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Preservation of dinosaur tracks induced by microbial mats in the Sousa Basin (Lower Cretaceous), Brazil

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ABSTRACT

Dinosaur footprints and tracks in the Sousa Basin (Lower Cretaceous, Brazil) occur in at least 37 localities, in distinct stratigraphic positions. Footprints are rare in the Antenor Navarro (lower) and Rio Piranhas (upper) formations, where lithofacies analyses point to sedimentation in ancient alluvial fan to fluvial braided palaeoenvironments. In the Sousa Formation, the generally finer grain sized sediments rendered them more suitable for footprint preservation, where lithofacies analyses point to sedimentation in warm, small/shallow and temporary lakes, swamps and meandering fluvial palaeoenvironments. Microbially induced sedimentary structures are observed in many of the fine-grained lithofacies where dinosaur tracks are also found, and the large number of these tracks in the Sousa Basin (particularly in the Sousa Formation, Lower Cretaceous) may be related to the role of the mats in their preservation. Observations on recent microbial mats show that footprint morphology is related to the mat thickness and to the water content of the mat and the underlying sediment. In dry mats, generally poorly defined or no footprints are produced, while in saturated ones the imprints are well-defined, sometimes with well-defined displacement rims. The formation of well-defined displacement rims around the prints of large dinosaurs occurs in thick, plastic, moist to water-unsaturated microbial mats on top of moist to water-unsaturated sediment. These aspects are commonly observed in the tracks of the Passagem das Pedras site in the Sousa Basin. The footprint consolidation and its early lithification probably occurred due the existence of microbial mats that allowed a more cohesive substrate, preventing the footprints from erosion. The sediments were initially stabilized by early cementation and by the mat fabric over the tracks. Successive flooding, and subsequent sediment influx allowed the large number of layers with dinosaur tracks and sedimentary structures.

1. Introduction

The intracratonic basins of Northeast Brazil were sites of Cretaceous sedimentation, which origin and development were controlled by fault reactivation that affected the Precambrian basement, showing a SW-NE orientation determined by the structures and competent supracrustal rocks within the Borborema Province (Lima Filho et al., 1999; Mabesoone, 1994; Valença et al., 2003). These sedimentary basins, are known in the literature as the intracontinental basins of Northeast Brazil (Ponte, 1992), showing great similarities in their origin and evolution (Fig. 1). They are the consequence of the tectonic movements which resulted in the separation of South America and Africa.

In this context, the Rio do Peixe basin complex is comprised of the Sousa, Uiraúna-Brejo das Freiras, Vertentes and Pombal basins, four intracratonic basins of Northeast Brazil (Fig. 2). These basins are related to a synrift context. Seismic sections presented by Córdoba et al. (2008) allowed a better view of the three-dimensional architecture of the Rio do Peixe basin complex. The combination of the present erosion level and the geometry of the main faults highlights the existence of different half-grabens (i.e., Pombal, Sousa, Brejo das Freiras). Their sedimentary filling (apart from Caenozoic deposits) defines the Rio do Peixe Group, lithostratigraphically comprising the Antenor Navarro (upper alluvial fans/braided channels), Sousa (mid shallow lacustrine/floodplain) and Rio Piranhas (lower alluvial fans/braided channels) formations. Based on the structural style and petrographic-diagenetic features, Córdoba et al. (2008) inferred larger original dimensions for this basin and similar counterparts in the region, which were reduced (with exposure of the crystalline basement highs) by the significant

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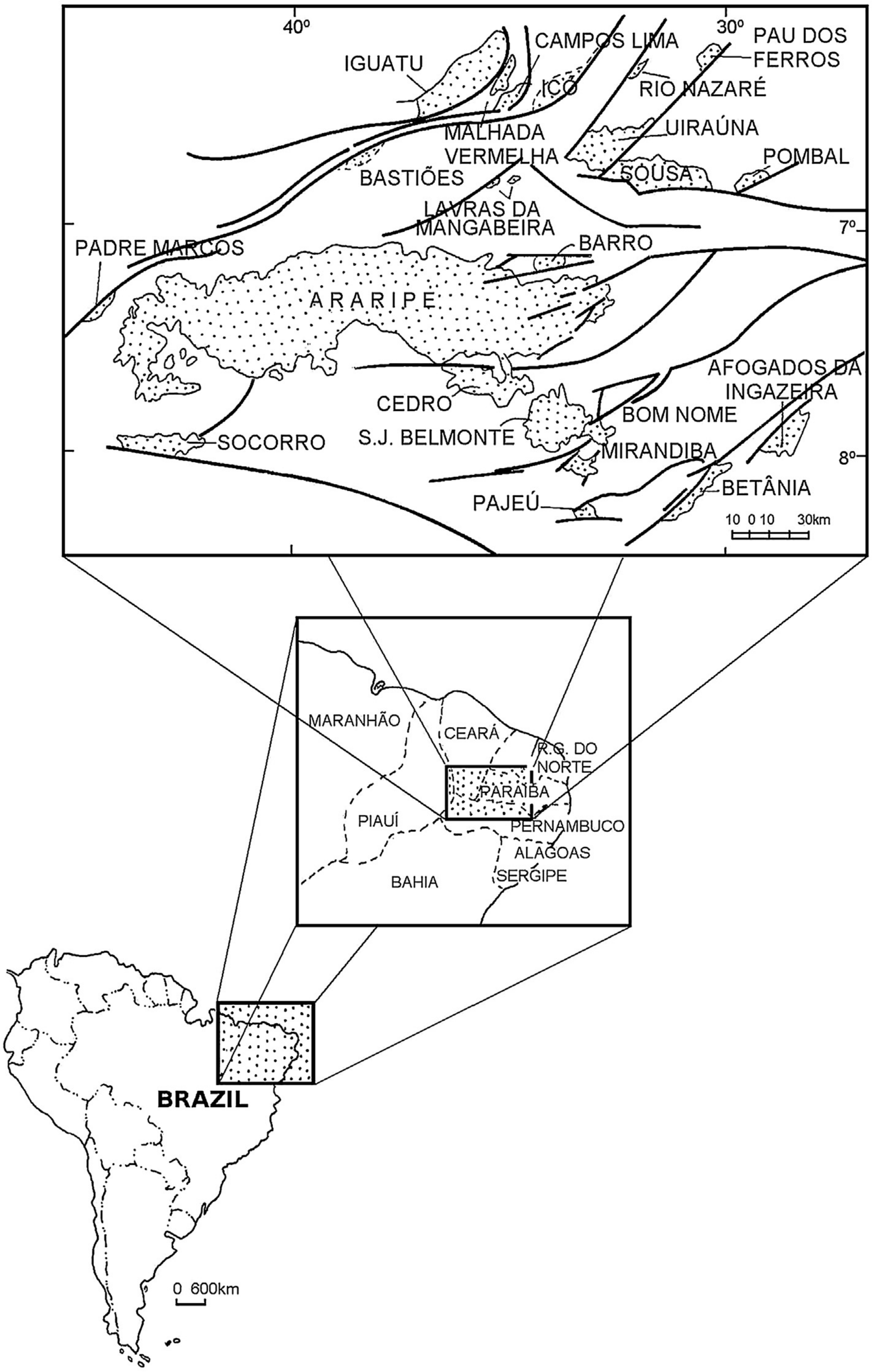

