GEOGACETA, 66, 2019

Giant theropod footprints in the Upper Jurassic of Morocco. Aït Mazigh site (Central Atlas)

Huellas terópodas gigantes en el Jurásico Superior de Marruecos. Yacimiento de Aït Mazight (Atlas Central)

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ABSTRACT

A new small site, not always outcropping, with large and giant theropod tracks in the Upper Jurassic of the Central High Atlas of Morocco is described. The ichnites and the typology of the rocks of the site are similar to those of the Iouaridène sites with which there is no cartographic continuity. The particular characters of the tracks and trackways are analyzed and highlighted and a hypothesis of distribution of this type of dinosaurs is pointed out.

Key-words: *theropod footprints, Oxfordian-Kimmeridgian, Morocco, giant theropods.*

RESUMEN

Se describe un nuevo yacimiento pequeño, no siempre aflorante, con huellas terópodas grandes y gigantes en el Jurásico Superior del Alto Atlas Central de Marruecos. Las icnitas y la tipología de las rocas en las que yacen son similares a las de los yacimientos de Iouaridène con los que no hay continuidad cartográfica. Se analizan y destacan los caracteres particularesde las huellas y rastrilladas y se apunta una hipótesis de distribución de este tipo de dinosaurios.

Palabras clave: *icnitas terópodas, Oxfordian-Kimmeridgian, Marruecos, terópodos gigantes.*

Geogaceta, 66 (2019), 83-86
ISSN (versión impresa): 0213-683X
ISSN (Internet): 2173-6545

Recepción: 1 de febrero de 2019
Revisión: 25 de abril de 2019
Aceptación: 24 de mayo de 2019

Introduction

Dinosaur ichnite sites were known (for example: 1BO, Fig. 1) on the northern shore of the Bin el Ouidane reservoir (Morocco), which occupies a part of the Ouaouizaght syncline core. 1BO is located in the Fm. Tilougguit (Jenny, 1985), to which Charrière and Hadoumi. (2016) give it a Bathonian age. Jenny *et al*. (1981), Boutakiout *et al*. (2006) and Nouri (2007) published studies of the local ichnofauna.

Recently, the water level of the reservoir of Bin el Ouidane has dropped and a new paleoichnological site (AMZ) has emerged in the so-called Aït Mazigh site.

The new site (AMZ) is located in the south limb of the syncline, on the south bank of the reservoir, in the lower part of the Iouaridène Fm. of Oxfordian-Kimmedridgian age (Charrière and Haddoumi, 2016), in red sedimentary rocks, formerly known as "les couches rouges".

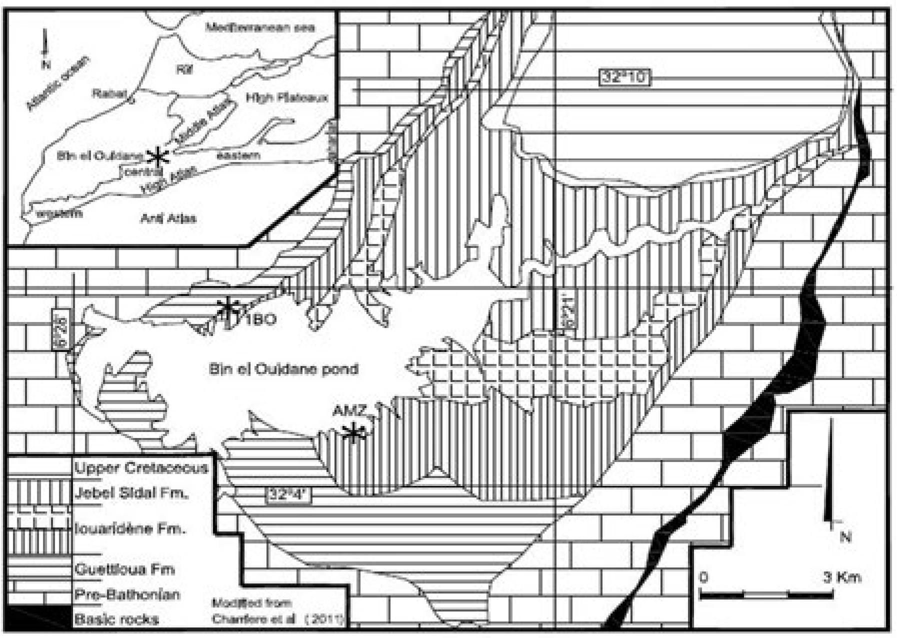

Fig. 1.- 1BO and AMZ sites location. Geology modified from Charrière *et al.* (2011).

