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DESCRIPTION AND INTERPRETATION OF THEROPOD TRACKS FROM THE BERRIASIAN TIDAL FLATS OF THE SOUTH-IBERIAN PALAEOMARGIN (INTERNAL PREBETIC, S SPAIN)

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Abstract: The study of the lower Berriasian (Lower Cretaceous) of the Sierra del Pozo (Internal Prebetic, Betic Cordillera) has made possible the discovery of three dinosaur tracks that correspond to the digitigrade footprints (28.7 to 26.1 cm long and 19.9 to 21.4 cm wide) of mesaxonic tridactyls. The tracks are located at the top of two shallowing-upwards sequences with desiccation-related mud cracks that correspond to supratidal facies. The trackmakers were medium-sized theropods, on the basis of the prints record, the claws, the elongated digits and the low interdigital angles. This is the only record at the South-Iberian Palaeomargin of theropod tracks, which are relatively scarce, compared to the Lower Cretaceous of other Iberian Palaeomargins.

Key words: Sedimentology, ichnology, 3D models, Lower Cretaceous, geoheritage, Digital Outcrop Model (DOM).

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INTRODUCTION

Dinosaur fossil footprints and trackways of Upper Jurassic to Lower Cretaceous age are relatively common in Iberia, namely from the Iberian Range (e.g., Moratalla *et al*., 1994; Fuentes Vidarte and Meijide Calvo, 1998; Alcalá *et al*., 2014; Castanera *et al*., 2015, 2022; García-Corbeña *et al*., 2023), the Basque-Cantabrian coast (e.g., Castanera *et al*., 2016; Rauhut *et al*., 2018), the Lusitanian Basin (e.g., Castanera *et al*., 2021; Figueiredo *et al*., 2022) and the Algarve Basin (Santos *et al*., 2013). However, the record of fossil footprints of Jurassic and Cretaceous dinosaurs or other vertebrates in the External Zones of the Betic Cordillera is almost absent. García-Hernández *et al*. (2003) described 5 dinosaur tracks in the Lower Cretaceous of the Internal Prebetic of the Sierra del Pozo in Jaén Province, and also Herrero *et al*. (2016) made discoveries in the uppermost Cretaceous of the External Prebetic of Jumilla, in Murcia Province. Most of the stratigraphic record of the Jurassic and Cretaceous of the External Zones of the Betic Cordillera is represented by marine sedimentary rocks. The shallowest or emerged environments of the South-Iberian Palaeomargin were eroded in different stages of the evolution of this Palaeomargin (García-Hernández, 1978). Therefore, Cretaceous continental and coastal deposits are relatively scarce and represented almost exclusively by the Tithonian-Berriasian tidal sedimentary sequences of the Internal Prebetic of Sierra del Pozo (e.g., García-Hernández, 1978; Jiménez de Cisneros and Vera, 1993), Cenomanian fluvial and mangrove environments of the External Prebetic of Albacete (e.g., Arias *et al*., 1979; Reolid *et al*., 2024), and shallow coastal lakes to peritidal environments of the Santonian-Maastrichtian of the Prebetic of Jumilla (e.g., Herrero *et al*., 2016).

The dinosaur fossil footprints reported by García-Hernández *et al*. (2003) were assigned to the lower Berriasian. However, most of these dinosaur tracks have disappeared after around 20 years and only three fossil footprints still exist, one of them being new. The aim of this work is to describe and interpret these dinosaur tracks and the facies, using field observations and digital 3D models, as well as analyses of the microfacies and the microfossil assemblages. In addition, the elaboration of digital 3D models provides a useful record in the light of future deterioration of the outcrops. This relevant outcrop for geoheritage is at high risk from erosion, slope instability and vandalism.

GEOLOGICAL SETTING

The Prebetic is the northern domain of the Betic External Zones (Fig. 1) and represents autochthonous to parautochthonous deposits of the South-Iberian Palaeomargin, deposited mainly during the Jurassic and Cretaceous on a relatively proximal epicontinental shelf (García-Hernández *et al*., 1980). The Prebetic is divided into the External and Internal Prebetic, according to stratigraphic and tectonic data. The Prebetic successions were mainly formed as shallow-marine facies, with continental episodes and recorded intervals of erosion. The thickness of the different formations decreases toward the External Prebetic with the extension of associated stratigraphic gaps (García-Hernández *et al*., 1980).