Fig. 1. Location map of the Sousa Basin among the Cretaceous NE basins of Brazil.

erosion that occurred in the late-and subsequent post-rift evolutionary stages.

During the early Mesozoic, a hot and arid climate was typical in the southern hemisphere (Lima, 1983). This is well-recognized throughout the widespread aeolian deposits along the Brazilian and African intracratonic basins. The connection between South America and Africa as a single, large continental block, did not permit a higher humidity in what was (at that time) the interior of a continent (Gondwana). With the break-up of the Gondwana and the initial establishment of a lacustrine and fluvial system in the new rifted basins, the climate gradually became more humid. These palaeoenvironmental changes are probably linked to the same tectonic events that drove the separation of South America and Africa and led to the origin of the South Atlantic Ocean.

Throughout the Early Cretaceous, hot climatic conditions were widespread, although there was probably a wide range of humidity conditions (Skelton, 2003). According to Petri (1983) and Lima (1983), during the earliest Cretaceous the climate was more humid in regions located to the south of the tropical domain

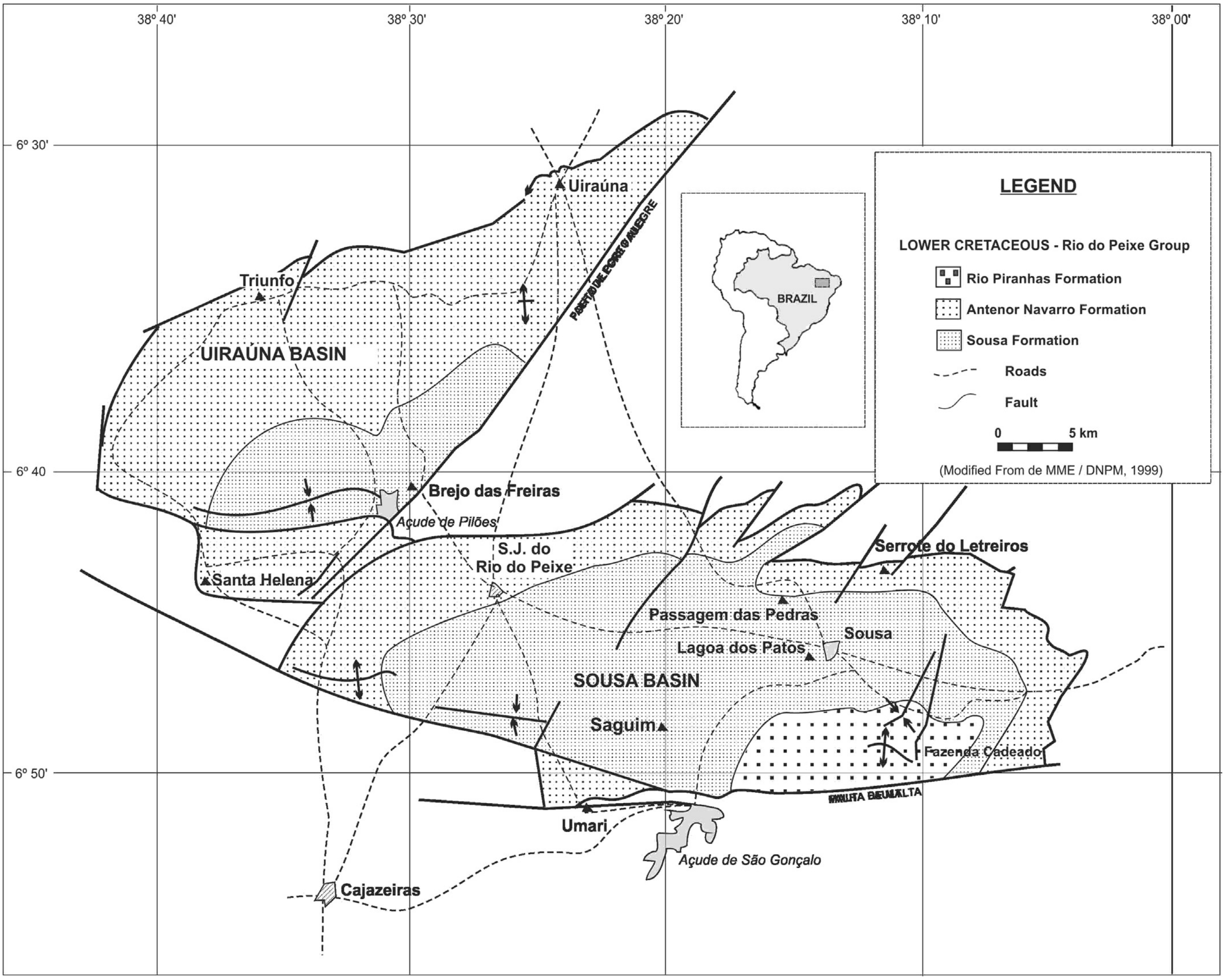

Fig. 2. Geological map of the Sousa Basin, in the Rio do Peixe Basin complex.

