

Dinosaur Footprints from Northeastern Brazil: Taphonomy and Environmental Setting

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The Brazilian Cretaceous basins located at the northeastern region of Brazil present a wide distribution of dinosaur tracks and isolated footprints in many environmental settings: alluvial fans, braided and meandering fluvial floodplains, marginal lake borders and tidal flats. They are mainly theropod and sauropod footprints of Neocomian and Cenomanian ages that are found in Sousa, Uiraúna-Brejo das Freiras, Araripe, Cedro, Malhada Vermelha, Lima Campos and São Luís Basins. The vertebrate ichnofossils are important biogenic sedimentary structures, a picture of the interaction between dinosaur's behavior and the substrate nature, allowing the paleobiological analysis and inferences about the palaeoenvironments.

Keywords Brazilian dinosaur footprints, Brazilian basins, geological context of footprints

INTRODUCTION

The Cretaceous sedimentation in the northeast Brazilian basins are related to the stages of the south Atlantic Ocean opening (Fig. 1). The widespread occurrences of dinosaur footprints (Viana et al., 1993) are found in intracratonic basins developed along pre-existing Precambrian structural trends in the basement located at Borborema Province. These basins are Sousa, Uiraúna-Brejo das Freiras, Araripe, Cedro, Malhada Vermelha, and Lima Campos, whose deposits are Neocomian in age (Rio da Serra and Aratu local stages). They are small half-grabens and the intense tectonic activity related to the initial stages of the Gondwanic crust rupturing led to rapid accumulation of continental sediments. Along the faulted borders of these basins, deposition occurred on alluvial fans; distally into braided and meandering fluvial systems and also perennial and temporary lakes (Lima Filho, 1991; Lima Filho et al., 1999; Mabesoone et al., 2000; Machado et al., 1990; Ponte, 1992; Poppoff, 1988; Regali, 1990). In the São Luís Basin the foot-

prints are found in Cenomanian strata of a low gradient coastal plain context. This basin had its origin during the Aptian-Albian opening of the Atlantic margin in the equatorial region.

The importance of the fossil vertebrate track analysis to paleobiology and palaeoenvironmental interpretation has been discussed by many authors (Avanzini, 1988; Cohen et al., 1991; Lockley, 1986, 1991). Cohen et al. (1991) in their study of modern vertebrate tracks at Lake Manyara (Tanzania) recognized the physicochemical and biological factors of importance to track preservation. They included the substrate composition and texture, groundwater table fluctuations, superficial drying, wind deflation, invertebrate bioturbation, and secondary vertebrate trampling. In this way, the classical idea of footprint preservation limited to fine-grained moist surfaces exposed to drying should be revised. 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 environmental settings to the track-bearing strata in these basins: alluvial fan—braided fluvial system, floodplain of meandering fluvial system, lake's marginal area, and tidal flat environment.

GEOLOGICAL SETTING OF THE FOOTPRINTS

Sousa and Uiraúna-Brejo das Freiras (or Rio do Peixe Basins) are located on Paraíba State, and comprise areas of 1,250 km² and 480 km², respectively. The most abundant ichnofauna from northeast Brazil comes from this region, where 22 ichnofossiliferous sites have already been identified. Theropods, sauropods, ornithischians, and ornithopods were preserved in deposits of Berriasian to lower Barremian ages. The lithostratigraphic subdivision of the Cretaceous on these basins was presented by Mabesoone (1972), and Mabesoone and Campanha (1973/1974) designated the Rio do Peixe Group, subdivided into the Antenor Navarro, Sousa, and Piranhas Formations. Footprints are rare in the Antenor Navarro and Piranhas Formations. The coarse lithologies of these units, such as conglomerates, coarse sandstones and sandstones interbedded with