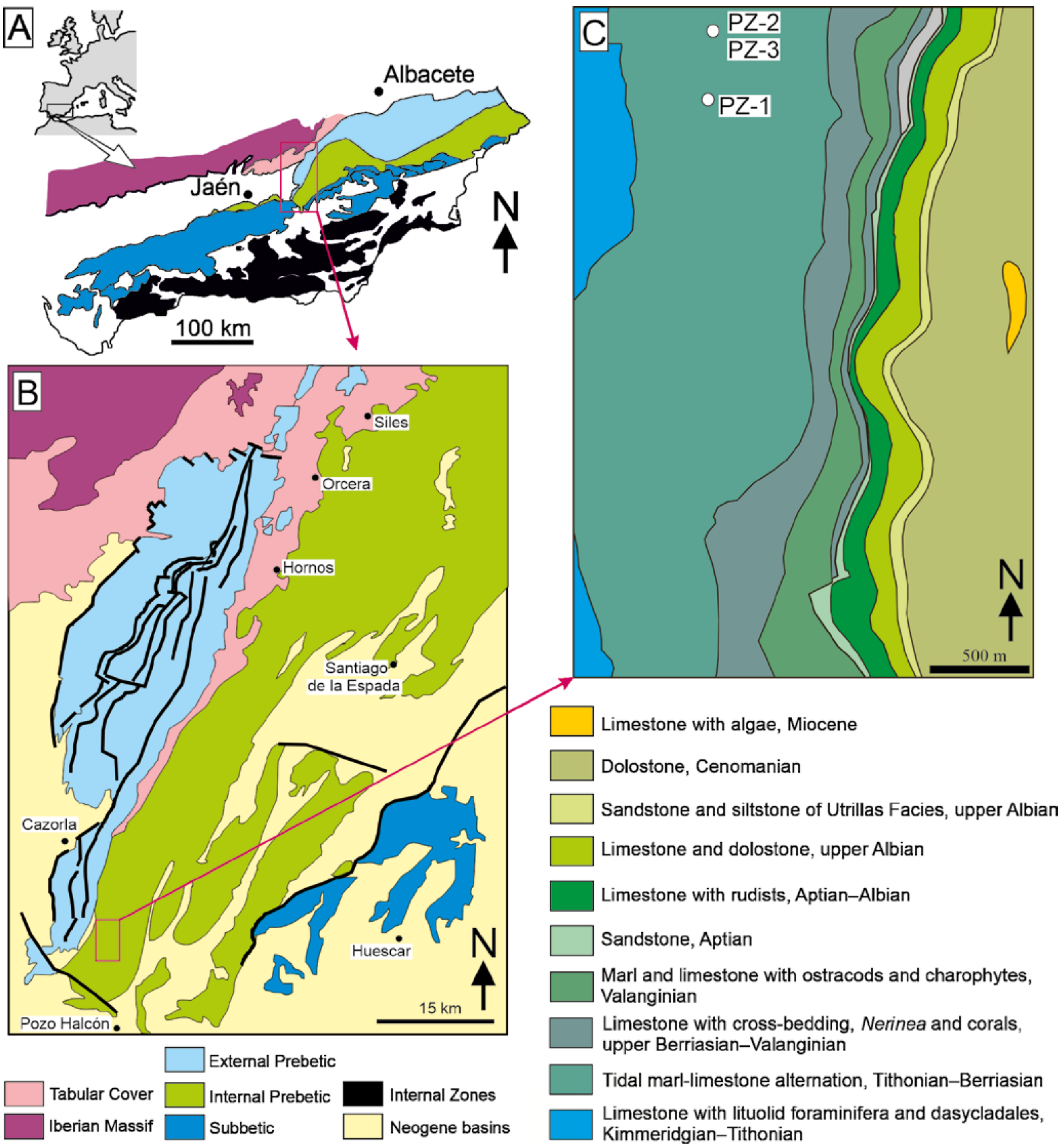


Fig. 1. Geological setting. **A**. Geological map of South Spain. **B**. Geological map of the Central Prebetic in the area of Sierra de Cazorla and Sierra de Segura. **C**. Geological sketch map of the area with the dinosaur tracks (white dots) in the Sierra del Pozo (southern part of the Sierra de Segura, Jaén Province).

In the Internal Prebetic of the Sierra del Pozo, the Jurassic-Cretaceous transition is represented by up to 400 m of Tithonian limestones, with Purbeck facies that have been defined as the Sierra del Pozo Formation (Vera *et al*., 1982). Two members have been differentiated in the type section of the Sierra del Pozo Formation (Jiménez de Cisneros and Vera, 1993; Fig. 2). The Lower Member is made up of a 325-m-thick succession of subtidal limestones, which pass upwards into peritidal facies, dated as Tithonian-Berriasian (García-Hernández, 1978; Fig. 2). The peritidal facies of the upper part of the Lower Member has been extensively studied by Jiménez de Cisneros and Vera (1993) and Anderson (2004). The Upper Member is 70 m thick, and it has been dated as uppermost Berriasian to lower Valanginian (García-Hernández, 1978; Geyer and Rosendahl, 1985; Jiménez de Cisneros and Vera, 1993). The Upper Member is represented by cross-bedded limestones with pebble layers and coral fragments, limestones with *Nerinea*, and clusters of corals (García-Hernández, 1978; Löser *et al*., 2021). The studied fossil footprints are in the upper part of the Lower Member of the Sierra del Pozo Formation on two different surfaces and in exposures of strata, called South and North, located a distance of 119 m apart (Fig. 1).

MATERIALS AND METHODS

The studied trace fossils are located in two limestone beds of the lower Berriasian of the Internal Prebetic of Sierra del Pozo (Jaén, Spain). Ten thin sections were prepared for analyzing microfacies with a SZ-PT Olympus microscope. A total of three samples underwent for analysis of microfossil content. About 200 g of dried rock were reduced into small pieces and introduced into water. The disaggregated rock sample was rinsed in a column of standard stainless-steel sieves with mesh sizes of 1 mm, 500 µm, 200 µm, 100 µm and 53 µm, and with a jet of water at the top. Microfossil remains (mainly dasycladales, foraminifera, and ostracods) were hand-picked under a Leica M205C microscope. The images of microfossils were obtained from the Centro de Instrumentación Científico-Técnica of the University of Jaén (Spain), using a Merlin Carl Zeiss Scanning Electron Microscope (SEM).

