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The Syngenetic Structure Suite of Dinosaur Footprints in Finely Laminated Sandstones: Site n°1 of Bin el Ouidane (1BO; Central Atlas, Morocco)

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In 1BO, one of the outcrops of Bin el Ouidane sites, there are theropod footprints with narrow toemarks that are small in size. The prints, even those from the same trackway, are formed in two superposed levels (from an earlier and later time) of finely laminated sandstones separated by some three centimeters of sediment. The upper level cannot be identified as the tracking surface, given that the structures that accompany the footprints are similar to those of the lower level, which are clearly undertracks. The characteristics of many of them (very narrow toemarks, high divarication, very elongated marks of toe III, width of the footprints and very narrow trackways) are typical of avian ichnites. In this work, such an attribution has been ruled out and it is postulated that the trackmaker is a small theropod dinosaur, from the description and origin of the print structures.

Keywords dinosaur, footprint structures, Bathonian, Morocco

INTRODUCTION

The paleoichnological site of Bin el Ouidane N°1 (1BO) shows structures associated with a series of footprints located simultaneously in two stratigraphical superposed layers.

The first problem faced with these footprints is their systematic classification, given that their morphological and morphometric features are a modified reproduction of the autopodium which made them. Generally in ichnological studies we try to establish three things from the structures that accompany each footprint: the parataxonomic classification, correlation with the dinosaur that made them, and the relation between the shape of the autopodium, the movement during the footfall cycle and the physical state of the mud. Attempts to find clues that allow us to analyze the three above-mentioned points, as well as the behavior of the animal at the site, are becoming more and more precise. (Lockley, 1991; Carrano and Wilson, 2001).

The previous considerations are not independent. Footprints are structures in the ground produced by the interaction between two elements, namely an animal and the natural environment. In Bin el Ouidane, such interactions are of the utmost importance due to the process implied in their formation and the response of the substratum.The influence of the physical properties of substrate is being studied with increasing intensity, describing the influence this has on the ichnology (Gatesy, 2003).The nature of a footprint depends directly on the "reological stratigraphy" of the affected sediment (Allen, 1997).

To date, many published works have considered that the structures associated with footprints allow us to recognize at what level the ichnites have marked an outcrop (true ichnites and undertracks). This error, which may lead to the studying of certain footprints without taking into account the perfect location of the tracking surface (Fornós et al., 2002) or the analysis of the sediments (Gatesy, 2003), may also lead to erroneous interpretations. Bin el Ouidane is a clear example of the fact that the shape and dimensions of the ichnites must be examined carefully, since they are not a true representation of the anatomical features of the dinosaur's autopodiums on the tracking surface. Due to the patrimonial interest of the sites with groups of dinosaur footprints in the Atlas region (Boutakiout, 2000), and their location at such a strategic point for their cultural and touristic exploitation, samples cannot be extracted from the outcrop. Thus, neither the base nor series of cuts of the ichnites have been examined, which would possibly have

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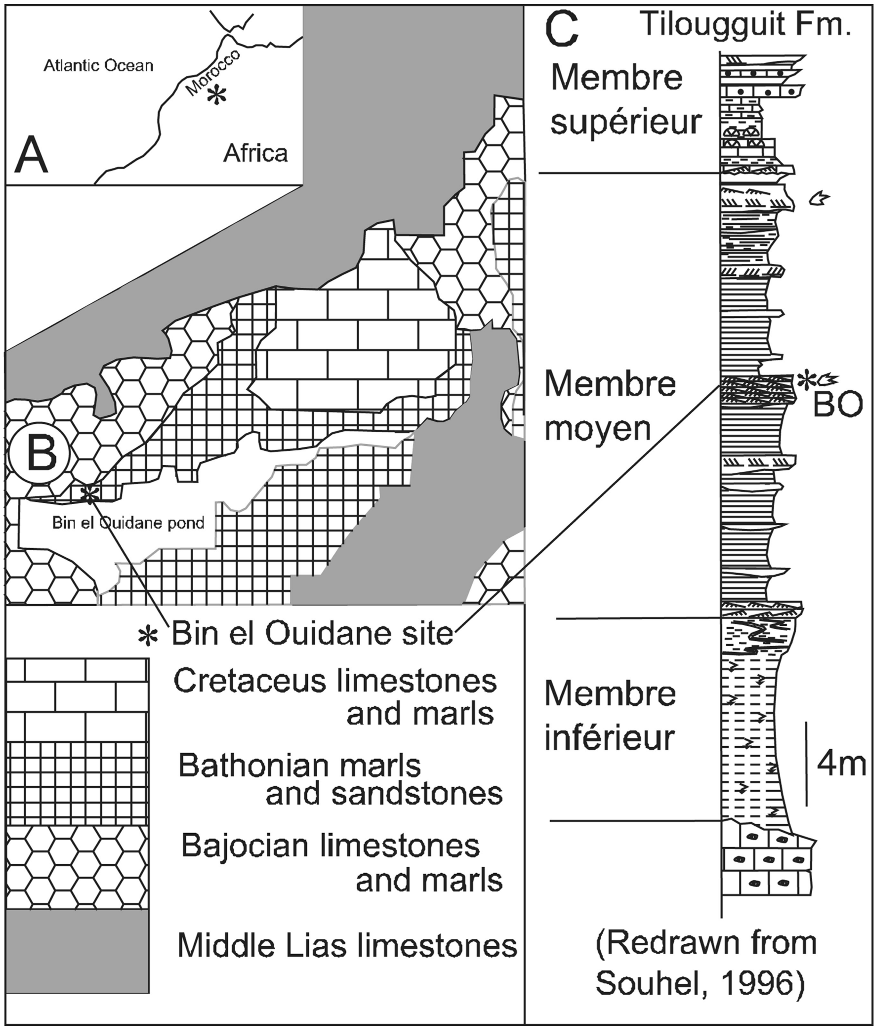

FIG. 1. Bin el Ouidane site location. **A**, in the NW of Africa; **B**, geological map of the area; **C**, local stratigraphic section. BO stratigraphic position of Bin el Ouidane sites.

allowed us to determine the geometry of the structures that accompany them.

GEOLOGICAL SETTING

In the Upper Central Atlas mountain range, the rocks of the Jurassic Period contain many sites with dinosaur footprints. The oldest are from the Carixian–Domerian, but the most well-known are from the Toarcian–Bathonian. The outcrops of the rocks are found in great syncline areas, separated sometimes by structures as a result of the Alpine orogeny. The discoverer of the Bin el Ouidane site was J. Jenny (Jenny et al., 1981), who included it in the Tilougguit Formation, whose age was presumed to be Bathonian. Monbarón (1983) describes it as . . . detritique, faite d'argiles, marnes et silts versicolores, à dominance lie de vin . . . entrecoupée toutefois d'épisodes récurrentes franchement marines, . . ."