Fig. 1.- Situación de los yacimierntos 1BO y AMZ. Mapa de Charrière* et al. *(2011) modificado.

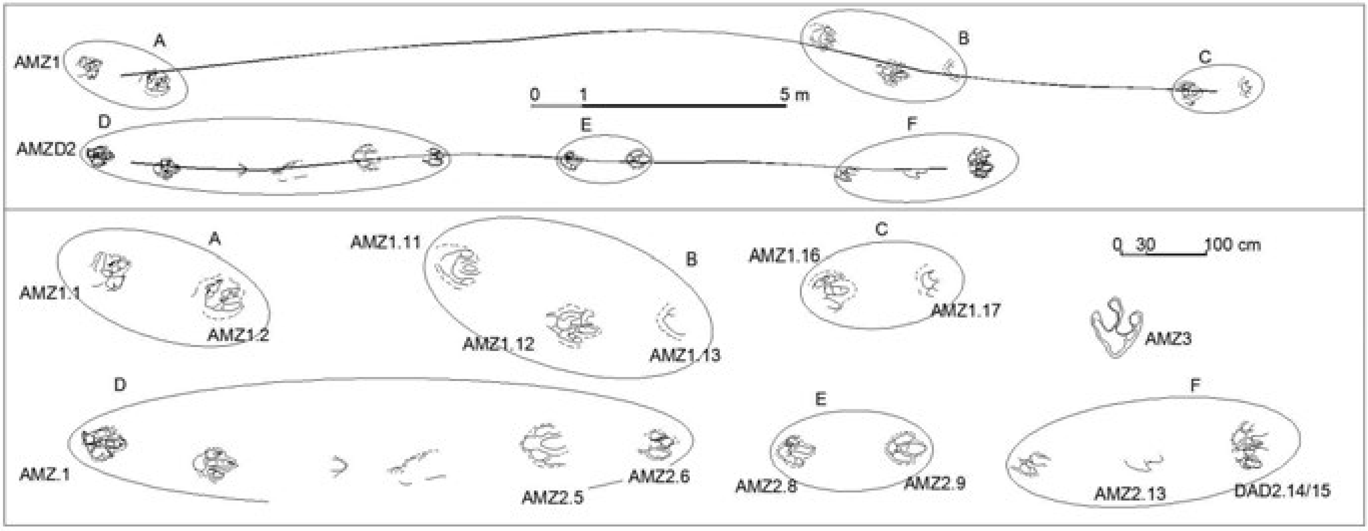

Fig. 2- AMZ1 and AMZ2 trackways (top). Detailed footprints of AMZ1and AMZ2 trackways, and AMZ3 isolate footprint (below).

Fig. 2.- Rastrilladas AMZ1 y AMZ2 (arriba). Detalle de las huellas de las rastrilladas AMZ1 y AMZ2 y (abajo) de la huella asilada AMZ3.

The site contains two trackways (AMZ1 and AMZ2) with 18 footprints and an isolated footprint (AMZ3), and may be below the water level or well above. On our work visit (October 2018), the water washed over the lower area of AMZ.

The sinsedimentary and/or diagenetic structures are similar to those of the Iouaridène sites (Boutakiout *et al*., 2009). The siliceous material of the sediments (silcretes) and the preservation of the desiccation cracks and the currents ripples are remarkable. Also noteworthy are the white concentric spherical nodules with a green nucleus that stand out for their color in the red sediments.

The ichnites discovered in Ouaouizaght are also similar to those of the Iouaridène syncline because of the large and giant theropod ichnotaxa they contain and because of the interaction structures of the tracks with the mud.

Material and method

AMZ (Fig. 1) is located in the Central High Atlas, south of the city of Beni Mellal, but in the province of Azilal. The UTM coordinates of the site taken on Google earth are 29S745823E / 3552400N. The study surface extends over a level of silcrets with current ripples and mud cracks. The direction and dip of the level is N100ºE, $\beta = 10$ºN.

For the collection of data, two straight lines have been drawn that roughly follow the path of the trackways. From them a grid with chalk has been made on which the geometric measurements have been taken. The contour lines of all traces and those of their mud extrussion rims have also been marked with chalk. All traces referenced with the previous network are photographed. The images and data obtained are finally treated with Adobe Photoshop and with AutoCAD.