The dinosaur footprints are located on the top surface of two limestone beds that were surveyed by means of UAS (Unmanned Aircraft Systems) photogrammetry, using a micro UAS (DJI Mini 3 pro) with an onboard DJI FC3582 camera (12 MP). This mini UAS has a maximum take-off weight (MTOW) lower than 250 g, which allowed the acquisition of very close-range images in difficult-to-access parts of the outcrop and, because of the light weight, partially overcame the restrictions of the National and European regulations on the use of UAS (AESA, 2025). This camera is equipped with a wide-angle lens (focal length of 6.7 mm or 24 mm in equivalent format).

An additional terrestrial laser scanner (TLS) survey was carried out with a Leica Geosystems C10 pulsed scanner. Laser data were processed with Leica Cyclone, FARO® Scene and CloudCompareV2 software. Because of the greater

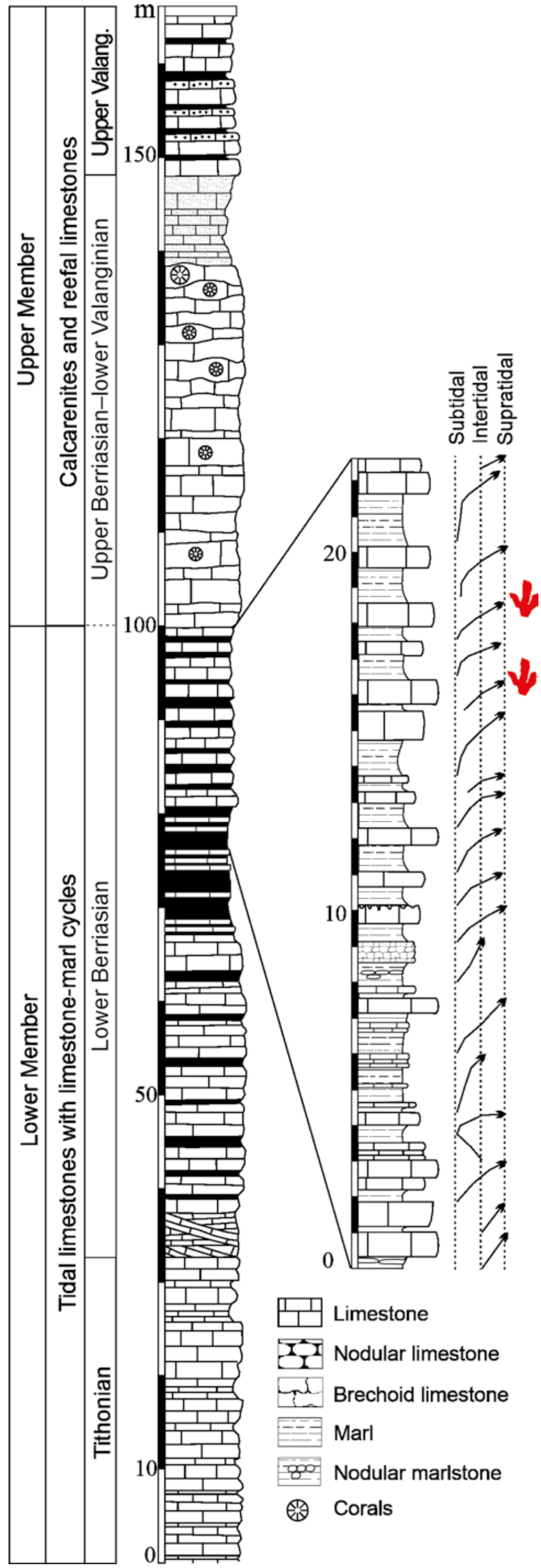


Fig. 2. Sierra del Pozo Formation and detail of the upper part of the Lower Member, where supratidal facies are increasingly abundant. The locations of the dinosaur tracks are indicated in red.

accuracy of the TLS ranging system (Plus/minus 2 mm on the modelled surface) with respect to the UAS positioning system, the TLS data were used to extract ground control points and as an independent check measurement. Some artificial targets (white circles on a black background, printed on a PVC foam board) and other well-defined targets were measured on both the TLS point cloud and the images.

The photogrammetric and TLS processing steps to obtain the 2.5D and 3D products (digital elevation models – DEM, height and contour maps, orthoimages and 3D models) are outlined in Reolid *et al*. (2020) and Reolid *et al*. (2023).

The average flying height was 2.8 m, which implied a mean ground sample distance (GSD) of 0.9 mm/pix. Images were processed with the photogrammetric software Agisoft Metashape Pro 2.01. Local coordinate reference systems were defined for each outcrop and were aligned with the planes, containing the main surfaces of the outcrops. A final adjustment was performed in this reference system, including a camera calibration and coordinate refinement. The error (with respect to the TLS data) at check points was ±3 mm.

Next, a general orthoimage and a digital elevation model (DEM) with 1 and 2 mm resolution, respectively, resolution were generated for each outcrop, which helped to locate and identify the traces. This final processing was carried out with Metashape and QGIS 3.34 software.

