the sediment from the cast was extracted and its chemical composition was compared with similar sandstone beds at Praia do Guincho. Three beds (PS1, PS2 and PS3), whose composition and grain-size resemble the sediment of the track, were sampled for this comparison. The samples (from the cast and sandstone beds) were crushed to pass a 200 mesh (0.075 mm) sieve and later immersed in diluted acetic acid (~ 17% in concentration) to remove the carbonate-bound component. Chemical analyses were later performed at the Bureau Veritas Minerals laboratories of Vancouver, Canada (preparation code LF200). A suite of 21 parameters, including oxide abundance, was determined by Inductively Coupled Plasma (ICP) Emission Spectroscopy, whilst the refractory

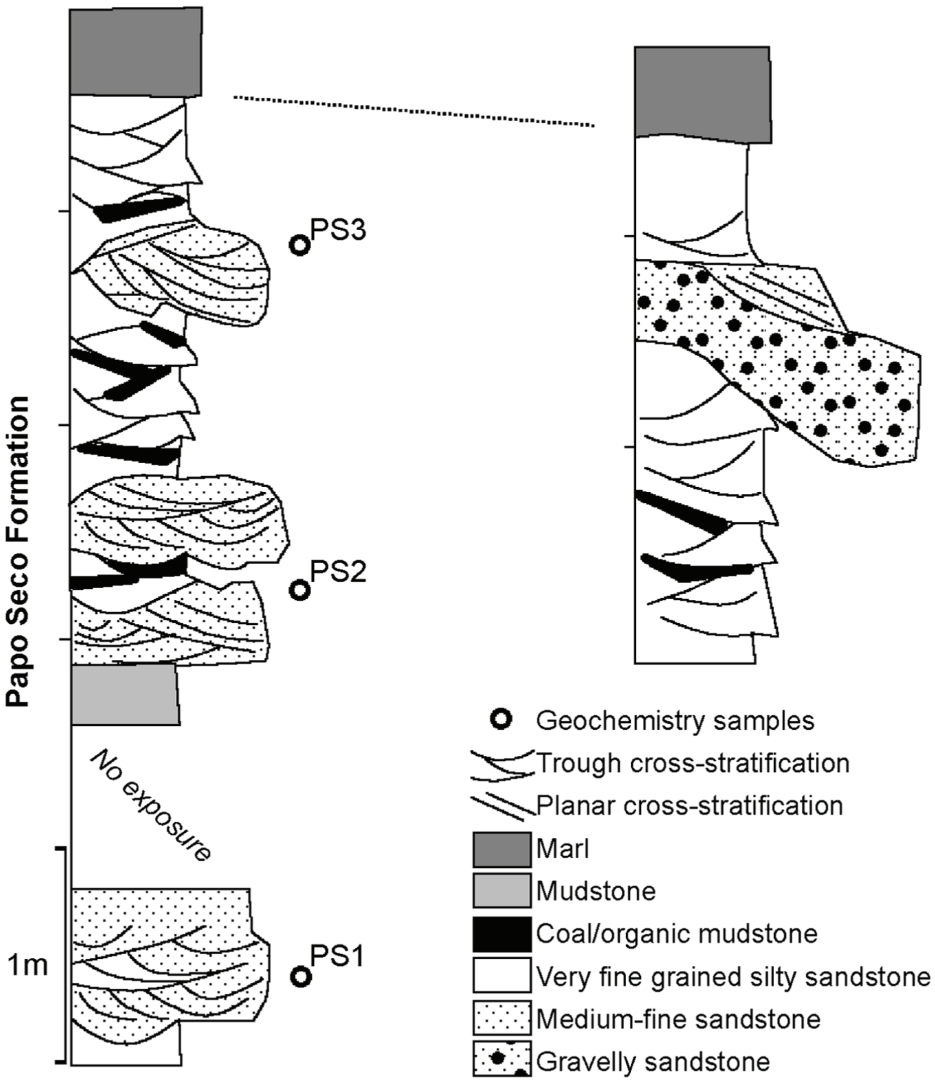

Fig. 2 - Stratigraphic sequence of the Papo-Seco Formation, at the footprint sampling site.

and rare earth elements (REE) were determined by ICP mass spectrometry following a lithium fusion.

The analysis of the footprint cast was carried out on the basis of visual analysis at different light angles and 3D photogrammetry. The 3D model used in this study (Fig. 4) was generated and modelled with freeware software, following e.g., Falkingham (2012), Castanera et al. (2013) and Neto de Carvalho et al. (2016). A Nikon Coolpix P520 camera was used to capture 58 overlapping photos with 16 megapixels (4608x3456) resolution in jpg format, to create the 3D model. The captured images were processed in VisualSfM software (Changchang Wu; http://ccwu.me/vsfm/), producing a dense coloured point cloud, exported in ply and mvs formats. In the additional VisualSfM tool CMPMVS (Jancosek & Pajdla, 2011), a mvs.ini file was also prepared and executed through the windows command line, to obtain an orthophoto and a digital surface model (DSM). MeshLab (Visual Computation Lab - IST CNR; http://meshlab.sourceforge.net/) was used for 3D editing and producing the mesh and the texture. In the Blender software (Blender Foundation; https://www.blender.org/download/) we performed visual analysis, orientation of the model on a plane, obtaining measurements and rendering of textured views. The 3D model has been exported on ply format, having a texture with spatial resolution of 0.2mm/pixel. The software QGIS (https://www.qgis.org/en/site/forusers/download.html) was used for the editing of the orthophoto and DSM previously obtained and for later production of contour-lines, shadows and curvature maps.

The visualization tools used curvatures, shadows and transparencies (Fig. 5). This helped to enrich the visualization of certain topographical and morphometric details such as the shape of the footprint plant and the fingers of the cast matrix. However, in the GIS environment, the DSM data were manipulated for the production of depth maps, contours and 2D visualization, which together with developed 3D models could contribute to a more consistent identification of the actual producer of the footprint. The digital model of the surface (DSM), shown in Fig. 5, records the depth (cm) of the cast of the footprint (negative), ranging from 0 cm (black: deeper area) up to 6 cm (white: more superficial). By these means, we analysed the areas where greater force (pressure) was

Fig. 3 - Block with the cast of footprint CPGP.3.11.1. This cast is now part of the permanent exhibition of the Museum of Centro Português de Geo-História e Pré-História.

exerted and for this reason are deeper. Applying false-colour, based on depth, the morphology can be more easily detected (Bates et al., 2008, 2009; Falkingham et al., 2009). A visual analysis of contour lines is presented on Fig. 5, identifying and measuring the morphology of the track cast.

To identify the producer of the footprint we calculated several indexes and morphometric variables (Figs 6-7) after Moratalla et al. (1988), Mateus & Milàn (2008) and Romilio & Salisbury (2011). Limb height was estimated following the methods of Alexander (1976), Thulborn & Wade (1984), Sanz et al. (1985) and Thulborn (1990). The measurements were performed in Blender software on the 3D model, from the creation of the various vertices necessary to measure, all on the same plane, to avoid possible errors.