Souhel (1996) places it in the middle section of the Bin el Ouidane Formation (sand, clays and silts) of Bathonian age (Fig. 1). According to this author, the sedimentary environment of the formation ranges from fluvio-deltaic to palustrine and lacustrine.

The 1BO site (site number 1 of the Bin el Ouidane dam) contains tridactyl footprints in fine, silty grey-green sandstone. This sandstone forms a layer of approximately 20 cm in thickness, intercalated between silts and clays of mixed colors. The sedimentary structures of the sandstone are fine plane laminations that are parallel to the top of the bed, and in which no sign of bioturbation or synsedimentary deformation is detected apart from the dinosaur footprints. The laminae, several of which measure 1 mm per thickness of rock, are more evident and easier to separate when the degree of alteration of the rock is greater.

In a sector of the outcrop, 3 cm of the upper part of the bed has been eroded, which permits a view of two surfaces

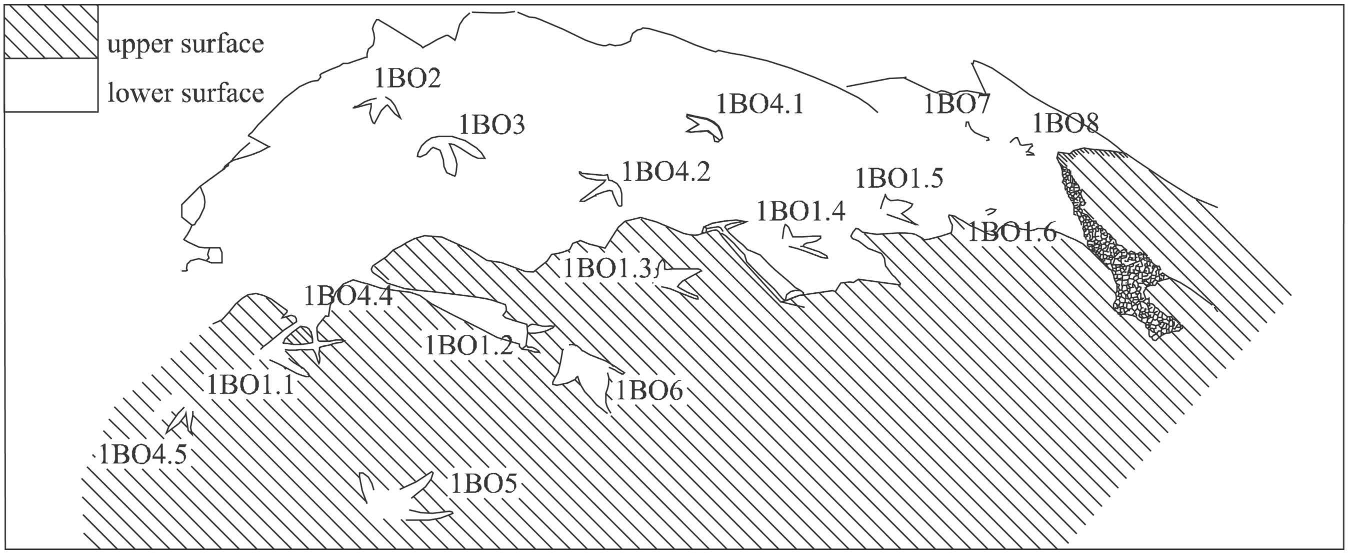

FIG. 2. Outcrop of the upper and lower ichnological surfaces of 1BO (Bin el Ouidane nb.1) site.

with footprints, herein termed "lower level" and "upper level" (Fig. 2).

ICHNOLOGY

History

The first dinosaur footprints of Bin el Ouidane were mentioned by Jenny (Jenny et al., 1981), who discovered them as he was carrying out the geological cartography of the region. In his work he mentions small sauropod and tridactyl footprints (less than 6 cm) and locates them at Ouaouizaght. The site, which is currently being studied, has been divided into four sectors (1BO, 2BO, 3BO, and 4BO) about 10 m from each other, with 1BO receiving the first mention.

Description of the Footprints

The 1BO site is made up of 16 footprints, some of which are incomplete and of differing states of preservation. Two trackways can be distinguished, which have been named 1BO and 4BO, made up of 6 and 4 footprints, respectively, and 6 isolated ichnites (Figs. 2, 6 and Table 1).

The complete footprints, which are somewhat longer than wide, generally measure less than 17 cm in length and width. The toemarks are thin, long and very separate from each other. The mark of toe III protudes a great deal, although in a differing proportion between one ichnite and another. The interdigital angle is elevated (IIˆIV between 90° and 100°; 1BO1 average, 97°).

The previously mentioned characteristics of the thin (or very thin), separated toes, elevated interdigital angle, very narrow tracks (pace angle of 180° for 1BO1) and rear incision marks (by way of hallux subsequently directed), are congruent with described avian tracks.

The description which follows leads us to the conclusion that the autopodium would be made up of relatively thin and separated toes with an acuminate termination, although neither the length nor divarication are known. According to the analysis which follows, the width and length of the foot were smaller than the imprints they made. Several small theropod dinosaurs must

TABLE 1
Footprint visible surface and described structures.

Footprint	Level	a	b	c	d	e
1BO8	1					
1BO5	1					
1BO6	2					
1BO5	2					
1BO4.5	2					
1BO4.4	2					
1BO4.2	1	Yes	Yes	Yes	Yes	Yes
1BO4.1	1	Yes	Yes	Yes	Yes	Yes
1BO3	1	Yes	Yes		Yes	Yes
1BO2	1					
1BO1.6	1					
1BO1.5	1	Yes	Yes	Yes	Yes	Yes
1BO1.4	1		Yes	Yes	Yes	Yes
1BO1.3	2		Yes	Yes	Yes	Yes
1BO1.2	2					
1BO1.1	2					

1 lower level; 2 upper level. a—dead zone; b—breccia: c—incision; d—tension tracks; e—marginal folds.