The DEM and 3D models allowed the analysis of different measurements, such as the track length, track width, track span, and the interdigital angles, as well as the pace length, following the review of terminology of Lallensack *et al*. (2025).

In addition to the morphometric analysis, both 3D models were incorporated in two digital outcrop models (DOM) for educational and dissemination purposes, but bearing in mind the fact that these are examples of geological heritage outcrops at risk, these DOM will facilitate its conservation. The models are available for visualization in the Museo Paleontológico Virtual of the Universidad de Jaén (PALEOV-UJA) at:

– Track PZ1: https://alquivir.ujaen.es/museo/huella-de-teropodo-cretacico-pozoalcon-jaen/
– Tracks PZ2-PZ3: https://alquivir.ujaen.es/museo/huellas-de-teropodo-cretacico-pozoalcon-jaen/

Different features have been described in the fossil footprints. such as the track length and track width, and interdigital angles. Track length is measured between the track walls and parallel to the long axis from the most anterior to the most posterior point of the outline (e.g., Leonardi *et al*., 1987). The track width is measured parallel to the transverse axis between the most medial and lateral points of the outline (Leonardi *et al*., 1987; Lallensack *et al*., 2025). The track span is the distance between the tips of the outer digit impressions (Thulborn, 1990) that in the case of tridactyl tracks is the width of the anterior triangle (Weems, 1992). The interdigital angles are measured between adjacent digits. For consecutive tracks, the present authors considered the pace length as the distance between two consecutive tracks of a contralateral limb pair *sensu* Weems (2006) and Lallensack *et al*. (2025).

RESULTS

Facies

The stratigraphic succession is composed of successive cycles of about 2 m thick, interpreted as tidal cycles by Jiménez de Cisneros and Vera (1993), comprising three clearly developed intervals. The subtidal facies are micrites and marly micrites with dasycladal algae (mainly *Aloisalthella sulcata*, and secondarily *Cylindroporella* sp.), agglutinated foraminifera (*Ammobaculites* sp., *Anchispirocyclina lusitanica*, *Gaudryina* sp., *Nautiloculina oolithica*, *Rectocyclammina* sp., *Freixialina* sp., and *Verneuilina angularis*), and ostracods (*Assiocythere circumdata*, *Favosella* sp., and *Paracypris* sp.; Fig. 3). Trace fossils are scarce and correspond to *Thalassinoides*.

The intertidal facies are characterized by micrites with fenestrae, poorly laminated. Microfossils are restricted to scarce small miliolid foraminifera.

The supratidal facies are relatively thick limestone beds and mudstone microfacies with lamination and the presence of fenestrae. Mud cracks, ripples and rain prints are recorded at the top (Fig. 3). Some variations with respect to this tidal sequence are described in Jiménez de Cisneros and Vera (1993) and Anderson (2004). The supratidal facies are progressively more important at the top of the Lower Member of the Sierra del Pozo Formation.

Dinosaur tracks

The studied dinosaur footprints are preserved at the top of the supratidal facies on surfaces with ripples and mud cracks (Figs 4 and 5). They are three footprints from two different surfaces, designated South and North, that constitute the tops of two depositional sequences.

The lower surface, located to the South, presents an isolated tridactyl footprint, designated PZ-1 (Fig 4). It is mesaxonic and has three digits, 26.1 cm long and 21.4 cm wide (Fig. 6). The footprint is oriented to the South. Claws are poorly preserved. Digits are straight to slightly bent (digit II). Digits II and IV are subequal in length. The surface is also characterized by the presence of ripple marks and mud cracks. The dinosaur footprint is located over the ripples and mud cracks. There are not the typical structures of fragmentation and deformation of the ground, such as folding, breakup or displacement of mud cracks, collapse of footprint walls, and ground liquefaction. The mud cracks are preserved inside the footprint. The track is not very deep. Mud extrusion is mainly observable in digit IV, coincident with this digit IV shows a deeper impression in the sediment than do digits III and II.

The upper surface, located to the North, presents two tridactyl footprints, here designated PZ-2 and PZ-3 (Fig. 5), that correspond to those described by García-Hernández *et al*. (2003) with the names 2CAZ1.1 and 2CAZ1.2 respectively. PZ-2 is a left pes, 27.1 cm long and 20.5 cm wide (Fig. 6). Claws are poorly preserved, and the digits are straight (digits II and II) to slightly bent (digit IV). Digits II and IV are subequal in length and digit III is the longest, having a low divarication angle (interdigital angle II–III is 30.8º and III–IV is 29.9º; Fig. 6).