ICHNOLOGICAL CHARACTERIZATION

The three-dimensional digital model (Fig. 4) helped us in the interpretation, allowing a detailed reconstruction of the positive/negative cast. The metrics, presented shapes and patterns were obtained from the 3D model. Fig. 4 shows the result of 3D digital modelling of the footprint illustrating 3D models of coordinated points, polygonal mesh, surfaces, textures and transparency.

The interpretation of the various 3D views presented a better understanding of the morphology, the volume, and the areas where more pressure by the foot of the dinosaur was exerted (Dardon et al., 2010; Lallensack et al., 2016). The analysis of the contour-lines, presented in Fig. 5, allows the identification and clear measurement of the morphology of the cast and its proportions. The 3D model let us verify that the proximal and the medial zone of digit III and the part of the palmar area of the footprint near digit III (Fig. 5) correspond to the area where more pressure was exerted.

Morphometric analysis of the footprint

The CPGP.3.11.1 footprint (Fig. 3) has a medium size of 29.7 cm, with a length similar to the width (respectively 29.7 cm and 28.4 cm). It corresponds to a right foot. It has a digitigrade and rounded morphology. It is tridactyl with short digits, rounded, with blunt tips. The heel area has a wide and rounded form. The total divarication angle formed between the digits II and IV is 61º, while the angle between digits II and III is 26º and between digits III and IV is 35º. Measurements, morphology of short and rounded digits and the proximal area and overall rounded outline of the footprint (Fig. 6) tend to indicate ornithopod characteristics. However, Mateus & Milàn (2008) cautioned that, while there may be a large number of variations in typical footprints of theropod and ornithopods dinosaurs, the analysis of isolated footprints can hinder the result, particularly if they do not appear as a "typical" morphology and parameters such as the inner rotation/exterior cannot be inferred.

Various morphometric parameters of the footprint CPGP.3.11.1 were therefore calculated for comparison following the method of Moratalla et al. (1988), Mateus & Milàn (2008) and Romilio & Salisbury (2011, 2014). The measurements used herein are based on the length of the vertices (measured in the 3D model) that are identified by acronyms (Fig. 7) adapted from Moratalla et al. (1988) and Romilio & Salisbury (2011, 2014), and subsequent calculation of ratios between the different parameters. Resulting data for the studied footprint are shown in Tab. 1.

After data analysis of the footprint CPGP.3.11.1 (see Tabs 1-2) we noted that the parameters (4 L2/WM2 4) tend to match more closely those of a theropod (Figs 6 and 8). All remaining parameters, however, show that the footprint corresponds more to an ornithopod trackmaker (Tab. 2). The L2 switch/WB2 can be found practically on the limit between the ornithopod and theropod morphologies. The morphometric analysis carried out using the methods of Moratalla et al. (1988), Mateus & Milàn (2008) and Romilio & Salisbury (2011, 2014) for the distinction between footprints of theropods and ornithopods, converges on the conclusion that the CPGP.3.11.1 footprint corresponds to an ornithopod according to five of the nine parameters (Fig. 8). As in Tab. 2, data obtained for all parameters coincide with the range of values for ornithopod affinities.

Results obtained for the footprint CPGP.3.11.1 (Tab. 2), even if slightly higher, approximate those obtained by Thulborn & Wade (1984) for the average values of 11 footprints of ornithopods. A comparison of both sets of data supports the concept that the trackmaker may correspond to a medium-sized ornithopod.

Alexander (1976) calculated the approximate hip height (sum of the femur, tarsus and metatarsus III) by multiplying foot length by 4. After we applied this formula to the footprint under study we concluded that the producer had a hindlimb with a hip height of 1.18 m.

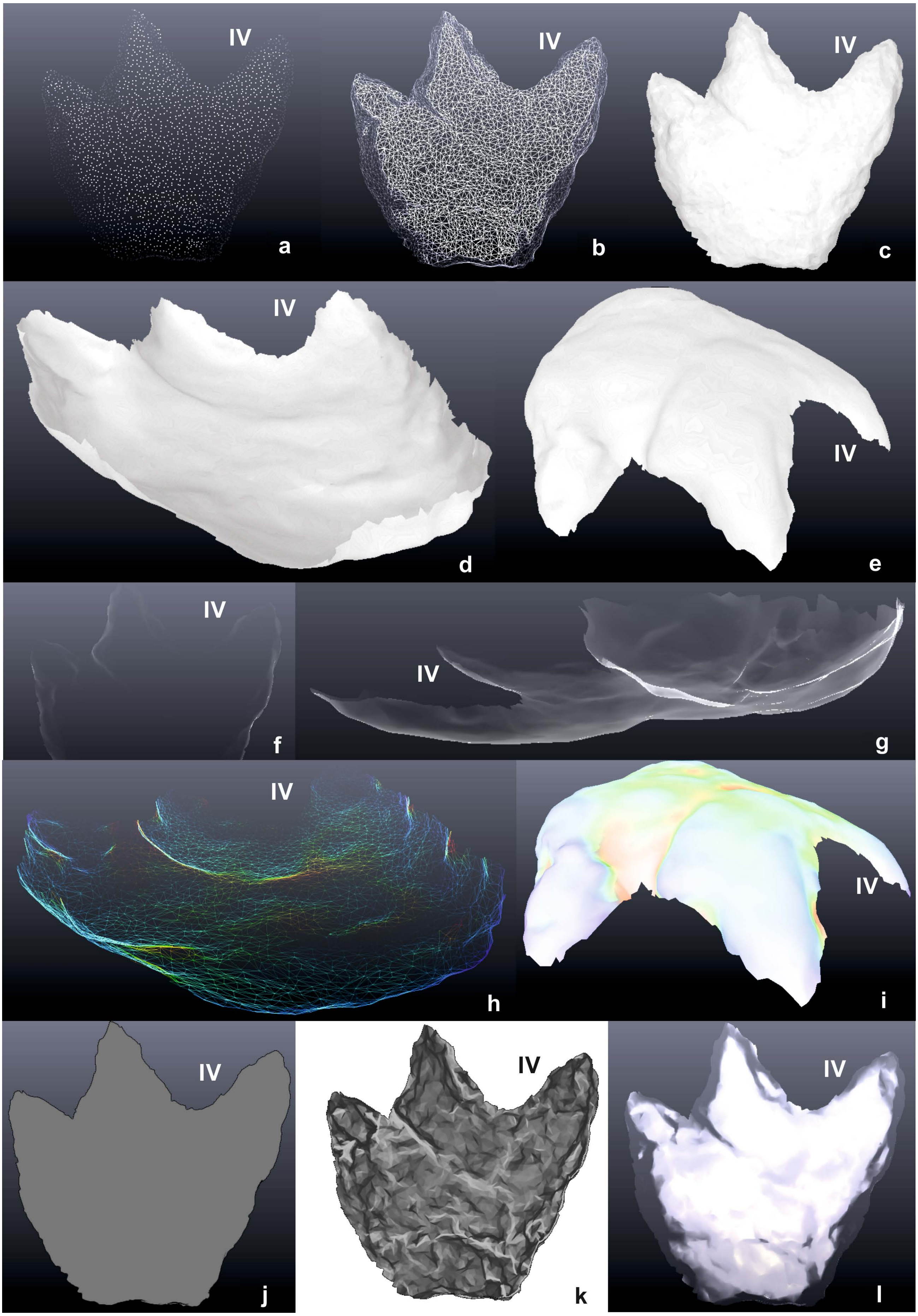
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Fig. 4 - 3D digital model seen from different angles according to different visualization tools. a) Point cloud (coordinated XYZ points with RGB color codes). b) Irregular polygonal mesh. c-e) Model surface shadows (enhance the morphology analysis by projecting shadows). f-g) X-ray visualization algorithm. h-i) Curvature mesh and curvature surface models (it aims to highlight the curvature presented by different colors: flattened areas in green tones, convex areas in red tones and concave areas in blue tones). j) Outside line. k-l) Radiance scaling and glass algorithm (help to highlight morphological aspects).