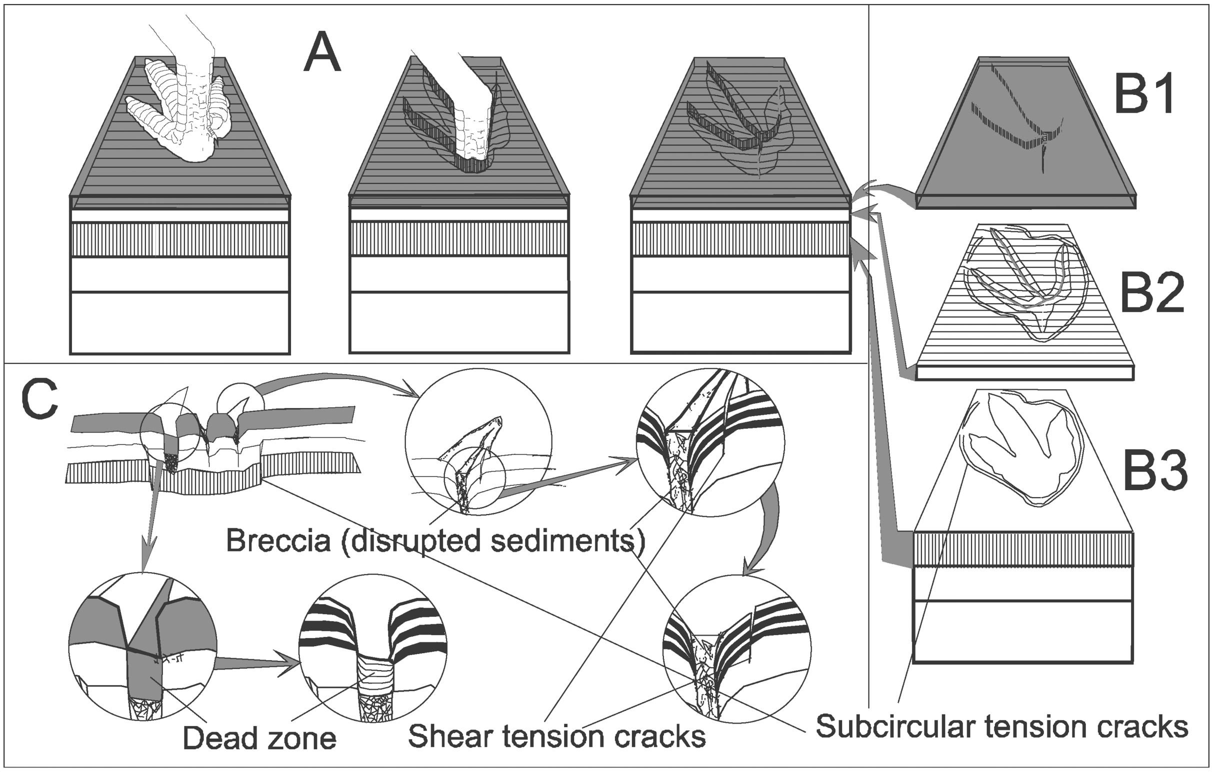

FIG. 3. Sedimentary levels, lamination and footprint structures from 1BO. **A,** pes penetration; **B,** structures in surfaces (B1 breccia and/or base striae and incisions, B2 incision, undertrack and subcircular tension cracks, B3 undertrack and subcircular tension cracks); **C,** structures in sections.

have left their marks here, as they have the same characteristics attributed to this type of dinosaur.

The bottom of all the marks reveal several types of structure (Figs. 3, 4, 5). They may be filled with a breccia of elements from the same sediments in which the footprints entered or simply be a deformed part of the sedimentary laminae. In the latter case, the lamination is in continuity with the rock, which is unaffected by the footfall or alternatively forms a kind of broken block, separated and dragged downwards by the foot. In most of the footprints, one or two incision marks cover the bottom of the footprints.

In the walls of some of the toemarks there are shear tension cracks subparallel to the elongation of the corresponding toe, which are found in the area of greater flexion of the sedimentary laminae. In one of the ichnites (1BO4.1) there is a similar tension fracture, although not subparallel to the toes but surrounding the mark.

Nomenclature and Previous Work

The structures associated with the footprints are related to the time of their formation. Herein we adopt the phases in which Thulborn and Wade (1989) divide the action of stepping, from the foot's first contact with the ground (phase T, touch-down phase), to its final withdrawal (phase K, kick-off phase), passing through the moment when the autopodium exerts the greatest pressure (phase W, weight-bearing phase).

Allen (1997) describes the structures associated with the footprints bearing in mind observations of the terrain and the result of the action of an indenter on laminated material. In his tests and examples the behavior of the material is predominantly plastic, although some compression fractures are formed due to the impulse of the displaced material from the shaft print volume and, moreover, plane sedimentary structures may be cut in the walls of the footprints. The foot goes through layers of sediment and the final footprint leaves a hollow of vertical walls which are filled with subsequent sediment. In this work, the above-mentioned author's nomenclature will be used.

Cases in Which the Mud Does Not Cover the Foot During the Stepping Process (Breccias, Incisions, Subtracks and Collapse)

Avanzini (1998) studied polished sections of sediments affected by carnivorous dinosaur footprints in Lavini di Marco (Italy). The deformed beds were made up of partially lithified plastic sediments and elastic cyanobacterial layers. In the ichnites he found convolutions of the laminations and a disrupted material mixture from all the penetrated sedimentary layers which fill the base of the prints. Examples are known both in dinosaur footprints as well as footprints of other types of vertebrates in which the substratum is deformed below the foot