The symbology, the terms (Table I) and the forms of measurement are those commonly used by our team (see Pérez-Lorente, 2015).

The ichnotaxonomic assignment is made according to the Romero Molina *et al.* (2003) criteria. Marty (2008) and Marty *et al*. (2017) consider giant tridactyl icnites those that are more than 50 cm long; but Boutakiout *et al*. (2009) consider giant icnites those that measure more than 70 cm in length. In the Iouaridène syncline there are three trackways with ichnites of the latter type, whose average lengths are: 90 cm, 77 cm and 75.5 cm. The percentage of giant theropod ichnites (more than 70 cm long) compared to that of theropod ichnites of all sizes in the Iouaridène syncline is 2%. Boutakiout *et al.* (2009) cite 15 places in the world with traces of this type. We should now add the one described by Marty *et al*. (2017), Rubilar *et al.* (2008) and those of this paper.

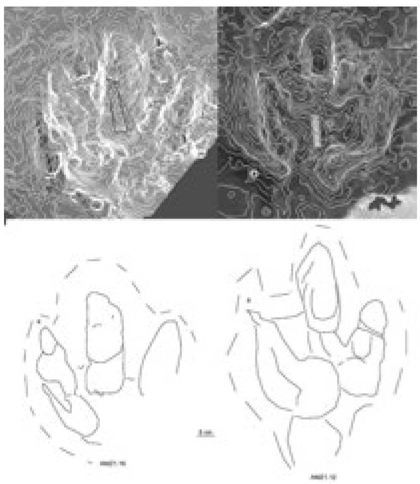

Fig. 3.- AMZ1.16 and AMZ1.12 images and outlines. Scale of images, 10 cm. See color figure in the web.

Fig. 3- Imágenes y línea de contorno de AMZ1.16 y AMZ1.12. Escala en las imágenes, 10 cm. Ver figura en color en la web.

Ichnology

The outline of the prints is not regular in any of the trackways (Fig. 2) but the determinative theropod characters are identified in them (Romero-Molina *et al*., 2003). The parameters used by Farlow (2018) cannot be measured to determine an accurate allocation of the ichnites or the trackmakers.

The ichnites are not stamps (Brown, 1999, Requeta *et al.,* 2006) but they are real prints. They are not stamps because they are deformed by structures associated with the movement during the three phases of the footprint creation (Tulborn and Wade, 1989). In: *Dinosaur tracks and traces,* (D.D. Gilette and M.G. Lockley, Eds.). Cambridge University Press, 51-56., but they are real footprints (Pérez-Lorente, 2015) because they have direct structures (Gatesy, 2003) in which the mark of the skin contact with the trampled surface (marks of the pads, and the claws) remains.

	l	a	P	z	Ar	Lr	II^III^IV	Ap	O	h	z/h	v1	v2	(l-a)/a	Ar/a	z/l	te	dII-IV
AMZ1	50	42	140	274	19	74	12-26	148	-11	216	1.2	5.9	5.1	0.18	0.49	4.4	15	37
AMZ2	45	36	137	267	5	53	16-22	171	2	205	1.3	6.4	5.2	0.3	0.2	6	14	29
AMZ3	75	60					14-38			309				0.3				

Table I.- Mean data of the AMZ dinosaur footprints and trackways. l, footpint length (cm); a, footprint width (cm); P, pace length (cm); z, stride length (cm); Ar, trackway deviation (cm); Lr, trackway width (cm); II^III^IV, interdigital angles (degres); Ap, pace angle (degres); O, orientatión (degres); h, acetabulum heigth; v1, v2, speed (km/h) Alexander (1976) and Demathieu (1986); (l-a)/a, relative pes length; Ar/a, relative trackway width; z/l, relative limb thickness; te, projection of digit III; dII-IV, toetip distance.

Tabla I.- Datos medios de las huellas de dinosaurio y rastrilladas de AMZ. l, longitud de la huella (cm); a, anchura (cm); P, paso (cm); z, zancada (cm); Ar, amplitud de rastrillada (cm); Lr, luz de rastrillada (cm); II^III^IV, ángulos interdigitales (grados); Ap, ángulo de paso (grados); O, orientación (grados); h, altura del acetábulo; v1, v2, velocidad (km/h) Alexander (1976) y Denathieu (1986);(l-a)/a, longitud relativa de la pisada; Ar/a, anchura relativa de rastrillada; z/l, grueso relativo de la extremidad; te, proyección del dedo III; dII-IV, separación entre la punta de los dedos.