Another method was later suggested by Sanz et al. (1985) 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). The application of this formula to footprint CPGP.3.11.1 resulted in a slightly higher value of 1.27 m.

Moreover, Thulborn & 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. Applying these values to the footprint CPGP.3.11.1, we estimated the total height of the limb (up to the acetabulum) to 1.75 m according to the formula for large ornithopods and 1.68 m according to the formula given for large dinosaurs in general.

Among all the methods used above to estimate the hip height of the producer, resulting values vary between a minimum of 1.18 m and a maximum of 1.75 m. In contrast to the methods suggested by Thulborn & Wade (1984) and Thulborn (1990), those proposed by Alexander (1976) and Sanz et al. (1985) appear inaccurate as too general and not tuned to the different groups of dinosaurs. Unluckily, the dealing with an isolated footprint prevents further considerations.

DISCUSSION

The presence of ornithopods and theropods in Portugal has been documented in the fossil record from the Middle Jurassic. The oldest theropods are known from footprints in Pé da Pedreira and Vale de Meios, both sites of Middle Jurassic age (Santos et al., 2000, 2016; Antunes & Mateus, 2003; Figueiredo, 2014; Razzolini et al., 2016) and the oldest ornithopods are known from several osteological remains from the Upper Jurassic (Dantas, 1990; Dantas et al., 1998; Antunes & Mateus, 2003; Ortega et al., 2006; Figueiredo, 2014). In the Portuguese fossil record, large theropods are identified such as *Megalosaurus*, *Lourinhanosaurus*, *Allosaurus*, *Torvosaurus* for the Jurassic, *Megalosaurus* and *Baryonyx* for the Cretaceous (Lapparent & Zbyszewski, 1957; Dantas, 1990; Dantas et al., 1998; Santos et al., 2000; Antunes & Mateus, 2003; Ortega et al., 2006; Malafaia et al., 2007; Mateus et al., 2011; Figueiredo, 2014; Hendrickx & Mateus, 2014; Figueiredo et al., 2015; Santos et al., 2016). From the ornithopod group, the remains of *Camptosaurus, Draconyx, Dryosaurus, Hipsilophodon, Thyllodon* and *Eousdryosaurus* have been identified in the Jurassic while *Iguandon, Mantellisaurus*(?) and Iguanodontia indet. for the Cretaceous (Lapparent & Zbyszewski, 1957; Antunes, 1976; Dantas, 1990; Crespo, 2001; Antunes & Mateus, 2003; Ortega et al., 2006; Escaso et al., 2014; Figueiredo, 2014; Figueiredo et al., 2015; Santos et al., 2016).

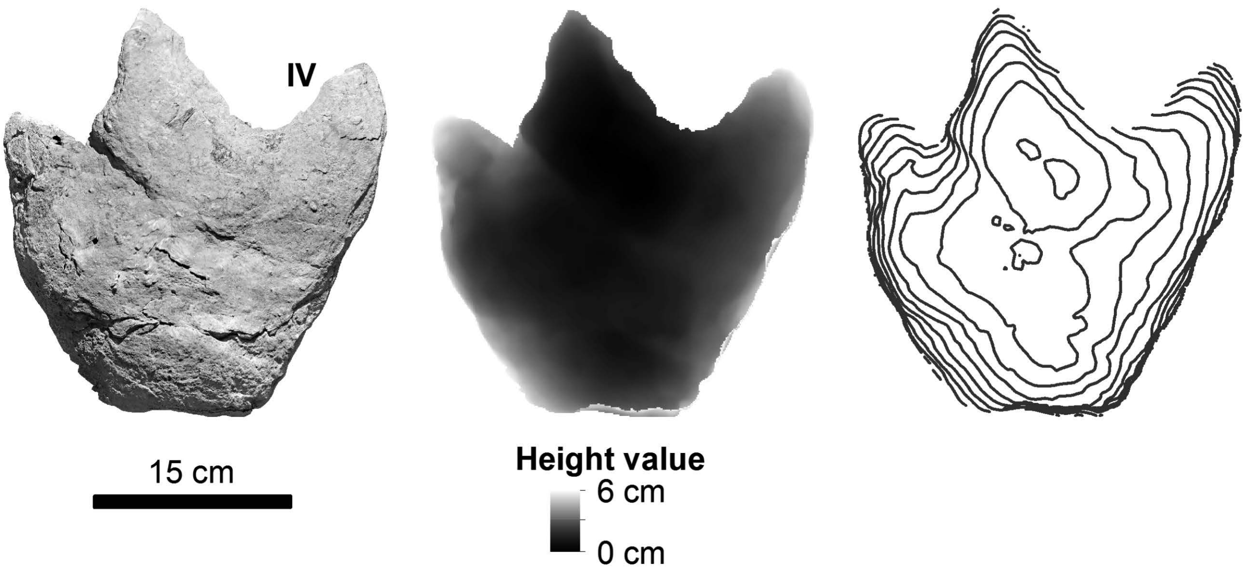

Fig. 5 - From left to right are ortophoto, DSM and contour-lines (0.5 cm of equidistance) that represent the depth of the footprint. The analysis of these elements made it possible to substantially improve the knowledge of the morphometric features (IV = digit IV). The track cast is mirrored to represent the actual footprint.