(Recôncavo, Tucano and Jatobá basins). Despite a hotter and drier climate to the north, paleoenvironmental interpretations mainly based on fossils suggest the existence of some lakes which, during the Neocomian, locally provided more humid conditions. The large-sized conchostracans *Palaeolimnadiopsis reali* that have been described from some lacustrine facies of the Sousa Basin (Carvalho, 1989) show optimum conditions for this group in a context of abundant freshwater and a warm, wet palaeoclimate. At that time, South America was still connected to Africa, and the Atlantic Ocean was in its initial developing phase. In the present Northeastern Brazil, in an area of hundreds of square kilometres, ephemeral rivers and shallow lakes constituted important environments for an abundant endemic biota in many fault-bounded basins.

2. The Sousa Basin

The Sousa Basin comprises an area of 1250 km^2, located in the west of Paraíba State, Brazil, in the counties of Aparecida, Sousa and Uiraúna. The basement is composed of highly metamorphosed Precambrian rocks (aligned structurally in a NW-SE or W-E direction). The predominant rocks are migmatites, granites, gabbros and amphibolites. The main lithologies in the Sousa Basin are clastic rocks, including breccias and conglomerates, sandstones, siltstones, mudstones and shales. In some cases, the carbonate content is high in the form of marls and thin (cm-thick) limestones.

A formal lithostratigraphic subdivision of the Cretaceous in the Sousa Basin, and the neighbouring Uiraúna/Brejo das Freiras and Pombal basins, was erected by Mabesoone (1972) and Mabesoone and Campanha (1973). These authors identified the Rio do Peixe Group with a total thickness of 2870 m, and subdivided it in the Antenor Navarro, Sousa and Rio Piranhas formations. The Antenor Navarro and Rio Piranhas formations are composed of immature clastics, including breccias and conglomerates, with pebbles of metamorphic and magmatic rocks in a coarse arkose matrix. These lithology types are located near the faulted margins of the basin. Towards the basin-depocenter, there are conglomeratic and fine sandstones, sometimes interbedded with siltstones and shales. Trough and planar cross-stratification, climbing ripples and asymmetric ripple marks are the main sedimentary structures. The Sousa Formation is composed mostly of reddish sandstones, siltstones, mudstones and carbonate nodules, but marls also occur. Common sedimentary structures include mud cracks, convolute bedding, ripple marks, climbing ripples, raindrop imprints and bioturbation.

The existence of an abundant vertebrate ichnofauna, consisting of footprints and tracks of theropods, sauropods and ornithopods, is one of the main characteristics of the basin (Fig. 3). Invertebrate ichnofossils such as tracks and burrows produced by arthropods and annelids are also common (Carvalho, 2004) Despite the strong reddish colour, typical of sediments that accumulated in subaerial environments, there are some levels of greenish shales, mudstones and siltstones where fossils are common. These consist of ostracods, conchostracans, plant fragments, palynomorphs and fish scales. The palynological assemblages associated to this fossil content are characteristic of the Rio da Serra (Berriasian–Hauterivian) and Aratu (Lower Barremian) local stages (Lima and Coelho, 1987; Regali, 1990).

3. Taphonomy and palaeoenvironmental setting of the footprints

The way that a track can be preserved has a direct relationship with its geological context, and the Northeastern Cretaceous Brazilian basins provide a wide variety of examples of fossil track preservation. It is possible to recognize the following palaeoenvironmental settings associated with the track-bearing strata in these basins: alluvial fan—braided fluvial, floodplain of meandering fluvial and marginal lake areas (Carvalho, 2004).

Footprints are rare in the Antenor Navarro and Piranhas Formations. The coarser lithologies of these units, such as conglomerates, coarse sandstones and sandstones interbedded with siltstones were certainly a limiting factor for fossil track preservation. The coarse-grained facies assemblages susceptible to reworking and scour presumably reflect a low preservation potential in these areas (Lockley and Conrad, 1989). The lithofacies analysis of those beds point to sedimentation in fan-delta, alluvial fan, and braided fluvial palaeoenvironments (Carvalho, 2000a, 2000b) under extremely oxidizing conditions, where organic matter preservation is rare. Despite the low preservation potential of alluvial fans and braided fluvial systems, dinosaur tracks and trackways are found in this context at Sousa and Uiraúna-Brejo das Freiras basins (Carvalho, 1989, 1996; Carvalho and Leonardi, 1992; Carvalho et al., 1993a, 1993b; Carvalho, 2004; Leonardi and Carvalho, 2002). The grain size of the sediments that formed the substrate over which the dinosaurs travelled, was probably a significant limiting factor on footprint preservation. But it is also important to consider the local paleoenvironment and associated substrate saturation. In the Sousa Basin, footprints are found in the Antenor Navarro and Piranhas formations preserved only in fine sediments that accumulated as subaerial sandy bars, influenced by seasonal groundwater fluctuations (Carvalho, 2000b, 2004).

Fig. 3. Ornithopod trackway in the Passagem das Pedras site (Sousa Formation, Sousa Basin). The exhumed paleosurface with the tracks is buried by subsequent river floodings (overlying strata).

The Sousa Formation is composed of reddish mudstones, siltstones, and fine-grained sandstones; carbonate nodules and marls also occur. Common sedimentary structures include mud cracks, convolute beddings, ripple marks, climbing ripples, raindrop imprints, and vertebrate and invertebrate bioturbation (Fig. 4). The data presented by Carvalho (2000b) and Leonardi and Carvalho (2002), concerning to the ichnofauna distribution in the Sousa Basin, do not support previous analysis of a theropod dominated fauna (Leonardi, 1989, 1994). The domain of theropod footprints is attributed to an ecological zonation of the dinosaurian biota and a taphonomic artefact. The theropods probably had a preferential distribution in the low floodplain areas, where the preservational possibilities are higher in the fine-grained sediments (Fig. 5). The sauropods otherwise were far from these regions. They lived in the higher areas of the basin near to its borders, where there is a lower potential for track preservation due the coarse and less satured nature of the substrate sediments.