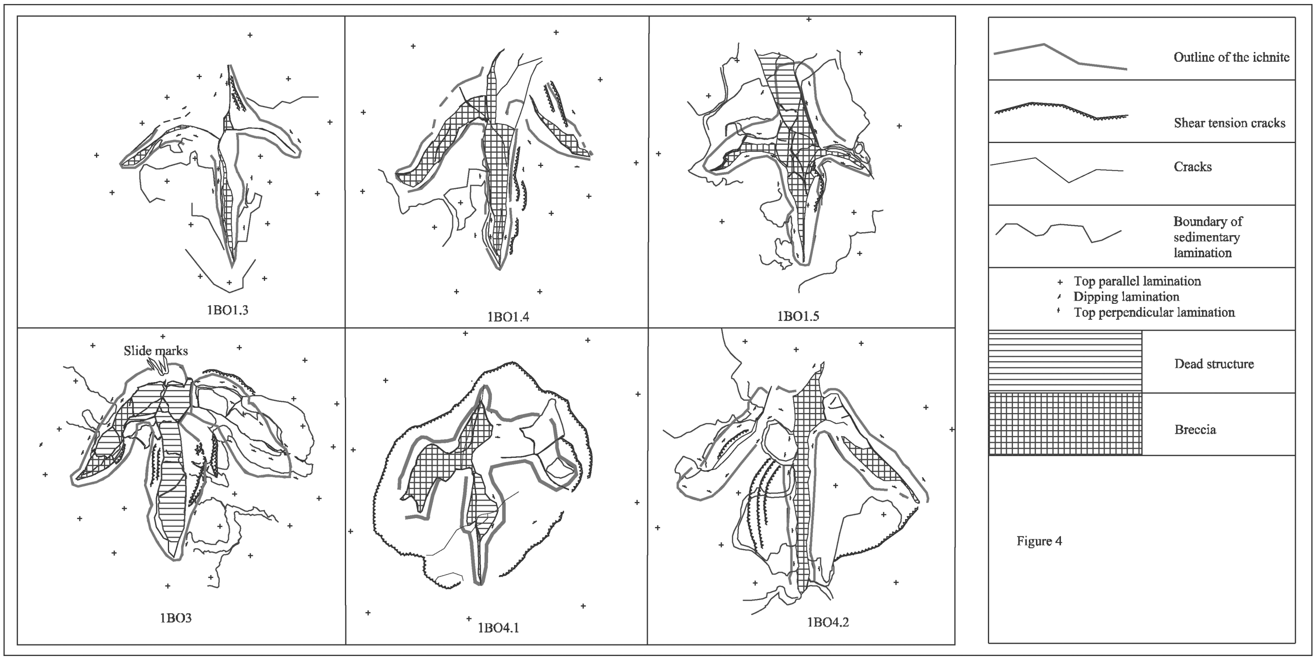

FIG. 4. Footprints and structures. Distribution and situation of the structures in some 1BO footprints. Description of the structures in the text (See Color Plate I).

impression and convolutions are formed in the laminae. These structures develop in mud and dry sand and have been mentioned in several locations and environments (Loope, 1986; Paik et al., 2001; Milán et al., 2004).

Demathieu et al. (2002) describe structures with cracks and plastic deformation produced by dinosaur footprints in algal mats (Lias de Les Causes, France). The toes penetrate the upper laminations of the ground until they reach sufficiently compacted levels. During this action the toes cut the laminations in places where they penetrate and bend them in the interdigital spaces. Some cracks are filled up with fragments and liquid mud which leave prisms of broken and mixed material.

The behavior of the elastic laminae that yield under the weight and fracture in the region of the footprint has been explained by Hernández et al. (2003). The clays of the lower, plastic level flow on receiving the new displaced volume. The upper level, which is relatively elastic, yields under the pressure of the foot until it reaches the rupture limit at which the fracture occurs. After the footfall, there remains as an ichnite a subcircular depression surrounded by a tension fracture with a separation of the fault blocks.

García-Ramos (2002) gives the name subtracks to ichnites where part of a rigid, upper level, which is broken and separated from the tracking surface, is pushed down under the foot and squeezed into the fluid substratum in the manner of a dead zone (Allen, 1997) squeezed into the mud. These structures have been described in sequences whose lower part is fluid and upper part elastic.

Finally, there are mud collapse structures associated with tridactyl footprints due to the low coherence of the walls of the prints. The walls of the ichnites are drawn inward once the foot has withdrawn from the ground (after phase K) so that the marks of all the toes become narrower and even collapse (Romero Molina et al., 2001; Gatesy, 2003). Pérez-Lorente et al. (2001) describe footprints in which there is total collapse of the lateral walls. The walls of the footprints which are deep enough in mud of little coherence are drawn inwards, obliterating the marks. The collapse, or falling of the walls of the ichnite leaves the trampled ground with marks of the toes (and metatarsus), which are very narrow and long. These ichnites are formed on theropod footprints with relatively long, narrow and separated toes.

In all the above examples, although the hollow left by the ichnite is filled with deformed and disturbed sedimentary material, the mud did not cover the autopodium in any of the footfall cycle.

Cases in Which the Mud Covers the Foot

There are references to dinosaur and bird ichnites produced by feet which pass through the superficial layer of mud and penetrate the lower layers in such a way that the mud covers the autopodium at least in phase W.

Gatesy et al. (1999) illustrate the case of ichnites found in Greenland, in which the foot sinks into the mud completely, comparing them with similar modern bird footprints. They deduce the relative depth of the sinking of the foot according to the shape of the resulting ichnite. Pérez-Lorente (2003) found similar footprints from the Lower Cretaceous in La Rioja showing the arc followed by the metatarsus during phase W and initial K, produced when the foot was pressed into the mud.