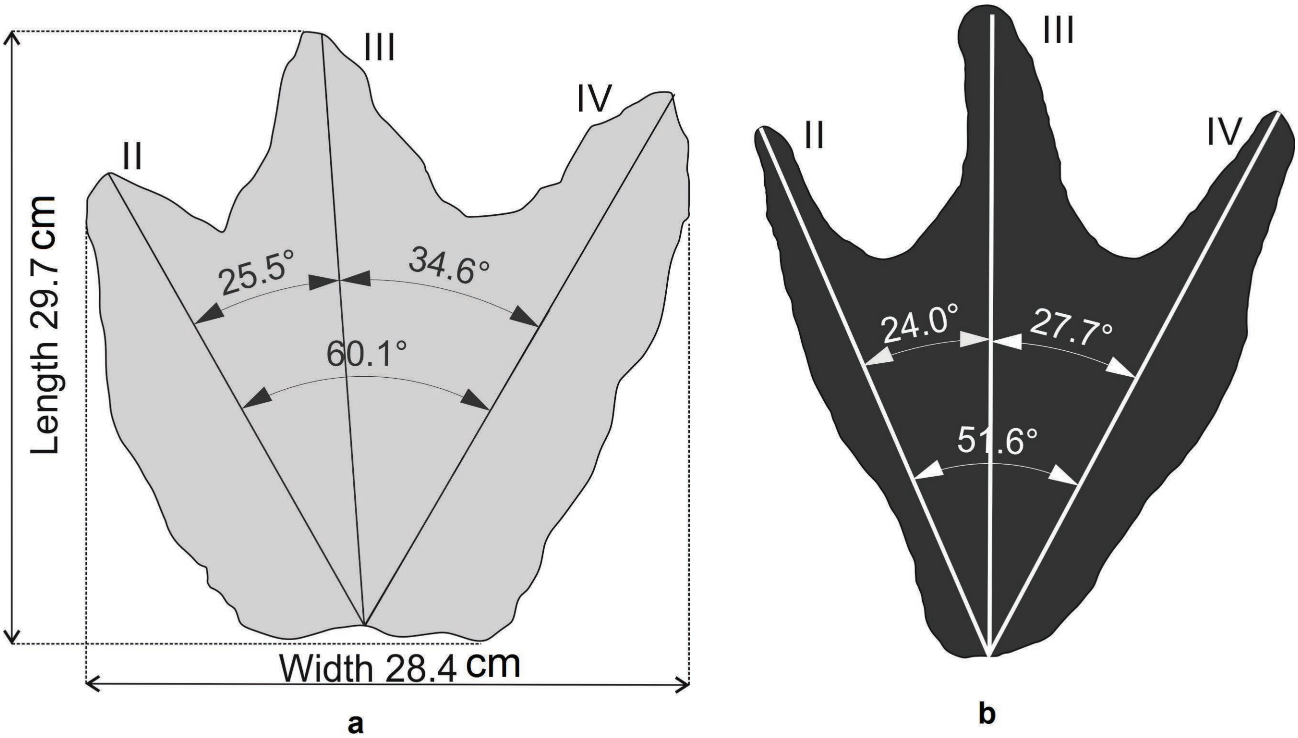

Fig. 6 - Representation of pattern and proportions for the studied footprint and footprint T5 of Lagosteiros. a) CPGP.3.11.1., in gray, dimensions of footprint and angles between digits. b) In black footprint T5 of Lagosteiros.

The occurrence of dinosaurs in the Papo-Seco Formation is verified by the occurrence of various remains of ornithopods and theropods. The ornithopod remains are represented by bone elements and the teeth of iguanodonts (Lapparent & Zbyszewski, 1957; Figueiredo, 2010, 2014; Figueiredo et al., 2015) and theropod remains by bone elements and teeth discovered such as those of *Baryonyx* and *Megalosaurus* (Lapparent & Zbyszewski, 1957; Buffetaut, 2007; Figueiredo, 2010, 2014; Mateus et al., 2011; Figueiredo et al., 2015). Remarkable also the occurrence of several other theropod teeth, discovered by CPGP team but as yet unpublished.

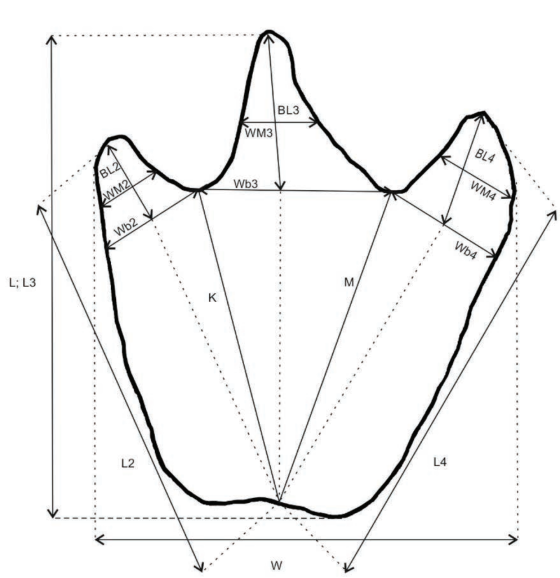

Fig. 7 - Outline and morphometric analysis of footprint CPGP.3.11.1 (dimensions and angles). W: width; L: length; L2 to L4: length digits 2 to 4; K and M:"heel" to interdigital (hypex) lengths, BL2 to BL4: digit lengths; Wb2 to Wb4: proximal basal digit lengths; Wm2 to WM4: middle digit widths. Adapted from Moratalla et al. (1988).

The likeliness of the footprint being derived from a specific sandstone bed of the Papo-Seco Formation was tested by a geochemistry provenance analysis. Non-mobile indicators, such as TiO_2, REE, Th, U, Zr and Hf, tend to concentrate in heavy minerals, reflecting the heavy mineral assemblages, which make them good provenance indicators (e.g., von Eynatten et al., 2003). When compared to the footprint sediment, samples PS2 and PS3, taken from the Papo-Seco Formation (in Praia do Gincho site), all are slightly enriched in CaO and depleted in TiO_2 (Fig. 9). The level of depletion in TiO_2 is comparable to that of most insoluble elements, indicating that the heavy mineral assemblages should be similar. These two beds are also more enriched in Eu than in light and heavy rare earth elements (REE). This suggests that the compositional differences may be attributed to the presence of higher abundance of Ca-feldspars, as these minerals tend to incorporate significant proportions of Eu. One may also consider the possibility that the Ca-carbonate was not entirely destroyed in PS2 and PS3, explaining the relatively high CaO content. Hence, CaO concentration cannot be used to discard these two sandstones as potential sources for the footprint cast. The sample PS1 is moderately enriched in TiO_2, but strongly enriched in REE, Th, U, Zr and Hf, pointing to different heavy mineral assemblages in the cast and PS1. Based on these compositional features, the sediment of the footprint

Parameter	New Track
L e L3	29.7 cm
W	28.4 cm
L4	28.6 cm
L2	25.8 cm
K	21.4 cm
M	21.7 cm
BL4	7.2 cm
BL3	10.4 cm
BL2	5.7 cm
WM4	5.1 cm
WM3	5.7 cm
WM2	4.8 cm
WB4	8.2 cm
WB3	14.3 cm
WB2	6.9 cm
L/W	1.0
L/K	1.3
L/M	1.3
L2/WM2	5.3
L3/WM3	5.2
L4/WM4	5.6
L2/WB2	3.7
L3/WB3	2.0
L4/WB4	3.4
BL2/WM2	1.2
BL3/WM3	1.8
BL4/WM4	**1.4**

Tab. 1 - Morphometric parameters used to differentiate between theropod and ornithopod tracks (after Moratalla et al., 1988 and Mateus & Milán, 2008). See Fig. 7 and text for explanations of track parameters.

cast is more akin to PS2 and PS3 than to PS1. Vertebrate remains were already found in Papo-Seco Formation, reinforcing the possible link of the footprint cast with one of these layers.