The footprints are preserved as concave epirelief, sometimes with detailed morphology, such as claws, digital pads and sole pads (Fig. 5). The essentially microclastic sequence allowed such preservation. Lockley and Conrad (1989) presented many examples from distal fluvial floodplain environments and lake borders, where occur diversity, abundance, and wide distribution of dinosaur footprints. Other studies, such as Hunt and Lucas (2007), Lockley (2007), Lockley et al. (1994) allow an overview concerning vertebrate tracks, ichnofacies, palaeoecology and palichnostratigraphy

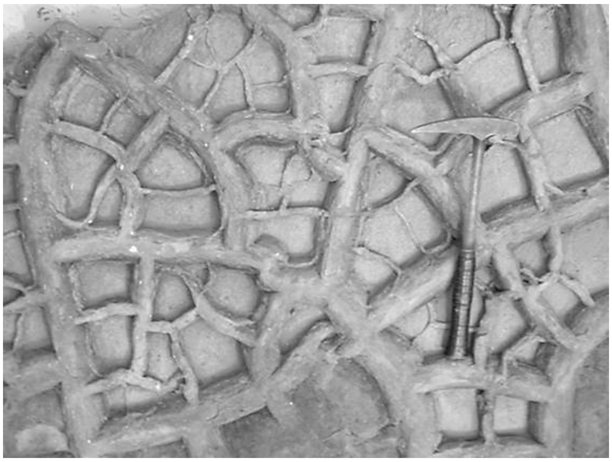

Fig. 4. Mud cracks are common structures in the Sousa Formation (Sousa Basin), associated to the dinosaur tracks.

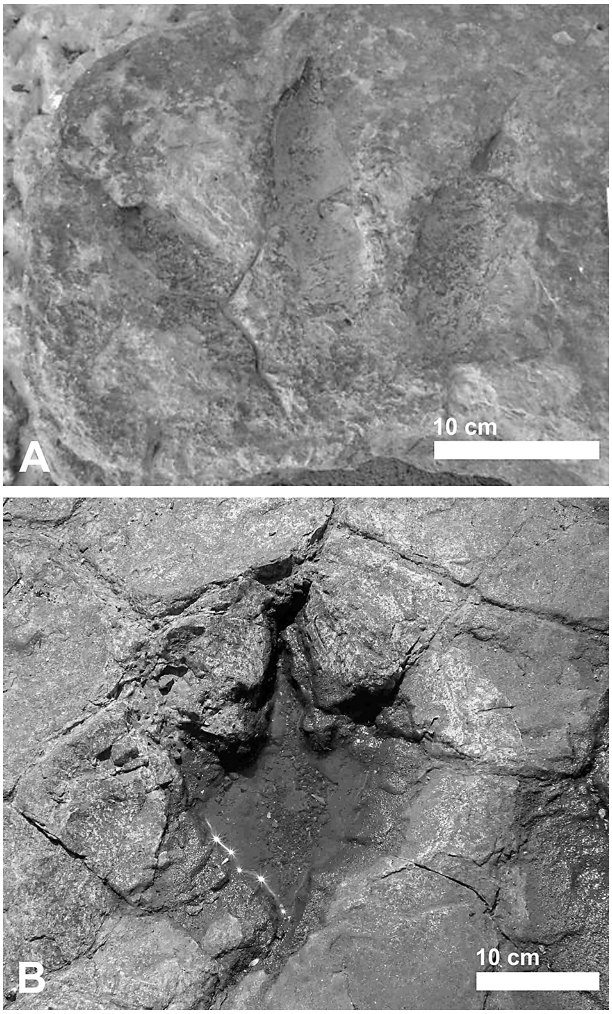

Fig. 5. Theropod footprint in the Sousa Formation preserved as concave epirelief. Observe the mud cracks developed after the print (A), and details of the preserved claws (B).

in many continental environments. Ancient lakes in the Sousa Basin developed in the depocenter areas and being characterized by clastic sedimentation. They result from fluvial palaeoenvironments that grading into fluvio-lacustrine ones. As the climate during the main deposition time was hot with a high evaporation rate, it is possible to have saline lakes rich in calcium carbonate (Carvalho, 2004).

The cyclic succession of mudstones, siltstones and fine-grained sandstones in fluvio-lacustrine palaeoenvironments, a product of periodic flooding and lake shoreline changes, allowed the establishment of many successive surfaces suitable for footprint preservation (Fig. 6). This can be observed in recent environments as described by Cohen et al. (1993) at Lake Manyara (Tanzania) and also in ancient lakes (Lockley, 1991). In the Sousa Basin, Leonardi (1989, 1994) recognized 25 levels with dinosaurian ichnopopulations in the Sousa Formation (Piau locality). These different levels represent the cyclic sedimentation along an ancient Cretaceous lake shoreline. Similarly, Paik et al. (2001) and Lockley et al. (2006) analysed the dinosaur track-bearing strata in the Jindong Formation (Upper Cretaceous, Korea), which were interpreted as the result of repeated deposition by sheet floods on a mudflat associated with a perennial lake, utilized by dinosaurs as a persistent water source, during drought in an arid climate.

Fig. 6. Exhumed footprints in an ancient floodplain of the Sousa Formation (Sousa Basin) overlayed by mudstones and siltstones with mud cracks.

4. Tracks and footprints consolidation and lithification

The quality of a footprint has generally a direct relationship with the substrate consistency at the time of their formation. After their formation, there is a fast degradation of exposed tracks and the low preservation potential is related to many destructive processes that include erosion, bioturbation, weathering, deformation during burial events and reworking during the successive depositional events (Nadon, 2001). According to Laporte and Behrensmeyer (1980) the amount of time between footprint formation and burial affects their preservation potential. Therefore, in part, it is the sedimentation processes that determine whether a footprint will be preserved or not. As noted above there are other factors also.