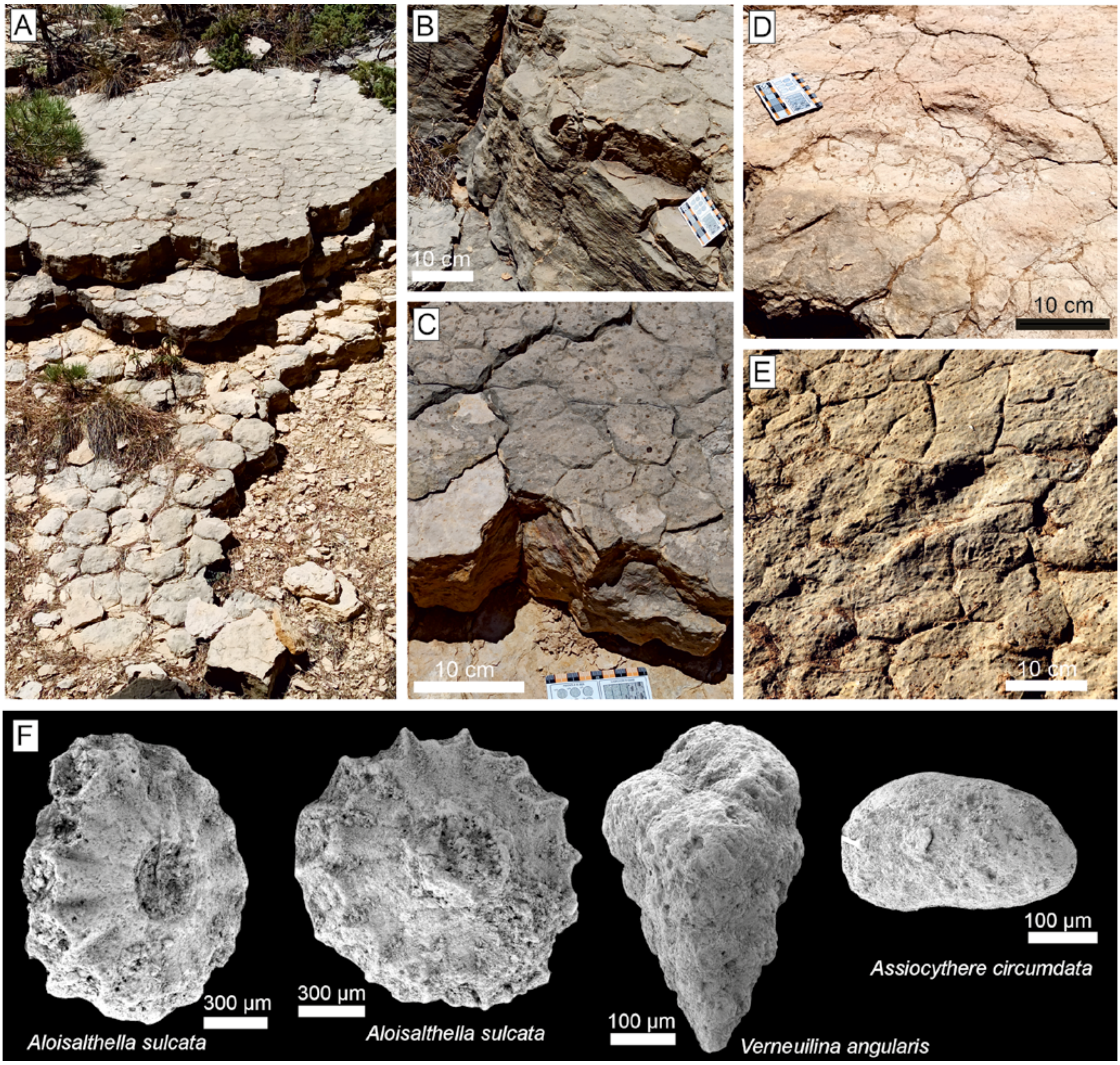


Fig. 3. Field view of the upper part of the Lower Member of Sierra del Pozo Formation, close to the Puerto Llano area, in Sierra del Pozo. **A**. Desiccation mud cracks of the supratidal facies. **B**. Detail of the lamination of the facies. **C**. Mud cracks and rain prints at the top of a shallowing-upwards sequence. **D**. Dinosaur tridactyl footprint PZ-1 on a surface with mud cracks. **E**. Dinosaur tridactyl footprint PZ-2 on a surface with mud cracks. **F.** Representative microfossils of the subtidal marly intervals (scale bar 100 µm).

The PZ3 corresponds to a right pes, being 28.7 cm long and 19.9 cm wide (Figs 5 and 6). Digit III is the longest, and digits II and IV are subequal in length and show a very low divarication angle between digits II–III (221.1º) and II–IV (11.6º) (Fig. 6). Claws are also poorly preserved, except for digit III, where the claw is sharp, and the digits are elongated and straight. Both tracks probably constituted part of a trackway with a pace length about 97 cm (Figs 5A and 6). However, two footprints are not enough for the authors to assume that they are part of a unique trackway. There are not ripple marks on this surface, only mud cracks that are relatively deformed in PZ-2. In addition, there is low mud extrusion in PZ-2. The PZ-3 track is poorly preserved. Both PZ-2 and PZ3 present the deepest part of the track at the front of the impression of digit III.