Taking into account the occurrence of several fossils of ornithopods and theropods in the Papo-Seco Formation, the likelihood that footprint cast CPGP.3.11.1 was produced by either of these groups is high. From the first analysis of the shape of the footprint, it appeared to be a theropod footprint, but during the laboratory study other hypotheses were raised (Fig. 10). The first hypothesis was that the shape of the black line corresponds to the morphology of the trace (thus corresponding to the entire block). Consequently, that would appear greater proportionally than that produced by a theropod. The second hypothesis, considering only the shape of the grey line shown in Fig. 10 as the one corresponding to the morphology of the footprint, would be a print produced by an ornithopod. The third hypothesis was that it might be two overlapping footprints. This last one was the first to be abandoned, since after thorough observation it was found that the third digit was extremely long and had a corresponding high topography (when walking, a theropod produces pressure in digit III, reason why usually the digit III produces a depression rather than a rise).

In considering the remaining two hypotheses, the morphological parameters (Tab. 2) such as lengths of digits II, III, and IV are slightly different, the digits are elongate and narrow, with rounded ends, the anteroposterior and mediolateral dimensions are similar (Fig. 6a) and the absence of claws marks, indicate that it is more likely that this footprint has been produced by an ornithopod. The features of the footprint are: large plantar surface, elongate, narrow digits, the angle of interdigital divergence (61º) and between the digits II - III and III - IV (26º and 35º respectively), that are not very different from each other (9º difference) and the overall rounded outline of the footprint, are described by Moreno et al. (2012) as the features of the ornithopod footprints and are present in several ornithopod footprints reported in literature (e.g., Madeira & Dias, 1983; Thulborn & Wade, 1984; Moratalla et al., 1988; Sarjeant et al., 1998; Santos, 2003; Mateus & Milàn, 2008; Romilio & Salisbury, 2011, 2014; Santos et al., 2013; Díaz-Martínez et al., 2015). The pes of ornithopods is broad and has a wide heel; three functional toes and the terminal phalanges are dorsoventrally

Track Parameters	Threshold values and probability (theropod or ornithopod track)	CPGP.3.11.1	Thulborn & Wade, 1984
L/W	80.0% Theropod > 1.25 > Ornithopod 88.2%	1.03	0.99
L/K	70.5% Theropod > 2.00 > Ornithopod 88.0%	1.38	1.58
L/M	65.0% Theropod > 2.00 > Ornithopod 90.7%	1.36	1.64
BL2/WM2	76.1% Theropod > 2.00 > Ornithopod 97.7%	1.41	0.87
BL4/WM4	76.1% Theropod > 2.00 > Ornithopod 97.7%	1.18	0.92
BL3/WM3	72.7% Theropod > 2.20 > Ornithopod 97.7%	1.82	1.67
L2/WB2	84.6% Theropod > 3.75 > Ornithopod 90.2%	3.48	2.77
L4/WB4	73.7% Theropod > 3.75 > Ornithopod 93.4%	3.73	2.70
L3/WB3	70.6% Theropod > 4.00 > Ornithopod 91.5%	2.07	2.11

Tab. 2 - Distinguishing parameters between theropod and ornithopod tracks. Adapted from Moratalla et al. (1988) and Mateus & Milàn (2008). See Fig. 7 for explanations of track parameters. The threshold values and probability that the track is either theropod or ornithopod from an average of 11 tracks (adapted from Thulborn & Wade, 1984).