The preservation of the dinosaur tracks from the Sousa Formation (Sousa Basin) is herein interpreted as related to the footprint consolidation by early lithification due the existence of algal biofilms (Fig. 7) which prevented them from desintegration. The sediments would have been initially biostabilized leading to preservation by the biofilms (Noffke et al., 2001) followed by early cementation (calcification). However, the thick microbial mats that may form continuously, produce a strongly cohesive zone of low permeability, separating the underlying sediment from the atmosphere and protecting it against water loss, so that the sediment below a dry mat is not necessarily dry (Porada et al., 2007). Prints on such surfaces have a typical cracked surface, exhibit the gross outline of the foot, and are clearly deeper as some of the tracks observed at Passagem das Pedras, Sousa Basin.

Kvale et al. (2001) showed a similar context to the preservation of the Middle Jurassic dinosaur megatracksite from the Bighorn Basin (USA). The tracks, found in carbonate rocks, were probably primarily preserved by the action of microbial mat growth that covered ancient tidal flats. The microbial mats apparently initiated

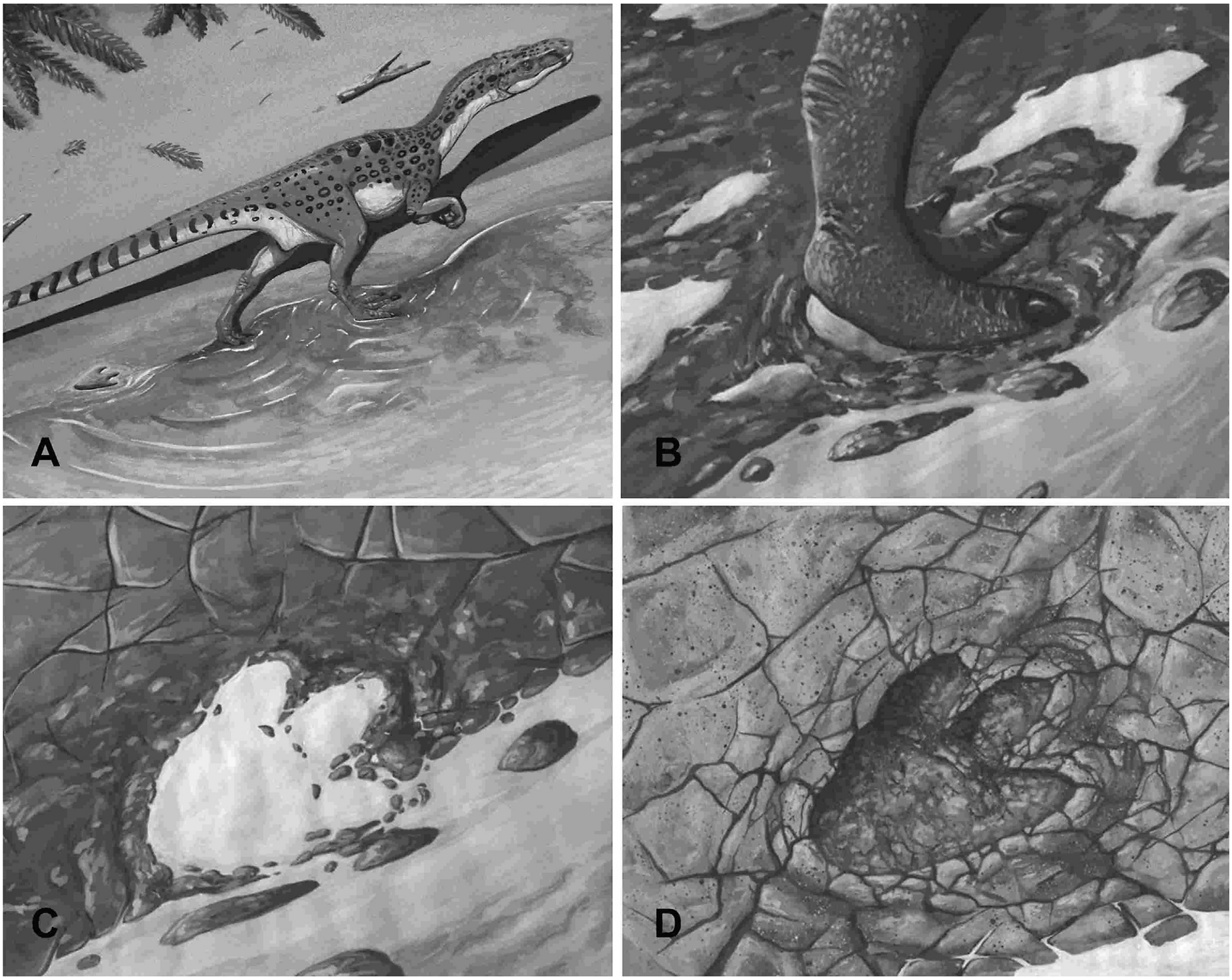

Fig. 7. (A) Taphonomic scenario for the footprint preservation. (B) Theropod print on a wet surface colonized by biofilms. (C) Biofilms continue to develop on the surface, biostabilizing and promoting imprinting of the footprint. (D) During a draught phase, calcification of the mat occurs, followed by mud cracking.

the preservation of these prints in at least a seasonally arid climate. The track preservation is related to penecontemporaneous microbial mats that biostabilized the tracks and prevented the initial reworking of the track-bearing surface by wind or water-driven currents (Kvale et al., 2001).

Marty et al. (2009) observed that thin moist mats, when compressed by the foot, develop shallow but well-defined prints with anatomical details of the toes. Therefore in water-unsaturated mats a great variability in footprint morphology can be produced, including well-defined and poorly defined footprints. Both on thin and thick mats, well-defined footprints with anatomical details of the toes and well-defined displacement rims (with radial fractures in Fig. 8) were formed if the underlying sediment still had a relatively high yield strength. Thus, the mat would have not been pierced but compressed and plastically deformed. Once the footprints were made, the mats kept growing as long as they remained moist. This growth modified the original morphology to different degrees.