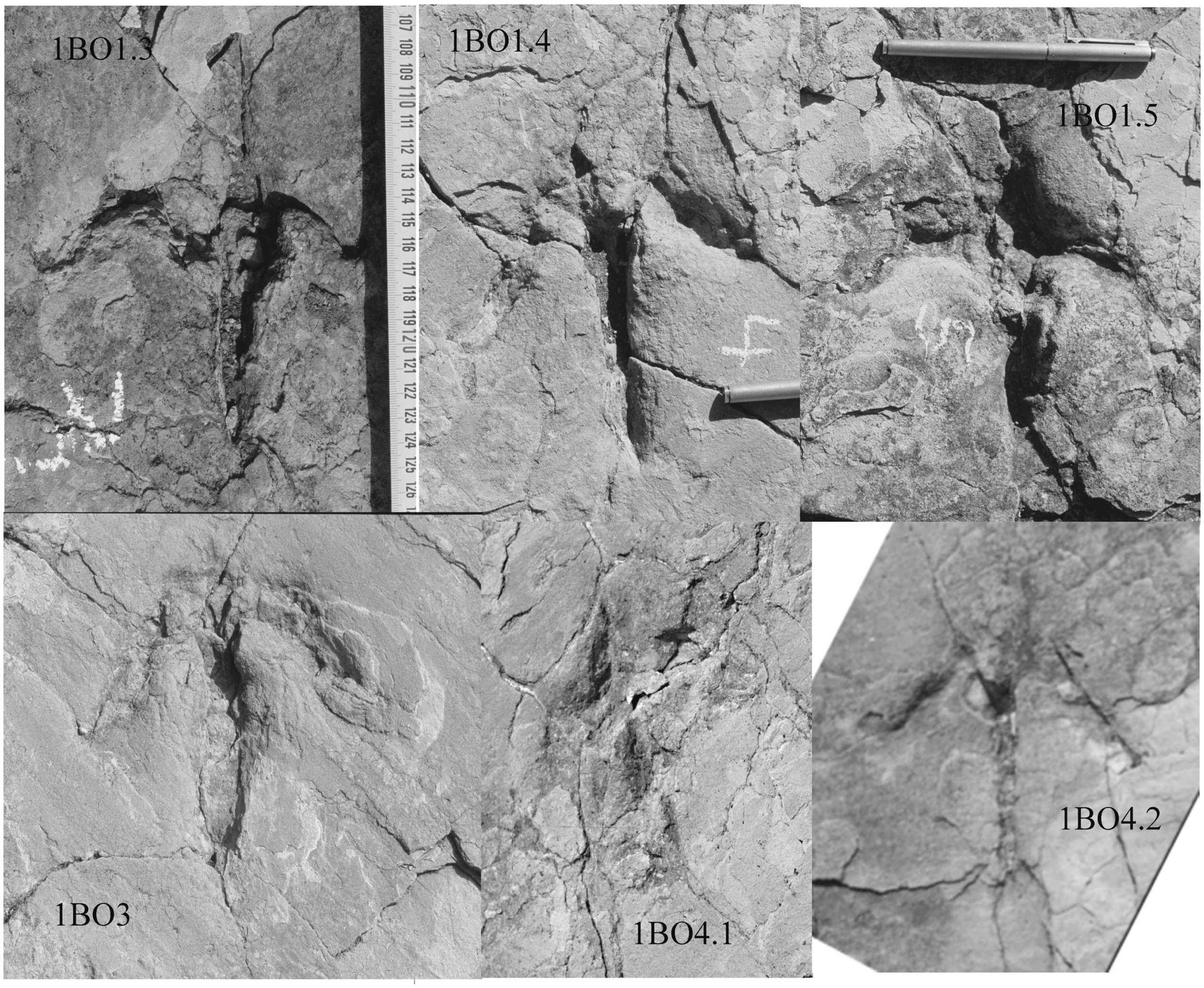

FIG. 5. Photographs of Figure 4 footprints (See Color Plate II).

In both works, mud collapse and incisions are described both in the zones penetrated by the toes as well as in the exit zone. The mud collapse occurs in places where the lateral toes sink into the surface and the location penetrated by the proximal zone of toe III. Incisions are found both in the above-mentioned lines of submersion as well as throughout the itinerary of the autopodium and the place where the foot emerges. The latter two examples are representative of mud which is not very

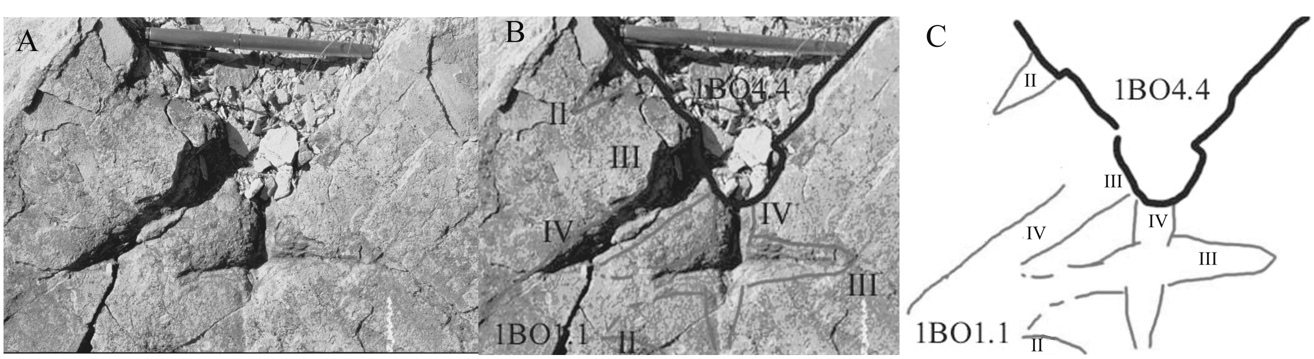

FIG. 6. A, 1BO1.1 and 1BO4.4 overprinting; B, outline of the ichnites; C, diagram. Observe the narrowness of the toemarks (II, III, IV). Pencil = 14 cm (See Color Plate III).

viscous, in which the feet penetrate the fluid interior of the substratum.

Gatesy's terms (2003) "direct" and "indirect structures" (the surface which has or has not been in contact with the dinosaur's skin), and pre-track and post-track surfaces will be used in this work with the meaning as defined by the author. The term "true footmark" will also be used to define the surface which has been in contact with the sole of the dinosaur's foot, i.e. the basal part of the direct structure of the post-track surface.

1BO Structures

The footprints at the site are on two levels of grey-green sandstones with fine parallel laminae (several layers per millimeter). The two surfaces of the outcrop are separated by some 3 cm, which is proof that the upper level would have had more than 3 cm of thickness when it was trampled. The two identified tracks in sites 1BO1 and 1BO4 show footprints in the two layers, so we can verify that the dinosaur feet produced structures associated with the stepping action in both of them. The structures that are present, or in some cases missing, and their implications are described below.

Dead Zone

This type of structure comprises undisturbed pieces of one or more upper beds, sometimes with the same outline of the ichnite maker's sole in which it is found. It is what is called a dead zone (Allen, 1997) or subtrack (García-Ramos et al., 2002). It cannot be said that the upper surface of the dead zones is a direct structure, nor that it would form part of the true footmark, because the erosion which affects all the outcrop eliminates an undetermined quantity of upper laminations. The dead zone begins to sink during phase T and completes its formation during phase W.

The dead zone is only seen in three of the six prints described in the lower level. If the pre-track surface is found at the limit of level 2, we deduce that the difference in the present height with respect to the pre-track surface is between 4 and 6 cm. If, in addition to the height, we add the decrease in volume due to the compression of the sediment, the original depth of the pre-track surface before its burial and lithification was perhaps around 10 cm.

Basal Breccia

The bottom of the footmarks of some ichnites is taken up by broken fragments of the same rock, filled into a mold. This mixture occasionally occupies the whole of the bottom of the footmarks. The breccias are found both in upper and lower level ichnites. These structures described by Avanzini (1998) are produced by the movement of the foot on passing through part of the sedimentary laminae. According to Gatesy's concept (2003), the breccia would be a mixed structure because only a single part of its unconnected elements would have formed part of the skin/sediment interphase, while probably most of the contact surface between the breccia and the walls would be the direct structure.

The breccia must have been formed when the foot entered and exited the substrate, that is to say phases T and K. Although the remainder of the structures observed are mostly from phase T, in this outcrop we cannot determine the relative importance of both phases in the brecciation of these sediments.

The contact between the breccias and the uncrushed sediment is brusque. In certain sectors of some ichnites the brecciated areas narrow until they disappear in an incision produced by the clean cut of the feet on the laminae.