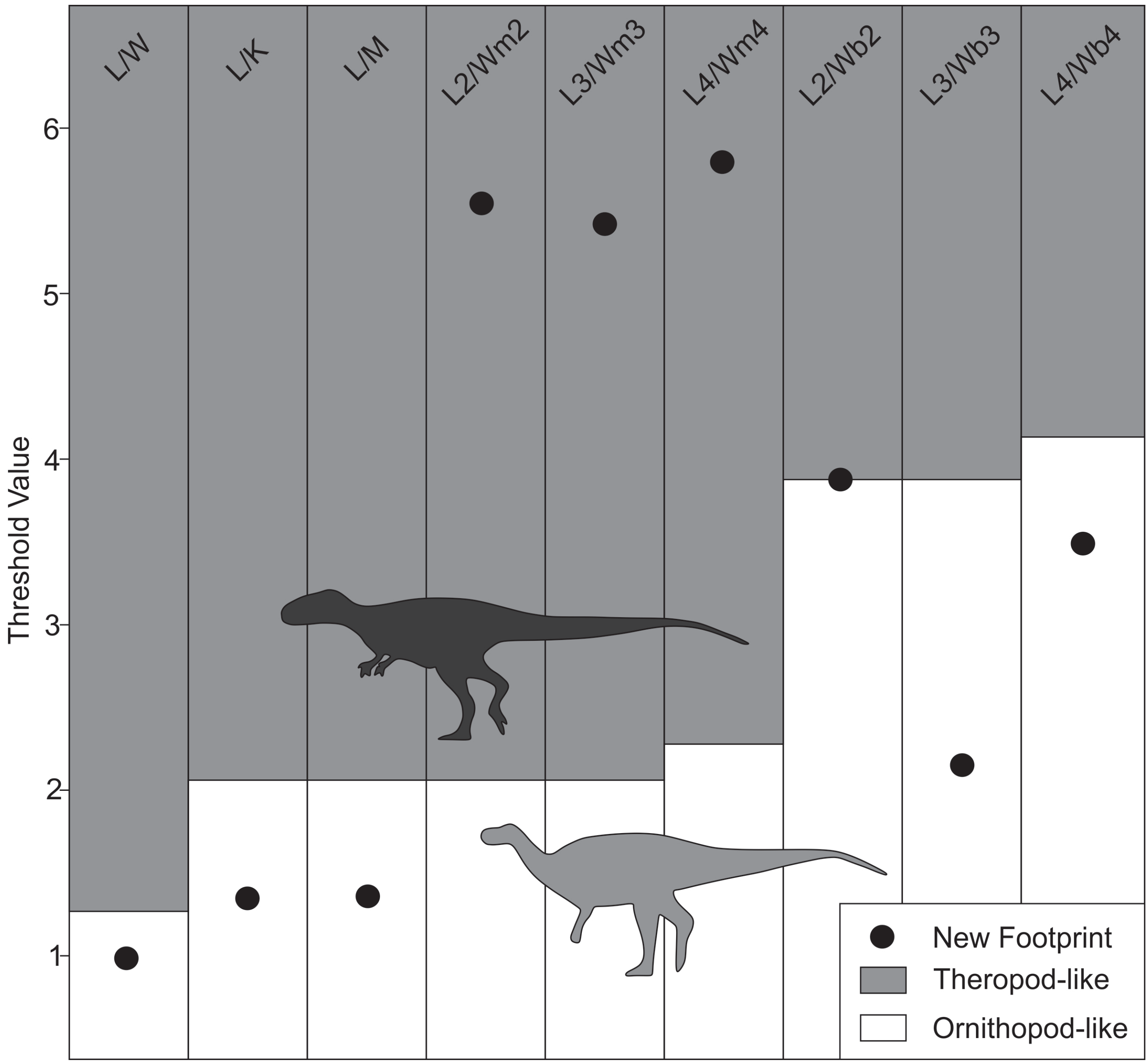

Fig. 8 - Multivariate analysis of the morphometric parameters of CPGP.3.11.1 footprint showing distinction values between theropod and ornithopod tracks. L/W: length/ width; L/K and L/M: length/"heel" to interdigital (hypex) lengths; L2/Wm2 to L4/Wm4: length/middle digit widths of digits 2, 3 and 4; L2/Wb2 to L4/Wb4: length/basal proximal digit widths of digits 2, 3 and 4. Adapted from Romilio & Salisbury (2011).

flattened and hoof like (Weishampel et al., 1990), causing broad footprints, with a broad heel and with rounded digits, without claw marks. Inverting the position of the footprint, in its natural position (Fig. 11) and inverting the 3D model (Fig. 3) allows its visualisation as a normal footprint corresponding better to an ornithopod footprint, than those of a theropod (Figs 6 and 11) it is clearly shown the difference between them. This comparison was made with the footprint T5 of the tracks from the theropod of Lagosteiros (Antunes, 1976), which was made by the CPGP team in 2001, a latex artificial cast, having the same type of structure (cast) for comparison. We used the original latex cast and a recent photograph (2016) of the same footprint (Fig. 6). Comparison between casts displays a clear difference in the digits and heel: the theropod digits are thin, long and narrow, claw marks are visible (especially DIII) and the posterior end of the foot is a narrow heel imprint; for its part, the posterior end of the foot of cast (CPGP.3.11.1) is wider, and the digits wider and rounded. Moreover, in CPGP.3.11.1 the claw marks are absent and heel is wider than in the theropod footprint. Differences can also be seen in comparing the angles between the digits. The angles are narrower in the case of the theropod footprint, while they exhibit a wider angle from specimen CPGP.3.11.1 (Fig. 6).

Dinosaur tracksites are well documented in Cretaceous formations from Portugal, but tracksites (and bones) are less abundant than in Jurassic. Five Cretaceous dinosaur tracksites have been described from the Lusitanian Basin (six, with Praia do Guincho) and two, from the Algarve Basin (Tab. 3). These tracksites contain sauropod, theropod

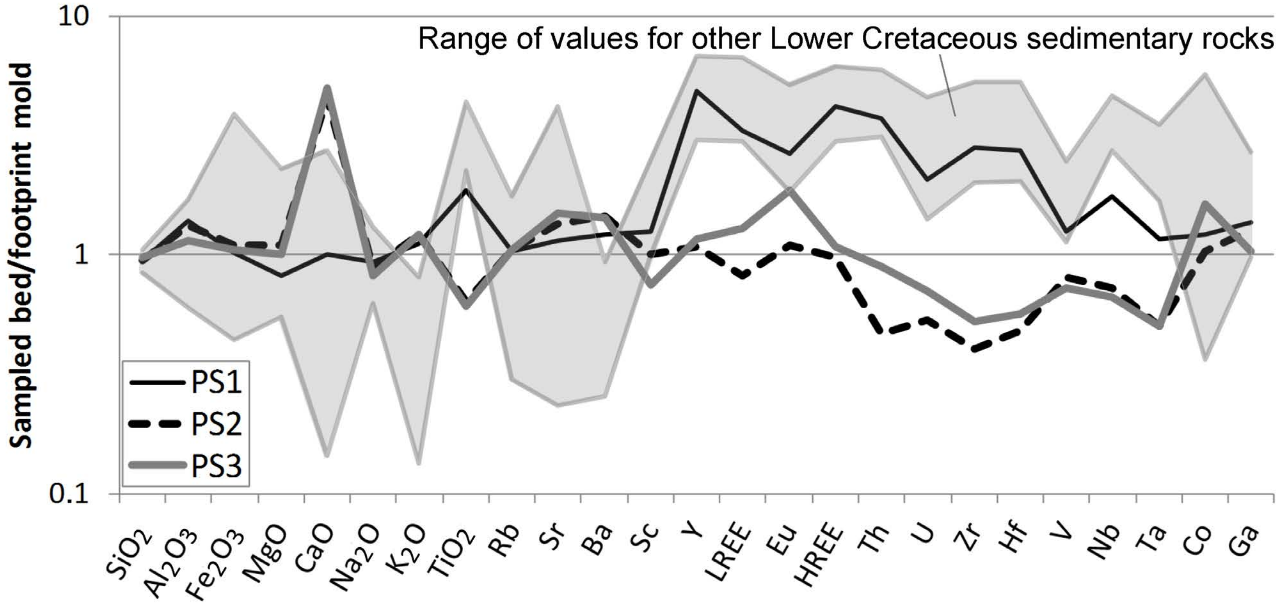

Fig. 9 - Composition of the sandstone beds from Papo-Seco Formation found in the site proximities, normalised to the sediment retrieved from the tridactyl footprint cast. Range of geochemical compositional data of Lower Cretaceous siliceous (SiO_2 > 66%) sediments from the Lusitanian Basin (from Dinis et al., 2016) is represented for comparison.