Considering the depositional environments, Thulborn (1990) showed that footprints are most commonly preserved in settings with cyclic accumulation of sediments. Besides, early cementation, rapid covering by sediment and overgrowth by microbial mats are

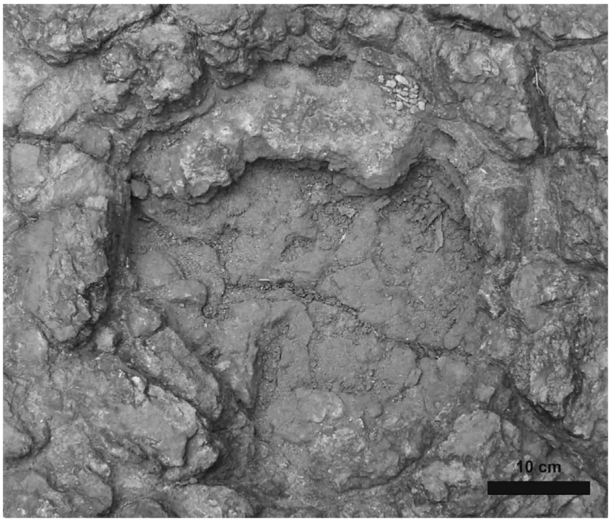

Fig. 8. Radial fractures (mudcracks) crossing well-defined displacement rims around a footprint.

the most important factors that potentially preserve footprints (Marty et al., 2009).

Marty et al. (2009) showed that microbial mats may enhance footprint preservation by binding and stabilizing the sediment in which the trace was made, by overgrowth, consolidation through drying, and also by lithification (carbonate precipitation within the microbial mat and early-diagenetic cementation). Binding and stabilization of sediments are mechanism also recognized by Noffke et al. (2001) as biostabilization and imprinting. Therefore mat growth also depends on other extrinsic parameters such as sedimentation rate, light, salinity, and temperature (Dupraz et al., 2004). It is important to observe that microbial mats are generally only produced during wet conditions, in this way limiting the time-frame during which footprints are registered/preserved and diminishing the time-averaging of an ichnoassemblage (Marty et al., 2009).

5. Footprints from Sousa Formation: preservation of dinosaur tracks induced by microbial mats

In the Sousa Formation the generally finer grain size of the sediments rendered them more suitable for footprint preservation. The essentially microclastic sequence points to lacustrine, swampy and meandering to braiding fluvial palaeoenvironments. Through the study of conchostracans, Carvalho and Carvalho (1990) and Carvalho (1993) inferred the physical and chemical characters of the ancient lakes along whose margins dinosaur disturbance was significant. They were interpreted as small temporary lakes, hot and shallow, in which the water chemistry conditions had an alkaline character (pH between 7 and 9). The dimensions of some of the conchostracans (up to 3.5 cm in length), suggest that an ecological optimum must have existed in which large amounts of nutrients and chemical ions such as calcium and phosphorus were present (Fig. 9).

Fossil tracks are preferentially found in the fine-grained sediments, such as purely terrigenous and carbonatic mudstones. This suggests that environments where fine-grained sediments are dominant provide a better settling for footprint preservation, although there are some exceptions (Carvalho, 2004; Shapiro et al., 2009).

Silva Filho (2009) described six lithofacies from the Sousa Formation, based on ca. 200 m of corings, drilled at Fazenda Cedro locality, Sousa County: two essentially microclastics; one interlaminated microclastic–microbialite; one laminated microbialite; and two interlaminated evaporitic–microbialite. Tracks may occur in anyone of these facies, particularly by undertracking. It is the infill of the track holes by microclastic–microbialite facies during floodplain flooding (Fig. 10A), and the calcification of the ancient mat in the laminated microbialite facies (Fig. 10B) that allow the track preservation. In the palaeonvironmental model of Silva Filho (2009), the tracks occur in ephemeral saline (alkaline?) lakes where biofilms and mats would develop during wet seasons or wetter climate phases, due to cyclic floodings. Microclastic input would result from hyperpycnal flows (inundite) in the flooded basin and produce the microclastic–microbialite facies. Drier climatic phases would result, therefore, in the evaporitic–microbialite facies, deposited in the exposed basin in a sabkha phase. Microbialites are identified in thin sections (Fig. 10) as dark organic very thin laminae (10–100 μm). These laminae may show continuity (Fig. 10A) or disruption by the tracks (Fig. 10B), and are associated with calcitic laminae or replaced by siderite (microbialite), imparting the characteristic reddish colour of the Sousa Formation.

It has been observed that sedimentary structures covered by microbial mats, help stabilizing the sedimentary surface and allow

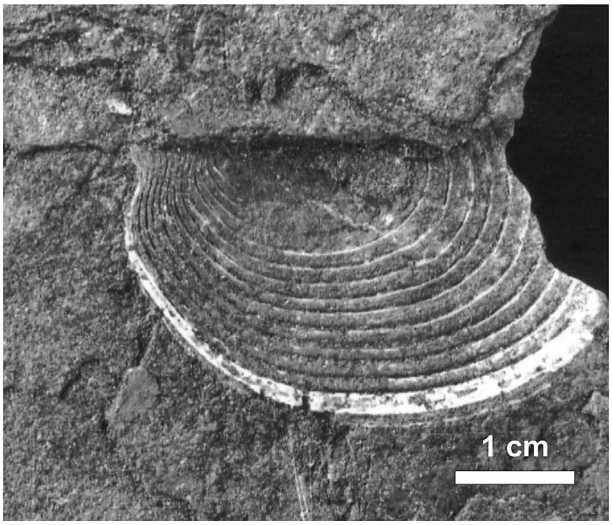

Fig. 9. *Palaeolimnadiopsis reali*, a large conchostracan, from the Sousa Formation (Sousa Basin), supports the interpretation of temporary lakes, with hot, shallow, and highly alkaline waters.