Basal Striae or Incisions

This is one of the types of direct structures which can be seen at the bottom of the footprints. They are long, narrow incisions generally in the center of the ichnites and the result of closing of the sediment after the foot passed through it. The passing of the fingers or the metacarpus through the sedimentary levels may produce the same effect as a knife cutting the layers, which then re-connect. The collapse or obliteration of the marks is produced by conjoining the walls of the true footmark due to the force of gravity and the degree of plasticity of the sediment.

Unlike the striae produced by the movement of the claws (Thulborn et al., 1989; Romero Molina et al., 2003), the incisions follow an irregular course and sometimes connect with the basal breccia. Some of these striae are the continuation through the thinning and disappearance of the above-mentioned breccia, which means they are genetically related to them.

In the two mentioned types (straight and irregular course: Romero Molina et al., 2001; Gatesy, 2003; Pérez-Lorente, 2003) the collapse would be produced after phases T and K due to coalescence of the walls immediately after penetration and/or the withdrawal of the foot from the penetrated substratum. The Bin-el Ouidane incisions are direct structures or the outcropping part of the footmark—vertical or leaning to one side or another—according to whether it was the entry or exit of the foot. Due to the sliding movement of the foot in the mud, once the penetration has taken place, the ichnites may be considerably longer than the size of the feet. This is perhaps shown most clearly in the length of toe III (see below).

If the basal incisions of the toemarks had been produced by the obliteration of the hollows as a result of wall collapse due to gravity, the sedimentary lamination of the marginal zone would show convolutions. The walls of the ichnites are formed by drag folds of the sedimentary layers similar to those described by Allen (1997), and they exhibit no convolutions. The position of the incision is usually central with respect to the elongation of the toes, in concordance with the symmetrical position of the cutting suture, as regards the walls of the closed hollow.

External Striae or Slide Marks

At the back of 1BO3 four short striae marks are preserved and are parallel and in a similar direction to the elongation of the footprint. The striae are superficial and do not indicate penetration into the sediment. The ichnite that contains them is in the lower level. This structure is not found in any other part of the outcrop.

Due to their position, it follows that they are genetically related to the ichnite. Given that they are not cracks we presume that they were produced by the sliding of an object, but being in the lower level there are no criteria to indicate that they were produced by part of a dinosaur's foot (direct structure) or by a fragment of sediment dragged by it (indirect structure). These striae are certainly from phase T due to their position in the ichnite,indicative of the foot entering the substratum.

Lamination Folds or Marginal Folds

The sedimentary laminations are folded and/or sectioned in the walls of the ichnite. At the time of the footfall, the pre-track surface was horizontal and the laminations parallel to it. In Figure 4, the laminations that maintain the same relative position of parallelism to the pre-track surface are indicated with the same symbol used for horizontal strata. The lamination folds are indicated with signs similar to strike and dip, considering the present position of the pre-track surface to be horizontal.

When the foot penetrates the mud (phase T), bending occurs in parts of some of the ichnites due to a dragging down effect, in the area around where the toes entered the mud. After the dinosaurs pass through, the laminations are either cut at the limit of the toemarks and remain horizontal (parallel to the pre-track surface) or dip toward the interior of the footprint and sometimes become vertical.

Shear Tension Cracks (Linear) and Subcircular Tension Cracks

These are indirect structures and do not belong to the post-track surface since some of them are below this surface or even below the pre-track surface. Today they would be hidden if it were not for the Quaternary erosion of the upper level. These cracks show separation of the walls and relative descent of the internal faulted blocks or those nearest the ichnites. They are not exclusive to either of the two levels since they are found in ichnites which are visible in both the upper and lower levels.

The linear cracks are open fractures parallel to the direction of the axes of the marginal folds, produced by shear due to the passing of the autopodium. They are situated in the areas of maximum bending of the sedimentary laminations.

Surrounding 1BO4 there is a more or less continuous crack which is subparallel to an enveloping footprint line. This type of fracture has been defined as a subcircular tension crack (Hernández et al., 2003) found in places where the ground walked upon behaves differently according to the levels. The formation of subcircular tension cracks requires a certain flexibility of the upper layer (laminations in this case) and fluidity of the underlying level. Although full development of the shear tension cracks will be produced during phase W, it very probably starts, at least in the upper level, during phase T.

Marginal Rough Ridges

When the foot penetrates the ground, the same volume of sedimentary material as that which the autopodium occupies must be displaced. This also occurs in the case of the metapodium if it penetrates the ground. The dead zones of several 1BO ichnites show that material is displaced towards the lower part, but in none of them did we observe the slightest marginal ridge or surrounding elevation.

If displacement of material that is not replaced does occur, the volume that moves has to be justified in some way, given that the hollows of the footprints are maintained. This fact is best explained in associations of elastic upper layers and lower layers of little viscosity. In this case they are laminated, fine-grained, silty sandstones (upper layers) and red claystones and mudstones (lower levels). The excess volume can disperse due to a lateral flow of the clayish mud in the lower part of the footprint so that the elevation is absorbed.

The lateral flow of mud from the substratum will take place during phases T and W.

Clarification on the Limit of the Footprint and Interpretation of its Features

Thulborn (1990) demonstrates in the outline of the same footprint drawn by several specialists the difference in interpretation of each one. This difference can be explained by the subjectivity of each individual and the variation in methodology used to situate such an outline according to the type of ichnite. In 1BO one of the authors of the work has marked a line, called "outline of the ichnite" in Figures 3 and 4, as close as possible to the point of tangency between the theoretical pre-track and post-track surfaces. As can be seen, the shapes of the outline of the footprint and the internal structures are only approximately subparallel.

The outstanding general features of the ichnites in the 1BO site are the following: thin, long and individualized toe imprints; very high divarification; very high digit III projection; elongated hind "heel" in the manner of a hallux mark These features are frankly avian.

In general, the toemarks of the ichnites in 1BO are narrow. However, there are some (1BO1.1, 1BO4.4; Fig. 6) in which there is a marked narrowness. The narrowness of the toemarks does not depend on the level in which they are produced, neither on their position (internal, middle or external) nor shape. The footprints from the same tracks exhibit narrow and wide toemarks both in the upper and lower levels.