and ornithopod tracks. In the Olhos de Água site 128 footprints have been recognized in 17 trackways within an area of ca. 80 square meters attributed to ornithopod (iguanodontid) and theropod (large and middle size theropods) (Mateus & Antunes, 2003). An early Aptian tracksite at Praia Grande (Sintra) consists of an upper level where 66 footprints (51 belonging to 11 trackways and 15 isolated) of theropods, sauropods and ornithopods were recognized (Madeira & Dias, 1983). Two track levels with dinosaur footprints (Lagosteiros A, from Berriasian and Lagosteiros B, from Hauterivian) with theropod and ornithopod footprints were recognized in Lagosteiros (Antunes, 1976; Santos et al., 1992; Meyer et al., 1994; Santos, 2003). Finally, the Cenomanian of Pego Longo (Carenque) tracksite is the only Late Cretaceous dinosaur tracksite known in Portugal. This tracksite consists of a 127 meters long bipedal dinosaur trackway (Santos et al., 1991, 1992). In the Algarve Basin, the fossil record of dinosaurs is scarce. However, two sites (Praia de Salema and Praia Santa) report dinosaur footprints near Vila do Bispo in the Salema Formation (Hauterivian-Lower Barremian). In the western sector of Praia de Salema at the surface there is a horizontal track level where a sequence of subcircular and tridactyl marks were described (Santos et al., 2013). At Praia Santa, three track levels and some, isolated and paired, ornithopod footprints exposed at three other levels in the same sedimentary succession were identified (Santos et al., 2013). At this tracksite it is possible to recognize the characteristic morphology of ornithopod footprints in trackways 1, 2, 3 and 4 (Santos et al., 2013).

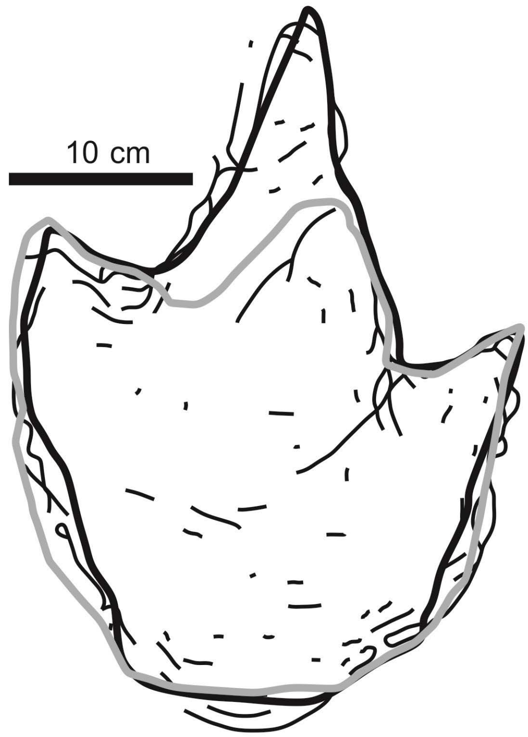

Fig. 10 - Outline of the footprint cast. Hypothesis 1: black; hypothesis 2: grey.

Iguanodonts had a wide geographical distribution in the Early Cretaceous, with a global range including Europe, North America, Africa, Asia and Australia (Weishampel et al., 1990). Their remains mainly occur in lowland, marshy and estuarine environments (Norman, 1985). This palaeoenvironment is compatible with the depositional sequence of the Papo-Seco Formation, which constitutes a transgressive unit deposited in an incised valley after a local sea level drop (Rey, 1992; Rey et al., 2003; Dinis et al., 2008).

Considering the occurrence of several iguanodon remains in the fossil record of this formation and according

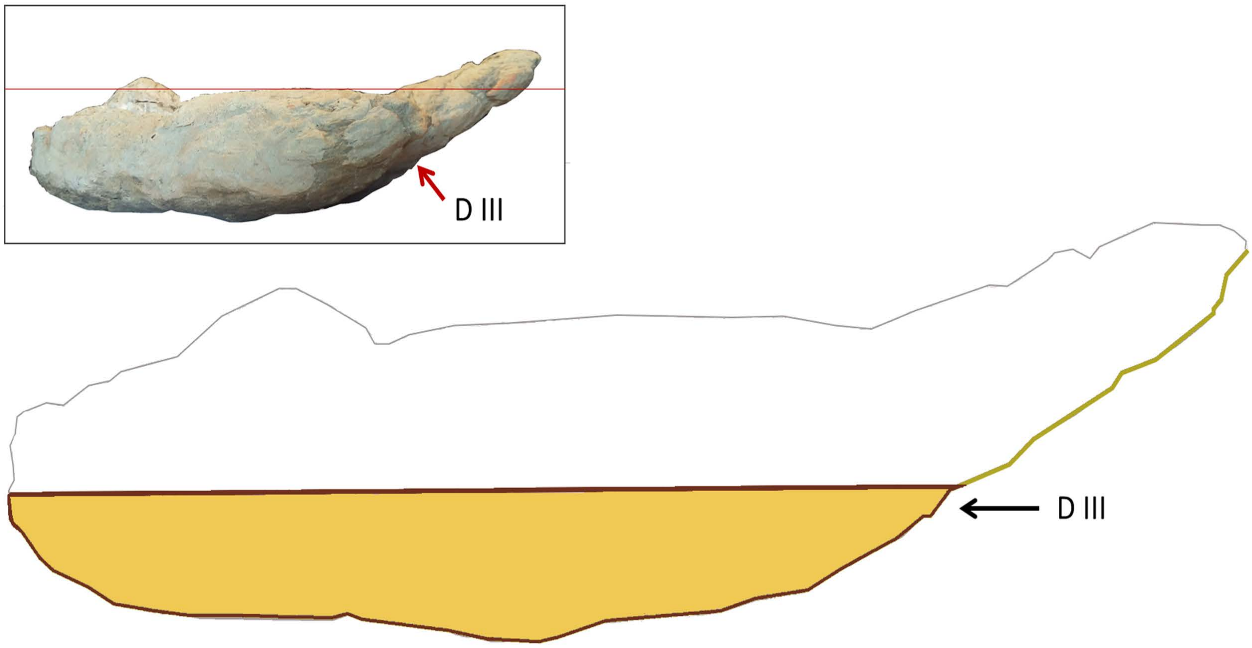

Fig. 11 - Inverted mold, corresponding to the footprint produced by dinosaur. Above, photography of the cast in inverted position (natural position). Below, featured of contour-lines of the base of the footprint. Contour-lines show a high angle in the extension of the block in the digit III.

to the characteristics identified and previously described, the studied footprint can possibly correspond to the ichnotaxon *Iguanodontipus* (Sarjeant et al., 1998; Díaz-Martínez et al., 2015). According to the general shape of the impressions of both the heel and digits, the eight-valid ichnospecies of large ornithopod footprints were grouped into three main groups (Díaz-Martínez et al., 2015). In group 1 only *Iguanodontipus* is included (Díaz-Martínez et al., 2015). We think that the CPGP.3.11.1 cast fits into this group (Fig. 12). The stratigraphic age of CPGP.3.11.1 (Barremian) is within the period of distribution of this ichnotaxon (Díaz-Martínez et al., 2015) that appears in tracksites from Europe (England, Spain, Germany and Switzerland) from Kimmeridgian to Albian (Díaz-Martínez et al., 2015).