AMZ1 trackway

It consists of 7 footprints (Fig. 2) of a set of 17 if the trackway was complete. AMZ1.14 and AMZ1.15 footprints are missing because they have been eroded, and the AMZ1.3-AMZ1.10 interval because it is covered by upper sedimentary layers.

They are large (l=50 cm), mesaxonic, tridactyl footprints (Table I), with digits of acuminate termination, separated and robust, with more than one phalanx per digit. The claw of digit II is the largest (Figs. 2 and 3). The footprints are narrow ([l-a]/a=0.18) but very close to the wide footprints numerical boundary (Pérez-Lorente, 2001, 2015), and the divarication between the digits is asymmetric (II^III>III^IV).

The trackway is of narrow gauge type (Ar/a=0.49) and has negative orientation (O=-11°, a single data) and relatively low pace angle (Ap=148°) considering the narrowness of the footprint. However, these values are congruent with the width of the footprint and the pace length. The average speed ([v1+v2]/2) is 5.5 km/h, that is to say moderate speed.

The height of the acetabulum is 225 cm and the ratio z / l = 4.4 is congruent with thick-limbed dinosaurs.

AMZ2 trackway.

This trackway (Fig. 2) retains 11 (12) tracks of a total of 14 (15) it would have if it was complete. AMZ2.7 AMZ2.10 and AMZ2.11 ichnites are missing. The number of 14 or 15 tracks depends on whether or not the AMZ2.15 belongs to the trackway. We have not been able to conclude anything about this question.

They are large footprints (l = 45 cm) somewhat smaller (Table I) than those of AMZ1, mesaxonic, tridactys, with digits of acuminate termination, separated and strong, with more than one pad per digit. The claw of digit II is the largest (Figs. 2 and 3. The footprints are somewhat narrower than those of AMZ1 ([l-a] / a = 0.3) and have lower digital divarication (Table I) .

The trackway is very narrow (Ar / a = 0.2), with an almost parallel orientation (O = 2°) and an high pace angle (Ap = 171°). The average speed is slightly higher than in AMZ1 (v = 5.9 km/h).

The acetabulum height (205 cm) is lower than that of AMZ1, and the ratio z / l = 6 is congruent with dinosaurs of normal to thin extremities (Pérez-Lorente, 2001).

In the first footprint of trackway (AMZ2.1) there is a mark similar to that of a hallux, but placed in posterolateral position. It is possible that this mark is due to another type of structure; there is no other trackway in the rock, and the position of this ichnite in AMZ2 is correct

AMZ3

It is a giant isolated footprint (l = 75 cm). As in the two previous ones is a mesaxonic tridactyl, with separate, with more than one pad and probably strong digits. Despite the rounded shape of toetips II and III it is very likely that all the digits had sharp claws. The relation (l-a)/a=0.3 indicates narrow footprint.

Structures associated with footprints

The mud-craks polygons are bent in the extrusion rims and in some cases have the cracks overopened. In addition, at the bottom of some footprints, they are brecciated due to foot pressure. The deformation, brecciation and separation of mud polygons occurs during the phases: touch-down (T) and weight-bearing (W) of the foot on the ground (Thulborn and Wade, 1989).

In AMZ3 isolated footprint, the deviation of the back mark of digit III from the medial mark of the digit IV is also a typical structure of footprints in which at least part of the foot sinks completely into the mud (Pérez-Lorente, 2015).

Finally, during the kick-off phase of the foot (Phase K), the mud falls into the footprint. In several tracks there are concave walls (bulging towards the interior) and/or collapse.

As in the footprints of Iouaridène, the dinosaurs stepped on a hardened soil (the upper part with mudcracks) that rested on a plastic level in which, at least parts of the foot could penetrate. The extrusion rims that accompany the ichnites and the deformed and broken mud polygons illustrate this model.

Discussion

The footprints studied in this work are: mesaxonic tridactyl, with separate, acuminate digits and with more than one pad per digit (2-3-4?). They have been assigned to the group of theropod ichnites.

The footprints of AMZ1 and AMZ2 trackways are large (<30 cm; Thulborn, 1990) or giants (>50 cm, Marty *et al.* 2017) and the isolate AMZ3 is giant (> 70 cm) according to Boutakiout *et al.* (2009).