In the morphometric study we observe that the interdigital angle is open, a typical feature of aviform ichnites if this is a reflection of an anatomical characteristic. Thulborn (1990) concluded that the interdigital angle increases as the foot of some dinosaurs penetrates the mud. Furthermore, the outermost toes of some footprints have an irregular course since there is retroversion in the direction of their central part (Figs. 4, 6). If the outline of the toes shows their shape, then their middle

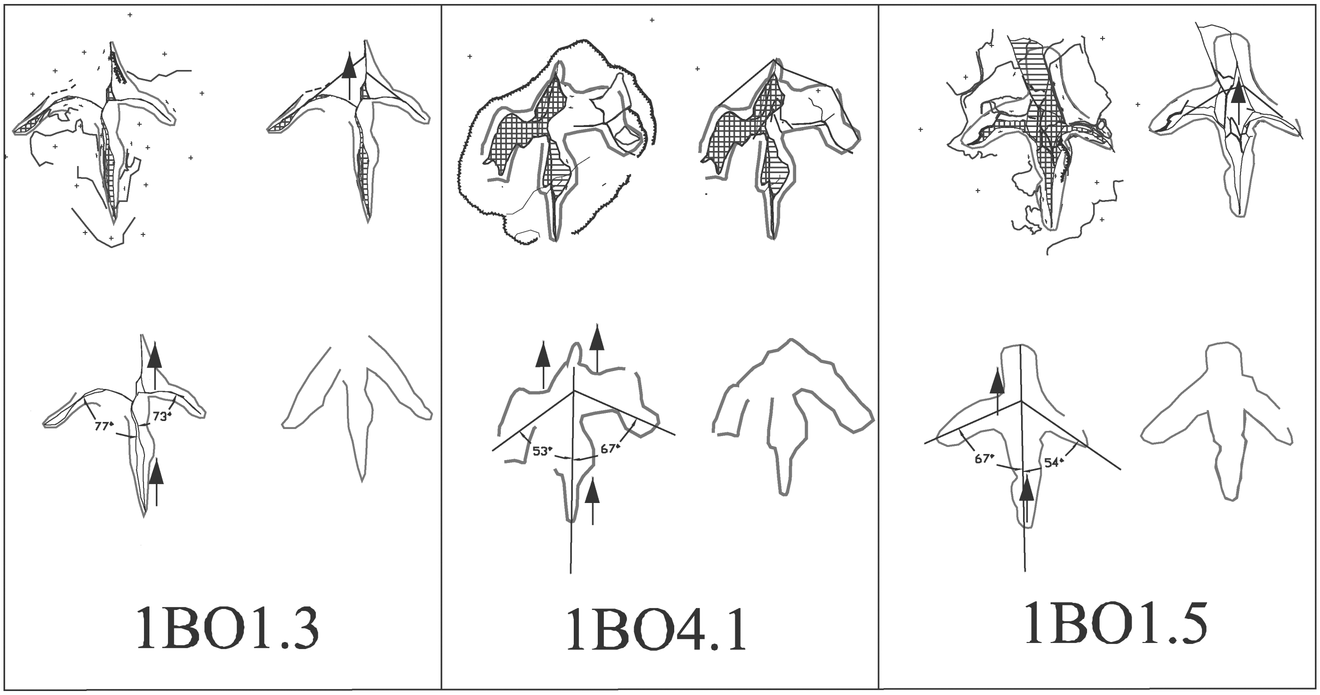

FIG. 7. Pseudoavian prints redrawn to show the morphology of the footprints before the pes forward sliding. Note the interdigital angles and the direction of toe III shortenings and II-IV digit prints modification, showed by arrows (See Color Plate IV).

part is further back than the metatarsal joint of the first phalanx, which is an unusual arrangement both in birds and dinosaurs.

The apex mark of digit III is far advanced with respect to the one left by the outermost toes. In some marks (1BO1.5, 1BO4.1) the apex zone is an incision left by the toe on passing through the substratum.

In 1BO1.3, 1BO1.4, 1BO1.5 and 1BO4.1, the outline of the footprint indicates a hind apex as if a hallux pointing backwards had left its mark there.

The true footmark is not shown in any of the 1BO ichnites, and none of them can be stated to be the post-track surface. In 1BO1.3, the incisions situated in the outermost toes and the corresponding part of the heel are indicative of the foot sliding forwards after sinking into the substratum (Gatesy et al., 1999; Pérez-Lorente, 2003). These ichnites are the result of the foot penetrating and sliding in the muddy substratum, a fact which justifies the noticeable morphology in both levels. It must also be said that in all the described cases (Gatesy et al., 1999; Pérez-Lorente, 2003) in which the foot is covered by the mud, there is a sliding forward of the foot during the interval when it is submerged. In 1BO it is not known whether the position in which the foot penetrates the mud is with the basal part of the autopodium parallel to the tracking surface or at an angle to it. There are cases that have been described of a nonparallel footfall in ornithopod ichnites, in which the heel contacts the ground (phase T) much earlier than the tip of toe III, (Romero Molina et al., 2001) which is different to that described by Gatesy et al. (1999).

During phase W, the foot is much further forward with respect to the position it would have at the beginning of phase T. In Figure 7, the footprints in which these structures are most evident have been modified (those with retroversion of the outermost toemarks and slide incisions). The outline corresponding to toe III has been moved backwards, assuming that the advancing of the apex is the same as the visible sliding of the lateral toes. The result shows shorter feet, with a lower interdigital angle, which are probably still very distorted.

If we want to identify the shape of the trackmaking dinosaur's autopodium, the only morphological conclusion we can reach is that the animal had relatively long and separated toes with an acuminate ending, probably with a high hallux since it is not imprinted on any of the ichnites.

Ichnite Formation

The process followed in the formation of these ichnites can be summarized as follows: During phase T, or the phase between initial contact of the foot with the ground and total weight-bearing, the foot passes through at least the upper part of the sandy sequence and penetrates into it.

Of the structures observed, the bending inwards of sedimentary laminations (by way of marginal folds) takes place, or at least begins, during this phase. Part of the laminations are penetrated (incisions) and part of them are dragged like a dead zone towards the interior of the substratum. The clay that is below the sandstone is displaced towards the sides. Part of the laminations, which sag and stretch, exceed their elastic limit and break. This produces linear fractures, which are subparallel to the axes of the marginal folds and directed towards the base of the toes, and subcircular fractures,which are concentric to the middle of the footprint and directed towards the general base of the foot. Below the toes, the dead zones keep sliding or the sedimentary lamination is destroyed by structural tension cracks. Above the toes, some of the layers join together again.

During phase W, the dead zone materializes and most of the ichnite structures acquire their final arrangement. This will be the moment when the rough ridges are largest, if they do form.

No structures have been detected from phase K, even at the tip of the longest toes, whose structures are congruent with those of phase T. In spite of this, there are no arguments to prove that such a toe was as long as its mark.