CONCLUSIONS

The photogrammetric methodology used in this study allows to create quickly and accurately a 3D model of a dinosaur footprint. The footprint morphology was digitally modelled in 3D with great detail. The possibility of applying a wide range of algorithms (altimetry, curves, shadows, normal, X-ray, transparency, radiance, etc.) may often facilitate the perception of morphological details

Tracksite	Localization	Geologic Unit	Age	Stratigrafic Unit	References
Praia de Olhos de Água	Óbidos	Lusitanian Basin	Aptian /Albian	Sandstone Complex of Olhos Amarelos e Pouso da Galeota	Mateus & Antunes, 2003
Praia Grande	Sintra	Lusitanian Basin	Aptian	“Camadas de Almagem”	Madeira & Dias (1983)
Pego Longo	Sintra/Carenque	Lusitanian Basin	Cenomanian	Formation of Caneças	Santos et al. (1991, 1992)
Lagosteiros B	Sesimbra/Cabo Espichel	Lusitanian Basin	Hauterivian	Formation of Ladeiras	Antunes, 1976; Santos et al. (1992); Meyer et al. (1994); Santos (2003)
Praia Santa	Vila do Bispo	Algarve Basin	Barremian	Formation of Salema	Santos et al. (2000a, b); Santos (2003)
Praia de Salema	Vila do Bispo	Algarve Basin	Barremian	Formation of Salema	Santos et al. (2000a, b); Santos (2003)
Praia do Guincho	Sesimbra/Cabo Espichel	Lusitanian Basin	Barremian	Formation of Papo-Seco	This study

Tab. 3 - Track sites with ornithopod footprints from the Cretaceous of Portugal.

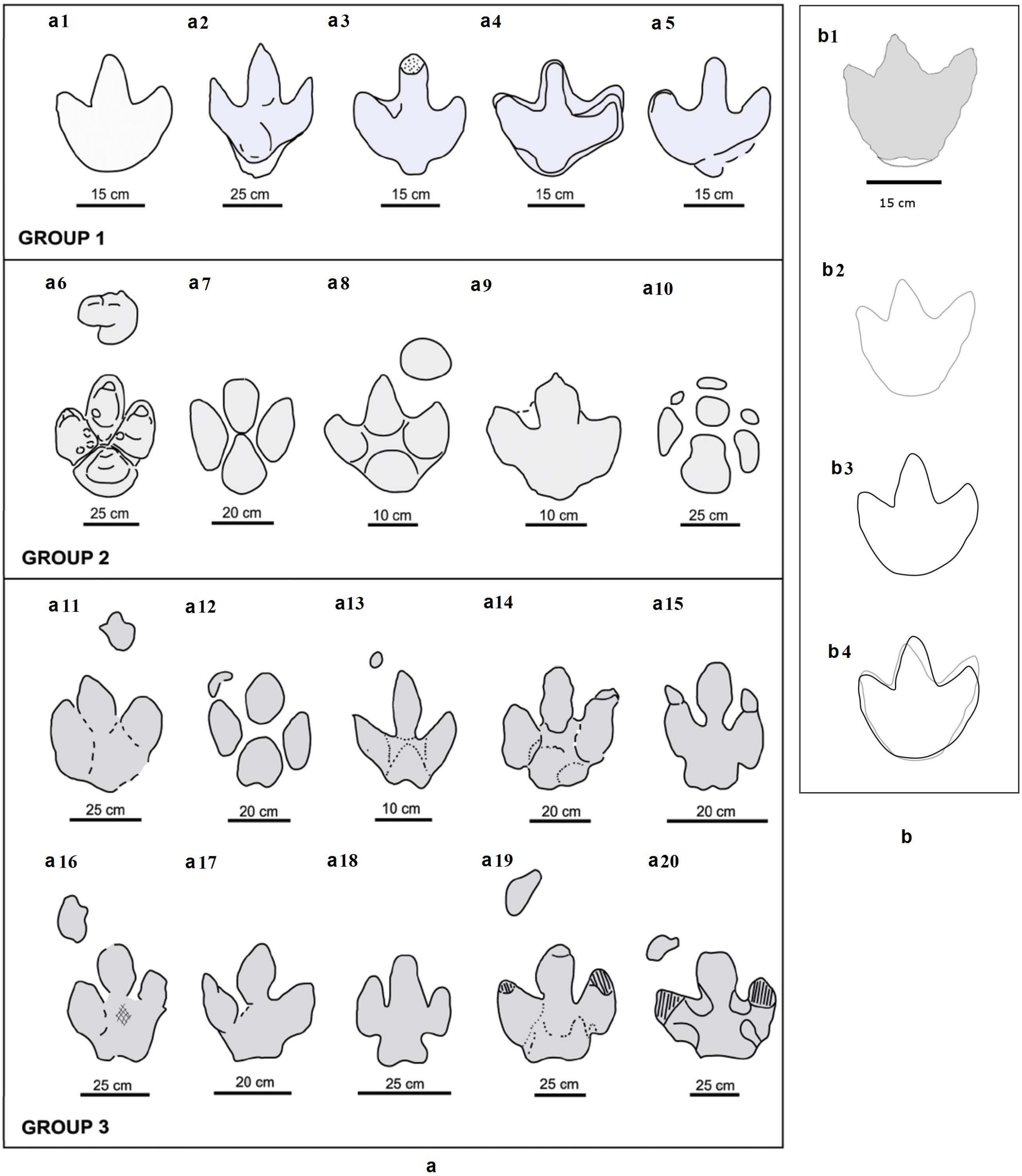

Fig. 12 - a) The three main groups of large ornithopod footprints defined by Díaz-Martínez et al. (2015), in comparison with CPGP.3.11.1 (b) (adapted from Díaz-Martínez et al., 2015).

of interest that cannot easily be seen by eye on the fossil specimens or in the field (Neto de Carvalho et al., 2016).

In our case study, analysing the cast in its original position and inverting the 3D model allows its visualisation as the footprint of the animal; we confirm that digit III is not as long as it first appeared to be, because the contour-lines show a high angle in the extension of the block in the digit III. The digit III is shorter and rounded, and a substantial part of the shape of digit III is sediment that does not belong to the shape of the footprint. On the other hand, the total divarication angle formed between digits II and IV, the angle between digits II and III, the morphological parameters, the rounded shape of the digits and the absence of the claws, allow us to attribute the footprint to an ornithopod dinosaur.

The Papo-Seco Formation contains the only sandstone layers in the region that resemble in lithology the sediment collected in the footprint cast and the assignment of the footprint cast to a sandstone bed of Papo-Seco Formation is not rejected by the geochemical provenance analyses. The sedimentary analyses of the three sandstone beds at the site where the footprint was found, however, do not clarify the precise bed of origin of the specimen with a high degree of certainty.

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