INTERPRETATION

The study of the upper part of the Lower Member of the Sierra del Pozo Formation confirms the interpretations of previous authors considering the existence of tidal facies (García-Hernández, 1978; Jiménez de Cisneros and Vera, 1993; Anderson, 2004). The microfossils recorded in the subtidal facies are consistent with the age of lower Berriasian, assigned by García-Hernández (1978). The record of *Aloisalthella sulcata* (ex. *Clypeina sulcata*, ex. *Clypeina jurassica*) confirms the lower Berriasian (Jaffrezo, 1980; Granier and Lethiers, 2018). *Anchispirocyclina lusitanica* has been also recorded in the lower Berriasian (e.g., Mircescu *et al*., 2016; Bakhmutov *et al*., 2018; Dorotyak, 2018). The sedimentation of the Lower Member of the Sierra del

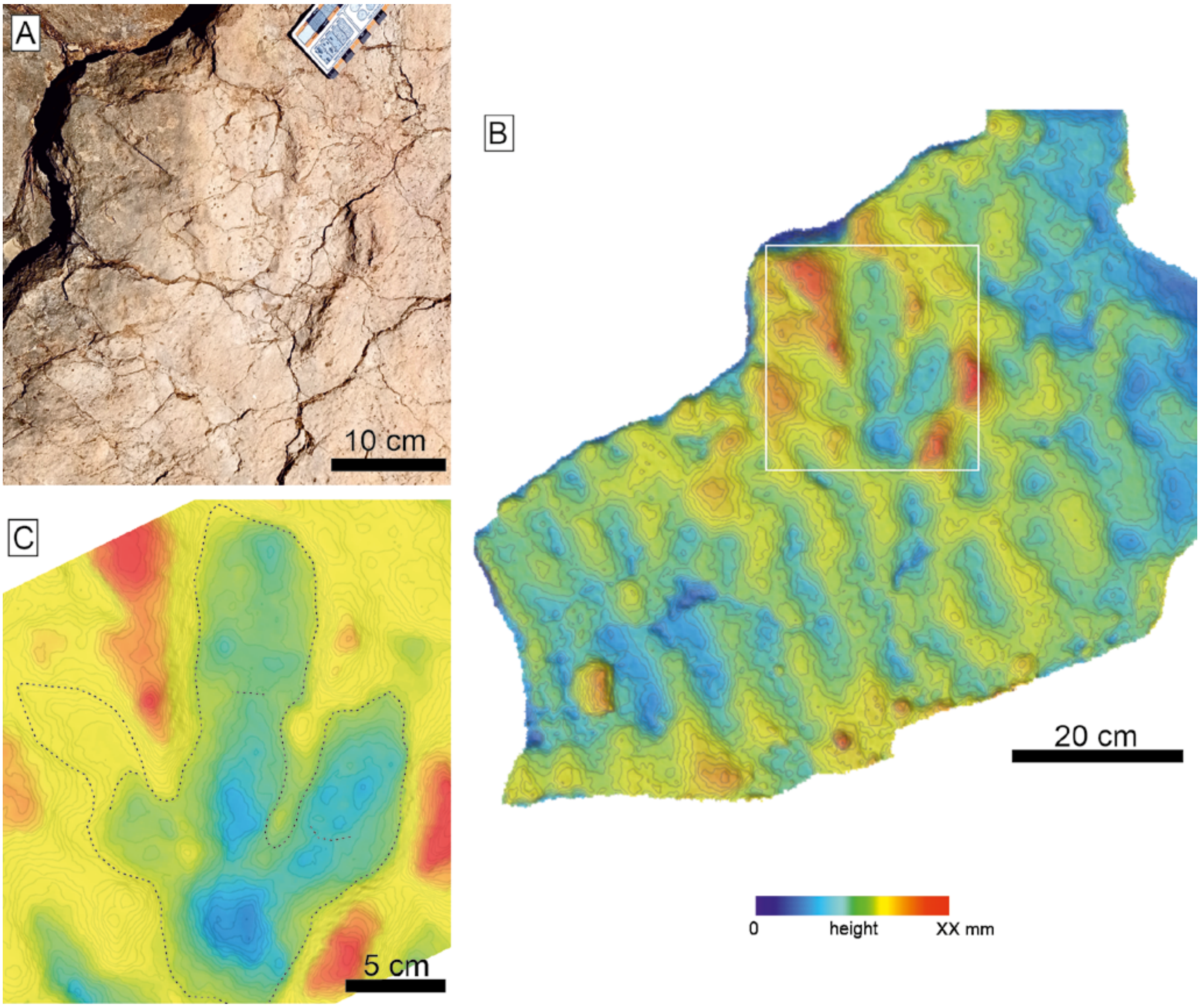


Fig. 4. Dinosaur track PZ-1, located on the South surface. **A**. Field view of PZ-1 and mud cracks. **B**. Digital elevation model (DEM) and contour levels of the surface that facilitate observation of the ripple marks. Note that mud extrusions are mainly located on the right side of the track near digit IV. **C**. Detail of the DEM of PZ-1 (the white rectangle in Figure 4B).

Pozo Formation was cyclic, represented by shallowing-upwards sequences terminating with supratidal carbonates that evidence emersion with desiccation. The presence of ripple marks at the top of the sedimentary sequences is not common and indicates the existence of currents prior to the desiccation. The depth of the footprints over the sediment is variable, but commonly not more than 2 cm in the deepest part, indicating relative compaction of the substrate, when the dinosaur walked on the tidal plain. On the two studied surfaces with dinosaur tracks, the footprints were formed after the formation of desiccation-related mud cracks.

Although the mud surface was dry and developed mud cracks, the lower part of the layer was sufficiently and water-saturated and plastic to flow under foot pressure, forming a low extrusion of mud at the edges of tracks PZ-1 and PZ-2.