AMZ3 has relatively strong, elongated and separated digits, with acuminate tip. The values II ^ III <III ^ IV, the strong claw of digit II, several pads per digit, and the protruding and probably bilobed heel formed by the proximal part of digits IV and II are highlighted. The prints are narrow and asymmetrical. The height of the acetabulum deduced from the footprint length is more than 200 cm for AMZ1 and AMZ2 and 309 cm for AMZ3 (Table I).

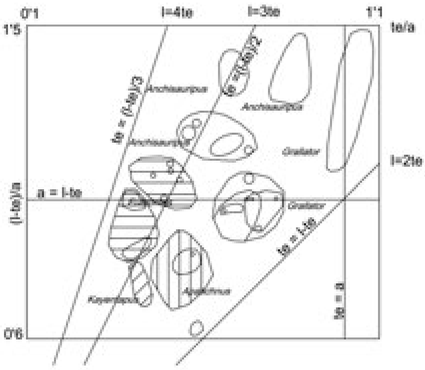

Fig. 4.- Weems`s proyection of the AMZ1 and AMZ2 average footprints data.

Fig. 4.- Diagrama de Weems con la proyección de los datos medios de AMZ1 y AMZ2.

The trackways are very narrow (Ar / a between 0.02 and 0.49), and have a sinusoidal trajectory (supposed in AMZ1). It has been proposed that this type of displacement may be due to the trajectory corrections, to lameness or to the laterality of the animals (Pérez-Lorente, 2015). This conduct should be translated into the alternating fixed sequence of long and short paces (lameness or laterality) or variable length paces according to a pattern (successive trajectory corrections). In this site there is no apparent pattern of variation due to their reduced extension.

The claw size of digit II is remarkable, similar to several large footprint ichnotypes from La Rioja (Pérez-Lorente, 2015) that also coincide in the asymmetry of the footprint and possibly also in the shape of the heel.

According to Marty *et al*. (2017), the giant footprints of Iouaridène "... shows some regular peace and lightweight inward rotation that is typical of *Jurabrontes* Marty, Belvedere, Razzolini, Lockley, Paratte, Cattini, Lovis, Meyer 2017. Here we propose on the basis of their similar morphology that the giant Late Jurassic tracks from the Iouaridène syncline can be addressed as *cf. Jurabrontes"*. Studying theropod footprints of Asturias, Rauhut *et al*. (2018) refer to the giant ichnites of Iouaridène considering them similar to associations described in Marty *et al*. (2017) but they refrain from making ichnotaxonomic attributions to Asturian footprints due to incorrect ichnotaxonomic definitions or to definitions on a single footprint (*cf*. Romero-Molina *et al*., 2003). The AMZ1 and AMZ2 ichnites projected in the Weems (1992) diagram are included (Fig. 4) in the lower part of the *Eubrontes* field.

In the previous studies (Marty *et al*., 2017; Romillo *et al*., 2017), the association of two different types of large theropod tracks due to their slenderness is postulated in the late Jurassic. This hypothesis cannot be confirmed neither in Iouaridène, because the theropod ichnoassociation is more plural (Nouri, 2007), nor in AMZ because it is not the slenderness of the footprints but the different size that indicates the difference of the two types.

Conclusions

The temporal range of sites with dinosaur footprints in the Ouaouizaght syncline extends from the Bathonian age (1BO, Fm. Tilougguit) to the Oxfordian-Kimmeridgian age of the site (AMZ, Fm. Iouaridène) described in this paper.

As in Iouaridène, in the lower part of the Fm Iouaridène, large and giant theropod traces coexist. The persistence of both types of tracks in the same stratigraphic levels, but separated by more than 50 km, allows us to suppose that the large and giant carnivorous dinosaurs would be normal fauna in this ecosystem.

AMZ with sinusoidal theropod trackways also supports the hypothesis that this type of displacement was common in bipedal dinosaurs.

As in other large and giant theropod tracks, what is remarkable is the presence of the rarely cited conjunction of the possible discriminatory characters: of the relative size of the claw of the digit II; the asymmetry of the footprint (interdigital angles); and the bilobed form of the heel.

Aknowledgements

We have to thank the help in the field of the local Aït Mazigh group that accompanied us to the site and helped us to clean it. We specially acknowledge the comments, notes and suggestions of the reviewers M.Masrour and D.Castanera. The English text has been corrected by R. Terleckis.

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