CONCLUSIONS

The outline drawings of the Bin el Ouidane ichnites do not reflect the shape of the autopodium which produced them. The morphological and morphometric aviform features are fundamentally due to the interaction between the movement of the foot entering the ground and the response of the hollowed-out substratum. The high divarification and the location of toe III's tip mark are due to the depth the foot reaches and the autopodium sliding inside the mud. The narrowness of the toemarks is produced by the flexible and fragile behavior of the sediment, which first flexes and is then transected in a way similar to a knife cutting through it.

The same type of structures are formed at different depths, even in the same track. In the study of the ichnites, therefore, only if there are direct structures at the bottom of the ichnite and continuity between the post-track and pre-track surfaces, will we be able to guarantee which footprint structures are above the true footmark and which are not.

For the first time, narrow toemarks produced by bending and cutting of the sedimentary layers are described. Up until now, toemarks (and even of the metatarsus) had been described as narrow due to gravitational fall and collapse in places with very fluid mud, which obliterates the remaining hollowed spaces.

The parataxonomical classification of vertebrate fossil footprints must take into account analysis and definition of the surfaces (pre-track, post-track and true footmark) on which they are being constructed. In the true footmark, the elements and structures that are going to be used in the allocation of the footprints to one ichnological group or another must be adequately defined.

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REFERENCES

Allen, J. R. L. 1997. Subfossil mammalian tracks (Flandrian) in the Severn Estuary, SW Britain: Mechanics of formation, preservation and distribution. *Philosophical Transactions of the Royal Society, London B*, 352:481–518.

Avanzini, M. 1998. Anatomy of a footprint: Bioturbation as a key to understanding dinosaur walk dynamics. *Ichnos*, 6:129–139.

Boutakiout, M. 2000. Géoparc M'Goum. Une prise de conscience pour la sauvegarde du patrimoine géologique et la conservation de la mémoire du passé. Holcim ed. Rabat, 34p.

Demathieu, G., Gand, G., Sciau, J., and Freyet, P. 2002. Les traces des pas de dinosaures et autres archosaures du Lias Inferieur des Grands Causses, Sud de la France. *Palaeovertebrata*, 31:163p.

Fornós, J. J., Bromley, R. G., Clemmensen, L. B., and Rodríguez-Perez, A. 2002. Tracks and trackways of *Myotragus balearicus* Bate (Artiodactyla, Caprinae) in Pleistocene aeolianites from Mallorca (Balearic Islands, Western Mediterranean). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 180:277–313.

Carrano, M. T. and Wilson, J. A. 2001. Taxon distribution and the tetrapod track record. *Paleobiology*, 27:564–582.

Garcia-Ramos, J. C., Piñuela, L., and Lires, J. 2002. Icnitas de dinosaurios, tipos de sedimento y consistencia del sustrato. *In* Pérez-Lorente, F. (ed.), *Congreso Internacional sobre dinosaurios y otros reptiles mesozoicos de España*. Resúmenes: 25–26.

Gatesy, S. M. 2003. Direct and indirect track features: what sediment did a dinosaur touch?. *Ichnos*, 10:91–98.

Gatesy, S. M., Middleton, K. M., Jenkins, F. A., and Shubin, N. H. 1999. Three-dimensional preservation of foot movements in Triassic theropod dinosaurs. *Nature*, 399:141–144.

Hernández, N. and Pérez-Lorente F. 2003. Un nuevo yacimiento de icnitas de dinosaurio. La Ilaga (Terroba, La Rioja. España). Suelo flexible y rastrilladas paralelas. *In* Pérez-Lorente, F.(ed.), *Dinosaurios y otros reptiles mesozoicos en España*. *Ciencias de la Tierra*, 26: 195–214.

Jenny, J., Le Marrec, A., and Monbaron, M. 1981. Les empreintes de pas de dinosauriens dans le Jurassique Moyen du Haut Atlas Central (Maroc): nouveaux gisements et precisions stratigraphiques. *Geobios*, 14:427–431.

Lockley, M. G. 1991. *Tracking dinosaurs*. Cambridge University Press, Cambridge: 238p.

Loope, D. B. 1986. Recognizing and utilizing vertebrate tracks in cross section: Cenozoic hoofprints from Nebraska. *Palaios, 1986*, 1:141–145.

Milàn, J., Clemmensen, L. B., and Bonde, N. 2004. Vertical sections through dinosaur tracks (Late Triassic lake deposits, East Greenland)—undertracks and other subsurface deformation structures revealed. *Lethaia*, 37:285–296.

Monbaron, M. 1983. Dinosauriens du Haut Atlas Central (Maroc). *Actes de la Societé Jurassienne d'Emulation,* 203–234.

Paik, L. S., Kim, H. J., and Lee, Y. I. 2001. Dinosaur track-bearing deposits in the Cretaceous Jindong Formation, Korea: occurrence, palaeoenvironments and preservation. *Cretaceous Research*, 22:79–92.

Pérez-Lorente, F. 2003. Aportaciones de los yacimientos de La Barguilla, Santisol y Santa Juliana (Hornillos de Cameros, La Rioja. España). *In* Pérez-Lorente, F. (ed.), *Dinosaurios y otros reptiles mesozoicos en España*. *Ciencias de la Tierra*, 26: 161–194.

Pérez-Lorente, F., Romero-Molina, M. M., Requeta E., Blanco, M., and Caro, S. 2001. Dinosaurios. Introducción y análisis de algunos yacimientos de sus huellas en La Rioja. *In* Pérez-Lorente F. (ed.), *Ciencias de La Tierra*, 24: 102p.

Romero Molina, M. M., Pérez-Lorente, F., and Pascual, R. 2001. Estructuras asociadas con huellas de dinosaurio en La Rioja (España). *Zubía*, 19:61–96.

Romero Molina, M. M., Sarjeant, W. A., Pérez-Lorente, F., López, A., and Requeta, E. 2003. Orientation and characteristics of theropod trackways from the Las Losas Palaeoichnological site (La Rioja. Spain). *Ichnos*, 10:241–254.

Souhel, A. 1996. Le Mesozoique dans le Haut-Atlas de Beni-Mellal: Stratigraphie, sédimentologie et evolution géodynamique. Thèse d'etat Univ. Cadi Ayyad. Marrakech. Umpubl: 335 p., 126 figs.

Thulborn, R. A. 1990. *Dinosaur tracks*. Chapman and Hall, London: 410p.

Thulborn, R. A. and Wade, M. 1989. A footprint as a history of movement. *Dinosaur tracks and traces*. *In* Gillette, D. D. and Lockley, M. G. (eds.), Cambridge University Press, Cambridge: 51–56.