The morphology of these marks suggests a tridactyl digitigrade elongated footprint. Due to the record of the claws (probably sharp, see digit III of PZ-3) and the elongated digits that make the track longer than wide, as well as the low interdigital angles, the trackmakers were surely medium-sized theropods. García-Hernández *et al*. (2003) also interpreted the five tracks they studied as being produced by theropods.

There are formulas for relative quantification of the size of a theropod from its tracks. Thulborn (1990) generated two formulas, relating the allometric proportions of foot length to hip height (h) for non-maniraptoriform theropod dinosaurs of small to medium size (track length < 25 cm) and of large size (track length > 25 cm). According to Thulborn (1990), the hip height for large-size theropods is $h = 3.06 * (\text{track length})^{1.14}$ giving a hip height of 126.1 cm for PZ-1, 131.6 cm for PZ-2 and 140.5 cm for PZ-3. The body length (L) of the theropod trace makers, applying Thulborn's methodology (Thulborn, 1990), adapted in Weems (1992) and Sciscio *et al*. (2017), $L = 4 * h$ results in specimens, ranging from 5.0 to 5.6 m for allometric body length.

The general morphology of the tracks resembles that of grallatorid tracks, characterised by their small to medium

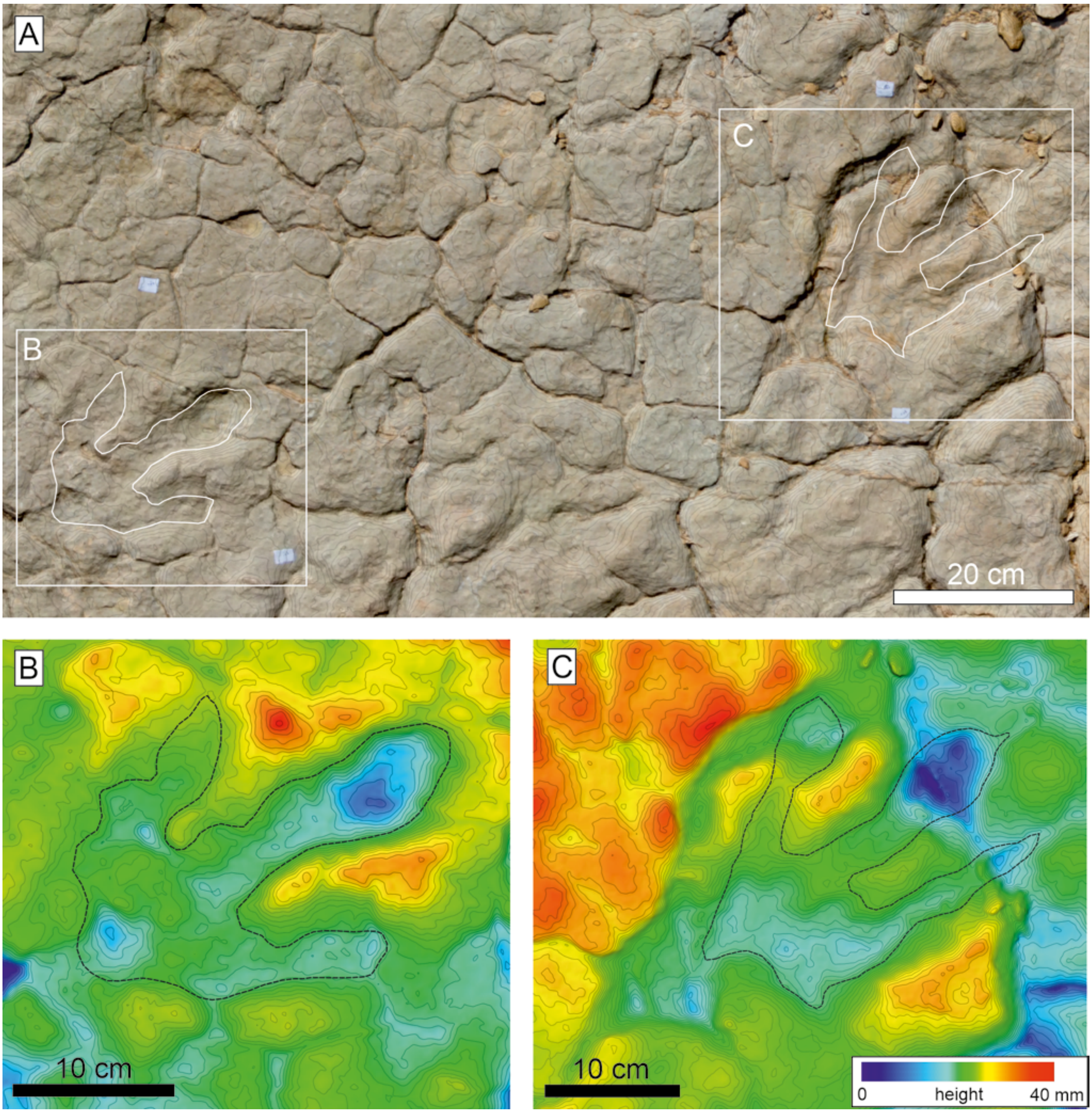
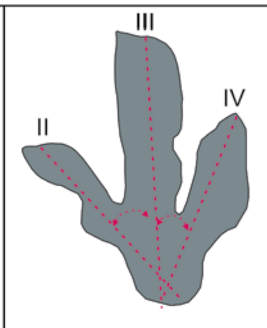
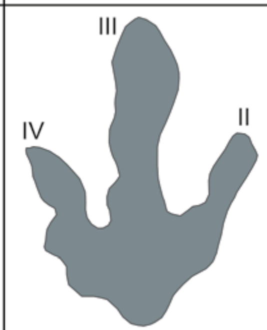
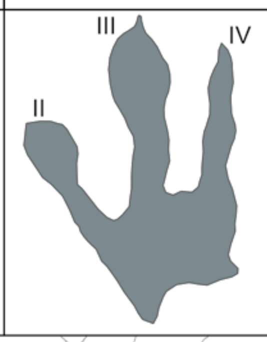