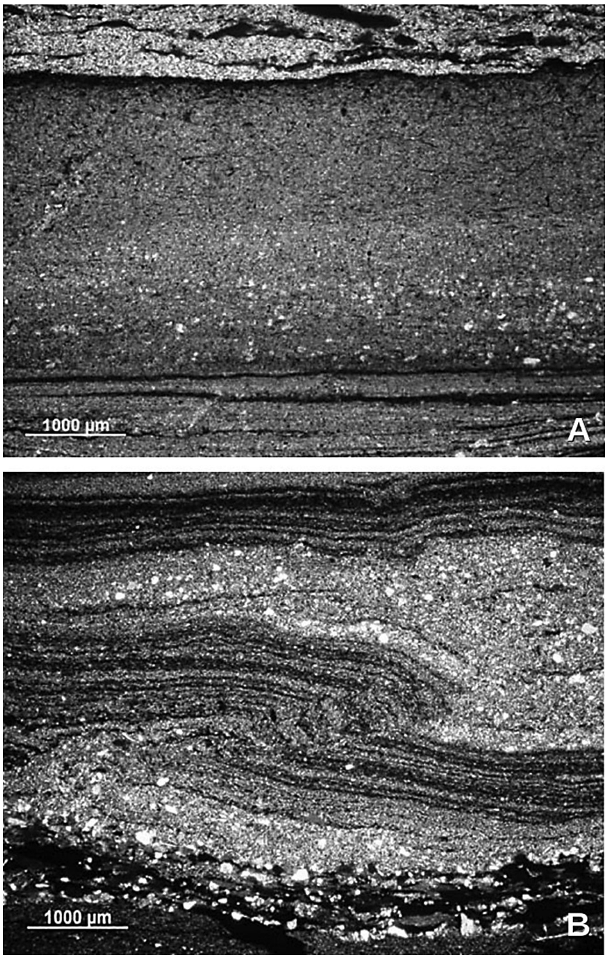

Fig. 10. Photomicrographs of the (A) microclastic–microbialite and (B) microbilite facies of the Sousa Formation. (A) Very thin (centimetre scale) graded terrigenous microclastic bed (flooding event), interbedded with microbial laminites, infilling the tracks. Observe biofilms/thin microbial mats (dark laminae). (B) Disrupted carbonatic microbial laminites, interbedded with very thin terrigenous microclastic beds, associated with the footprints. Observe the dark laminae (reddish colour), related to organic matter replaced by siderite.

the preservation of primary structures, such as ripple marks and mud cracks (Noffke et al., 2001), as they allow the surface to lithify by the precipitation of calcium carbonate (Chafetz and Buczynski, 1992; Dupraz et al., 2004; Dupraz and Visscher, 2005), and consequently enhance the preservation potential. Microbial mats are organosedimentary deposits of benthic microbial communities, a multi-layered sheet of micro-organisms, mainly bacteria and cyanophyta, that grow at the interfaces between different types of material, mostly on submerged or moist surfaces. The geological products of benthic microbial communities are called “biolaminites” or “biolaminations” for the flat laminated type of stromatolites or “biolaminoids” for less significantly laminated sediment that accumulated through the activity of microbial communities (Marty, 2005; Marty et al., 2009).

Preservation of animal footprints in the fossil record is strongly dependent on taphonomic processes, although it is the grain size and the sedimentation regime that determines if preservation will take place and if a footprint will be incorporated into the sedimentary record. The possibility of preservation is minimal during long-lasting periods of exposure without any sedimentation, and preservation is favoured by rapid and significant preservation events. This results that in environments of cyclic sedimentation, footprints are most commonly preserved. Therefore the final preservation of fossil vertebrate tracks in laminated sediments has been explained by the stabilization process of the sediment surface by microbial mats which would cover the tracks and protect them from erosion (Thulborn, 1990; Avanzini, 1998; Conti et al., 2005; Marty, 2005).

Marty et al. (2009) showed that microbial mats play a major role in the preservation of footprints as they may be consolidated by desiccation or lithification of the mat, or by the ongoing growth of the mat. The formation and morphology of footprints in microbial mats depends on the nature of the mat itself but also on the characteristics (water content, grain size, lamination, degree of consolidation, presence of a lithified horizon) of the underlying sediment. Then the footprint morphologies are controlled and affected by substrate properties such as consistency, sediment composition, grain size, texture, yield strength, water content, rate of consolidation, but also by the presence and nature of microbial mats.

Marty et al. (2009) observed that the footprint morphology is a function of microbial mat thickness and water content of the mat and the underlying sediment. In dry mats, generally poorly defined or no footprints are produced, while in water unsatured microbial mats the imprints are well defined, sometimes with well-defined displacement rims. The formation of well-defined displacement rims around the prints of large dinosaurs occurs in thick, plastic,