Fig. 5. Dinosaur tracks PZ-2 and PZ-3, located on the North surface. **A**. Orthoimage of the limestone surface, showing the dinosaur tracks and mud cracks. **B**. DEM and contour levels of the PZ-2 track (rectangle B in Figure 5A). **C**. DEM and contour levels of the PZ-3 track (rectangle C in Figure 5A).

size, well-defined digital pads, digits II and IV being subequal in length, with digit III being longer (high mesaxony), a low interdigital angle, and an oval/subrounded "heel". Classically, this group includes theropod ichnogenera *Grallator-Anchisauripus-Eubrontes* (see discussion in Castanera *et al*., 2016), typically reported from the Upper Triassic and Lower Jurassic (e.g., Olsen *et al*., 1998; Thulborn, 2000; Lucas *et al*., 2001; Petti *et al*., 2011). However, younger examples of grallatorids have been described from the Upper Jurassic and Lower Cretaceous (e.g., Avanzini *et al*., 2012; Lockley *et al*., 2013, 2014, 2015; Castanera *et al*., 2015, 2016).

Compared with other Lower Cretaceous outcrops with similar environments, such as the Iberian Range (e.g., Hernández-Medrano *et al*., 2008; Castanera *et al*., 2013, 2015, 2018, 2023; Pérez-Lorente, 2015), dinosaur footprints are very scarce in the Prebetic. Therefore, it is probable that a palaeogeographic barrier avoided the proliferation of terrestrial vertebrates, including dinosaurs, in the Prebetic. The studied tracks are located in the Internal Prebetic, located in a more distal position with respect to the continent than the External Prebetic and the Tabular Cover (Vera, 2001). However, there is no record of the Jurassic–Cretaceous transition in most of the External Prebetic and Tabular Cover. It is not

Track		Track length (cm)	Track width (cm)	Track span (cm)	Interdigital angle II–III	Interdigital angle III–IV
PZ-1 (right)		26.1	21.4	20.5	36.1º	25.9º
PZ-2 (left)		27.1	20.5	19.3	30.8º	29.9º
PZ-3 (right)		28.7	19.9	19.6	22.1º	11.6º

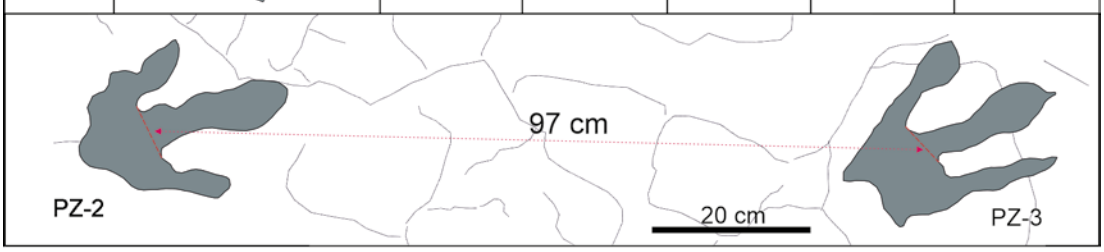


Fig. 6. Main data on the studied dinosaur tracks from the lower Berriasian of the Sierra del Pozo section.

possible to know if the tidal plain, represented by the Lower Member of the Sierra del Pozo Formation, was directly connected to Iberia or developed on isolated islands with a low abundance of dinosaurs.

CONCLUSIONS

Three dinosaur tracks were found after the examination of the Lower Member of the Sierra del Pozo of the lower Berriasian (Lower Cretaceous), one of them a new footprint and two previously reported tracks. These footprints are located at the top of two different shallowing-upwards sequences that terminate with supratidal limestones exhibiting desiccation-related mud cracks. The low depth of the tracks and minor mud extrusion indicate relative compaction of the substrate, when the dinosaurs walked on the tidal plain.

The morphology of the tracks suggests a mesaxonic tridactyl digitigrade footprint. Considering the record of the claws (locally sharp), the elongated digits, and the low interdigital angles, the trackmakers were medium-sized theropods (28.7 to 26.1 cm long and 19.9 to 21.4 cm wide), between 5 and 6 m in body length. This is the only record of dinosaur tracks on the South-Iberian Palaeomargin.

The poor record of dinosaur tracks in the Prebetic during the Berriasian, compared with other basins of the Iberian palaeomargins, where dinosaur tracks are abundant and diverse in the latest Jurassic and Early Cretaceous, indicates a potential geographic barrier for dinosaur dispersion to this sector. The stratigraphic gap in the External Prebetic domain, located between emerged lands and Internal Prebetic, makes it difficult solve this hypothesis.

Acknowledgements

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