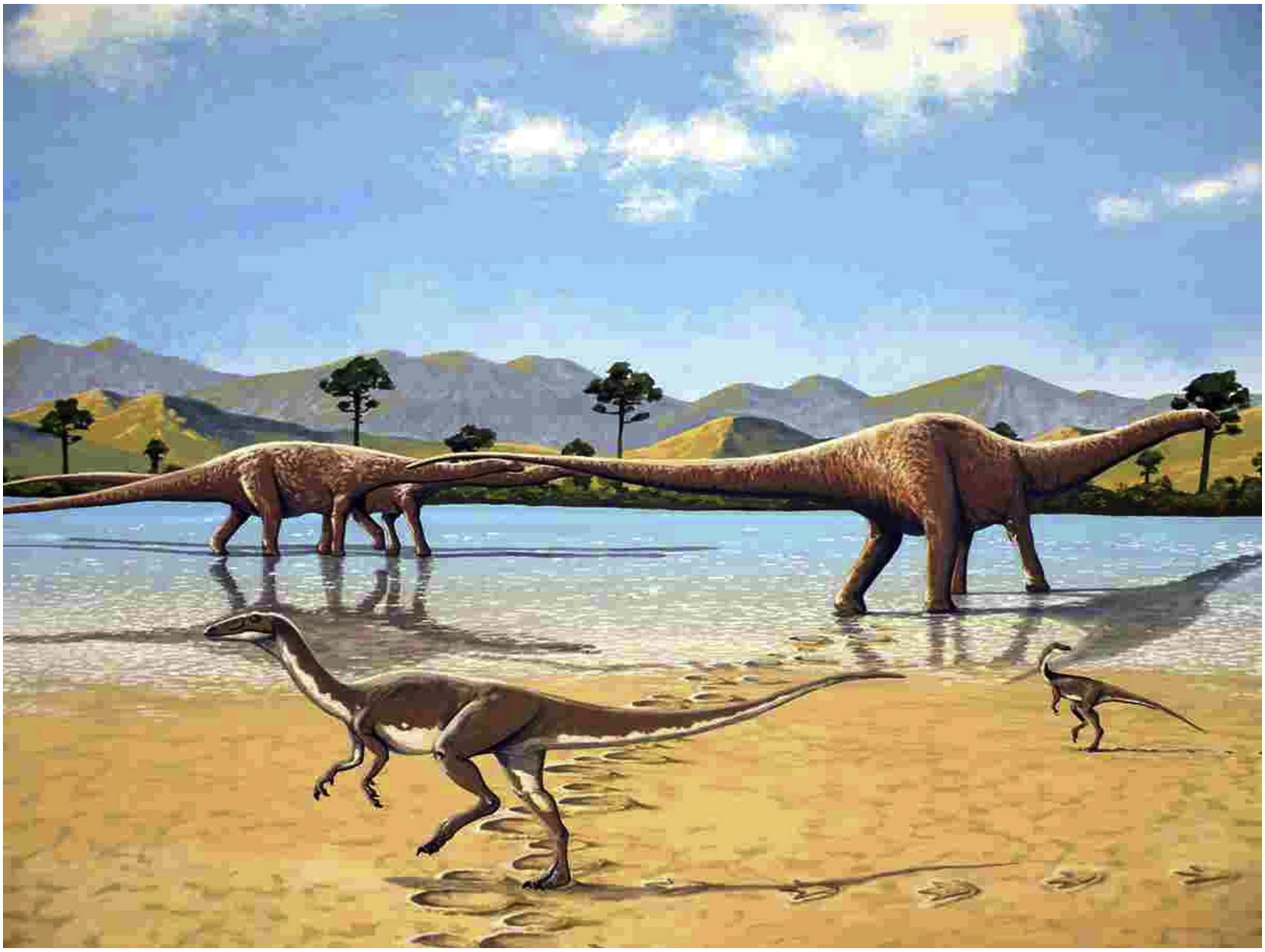

Fig. 11. Environment scenario of the Sousa Formation (Sousa Basin) during the Early Cretaceous, where more perennial floodplains are transformed in temporary hot, shallow, and alkaline lakes. This characterizes an optimum environment for the development of biofilms and algal mats and the preservation of the trackways, and sedimentary structures (Drawing by Ariel Milani Martine).

moist to water-unsaturated microbial mats on top of moist to water-unsaturated sediment. These aspects are commonly observed in the tracks of Passagem das Pedras, Sousa Basin.

The occurrence of microbial structures in Sousa Basin was firstly characterized by Silva Filho (2009). Distinct sedimentary facies of microbial and siliciclastic origin were recognized. The lithologies are marls, sandstones, siltstones and mudstones, interpreted as the accumulation of fine-grained sediments on microbial mats in which the dinosaur tracks are found.

The large amount of dinosaur tracks in the Sousa Formation (Sousa Basin), and the associated sedimentary structures, are related to the role of biofilms in consolidation. Footprint consolidation and its early lithification probably occurred due the existence of algal mats that allowed more cohesion preventing substrate desintegration. The sediments were initially stabilized by early cementation and by a network of biofilms over the tracks. Ultimately the cyclic events of sedimentation, resulting from successive flooding, and subsequent sediment influx allowed a large number of layers to bury and preserve dinosaur tracks (Fig. 11).

6. The ecological aspects of the dinosaur tracks environments and the biofilms

The palaeoenvironment where the biofilms developed can be interpreted from the associated conchostracofauna. The proliferation of the abundant conchostracan fauna found in the Sousa Basin required water with specific physical-chemical characteristics and availability of nutrients. The chemical character of the water in small lakes where living conchostracans are presently found is very important for the morphological aspects of their shells. They inhabit fresh alkaline waters (pH between 7 and 9), usually in well-oxygenated environments that have a clay substrate. Geochemical analyses of some samples of terrigenous and carbonatic rocks (mudstone, marl and limestone) in which the Cretaceous conchostracans of Sousa Basin are found (Carvalho, 2009) allow the evaluation of the ancient chemical conditions of the environment, since there is a relation between sediments, that would have served as substrate and nutrition medium for the conchostracofauna, and the chemical conditions of the surrounding watery microenvironment. The abundance of the conchostracofauna in the Sousa Basin can be related to two factors. The first one is the relationship between an active tectonics (wrench faults) and hydrothermalism, which might have been quite intense, indicating a region where there is high heat transference. The hydrothermal activity in these regions would probably reflect the mechanical importance of fluid pressure in the fault mechanism. Thus, the tectonic activity in Northeastern Brazil during the Early Cretaceous could have led to the remobilization of chemical elements, such as calcium, sodium, iron, fluorine, phosphorus, manganese, magnesium, potassium and sulphur, through hydrothermal solutions, which would rise through the reactivated faults and comprise the chemical character of the waters inhabited by the conchostracans. The existence of hydrothermal springs that fed into the lakes during the beginning of the Cretaceous might have been responsible for nutrient-enrichment and the maintenance of the alkalinity. These factors propitiated the blooming of the conchostracofauna and also of microbial mats. Another possibility for the increase in the amount of nutrients in the bodies of water in which the Sousa Basin conchostracans lived is the dissolution of the rocks that comprise the Precambrian basement and the basic rock intrusions, such as it occurs in the Lavras da Mangabeira Basin. The alteration of the minerals in the country rocks such as syenite, granite, granodiorite, gabbro, phyllite, quartzite, marble and diabase, would provide that rich ionic variety progressively concentrated within the pull-apart basins due to the predominantly endorheic drainage. Currently, the ground waters almost always reflect the geological conditions of the region, with their ions originating from the weathering of rocks and soils.

7. Conclusions

In this study the origin and preservation of the dinosaur tracks from Sousa Basin (Sousa Formation, Lower Cretaceous) and the role of biofilms in the consolidation of these footprints was analysed. The preservation of the dinosaur tracks was interpreted as related to the footprint consolidation and early lithification due the existence of algal biofilms that allowed a more cohesive substrate to form. The sediments were initially stabilized by early cementation and by a network of biofilms over the tracks.

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