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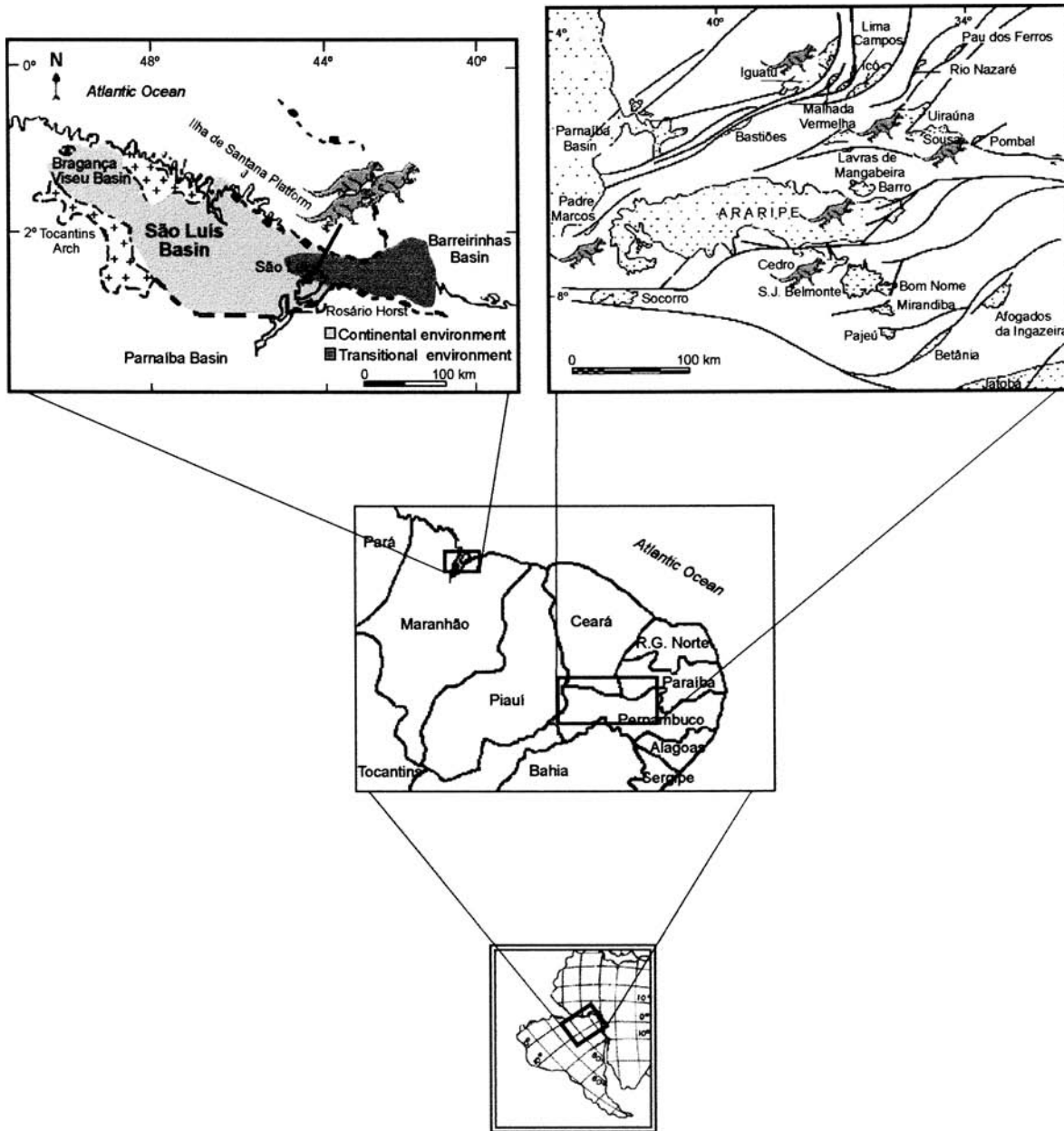


FIG. 1. Location map of the dinosaur footprints of Brazilian northeast basins.

siltstones were certainly a restrictive factor for fossil track preservation. The lithofacies, sedimentary structures, and geometry of the beds point to sedimentation in fan-delta, alluvial fan, and braided/anastomosing fluvial environments (Carvalho, 2000a, b). The essentially microclastic sequence of Sousa Formation was more suitable for footprint preservation, pointing to lacustrine, swampy and meandering-braided fluvial paleoenvironments.

Araripe Basin has an area of 12,200 km² spread over three states, the southern part of Ceará State, in the West of Pernambuco State, and in eastern Piauí State. Its Cretaceous history spans from Berriasian to Albian times, and until now footprints

have been identified only at one location. They occur in a fine-grained sandstone interbedded with coarse sandstones within the Cariri Formation that originally was considered part of a Palaeozoic depositional cycle. As shown by Carvalho et al. (1993b, 1994, 1995b), the Araripe Basin had its origin during the tectonic event that led to formation of all other intracratonic basins from northeast Brazil. The palaeoenvironmental interpretation of Cariri deposits is one of coalescent alluvial fans and an anastomosing fluvial system.

The Cedro Basin is located on the border between Pernambuco and Ceará States, in an area of 690 km². Similar to the

Araripe Basin, the footprints of this area have been found in clastic rocks previously mapped as Palaeozoic deposits (Tacaratu Formation). The depositional environments are alluvial fans and anastomosing rivers close to the basin margins (Carvalho et al., 1993a, 1995a).

Malhada Vermelha (65 km²) and Lima Campos (105 km²) basins present theropod and ornithopod dinosaur tracks in conglomeratic and fine sandstones (Leonardi and Muniz, 1985; Leonardi and Spezzamonte, 1994). The lithostratigraphic units are the Malhada Vermelha Formation (fine sandstones, shales, and marls) and Quixoá Formation (conglomeratic and fine sandstones) considered as the deposition of alluvial fans and anastomosing-meandering fluvial environments during Berriasian to lower Barremian times (Mabesoone et al., 1979).

The São Luís Basin is geographically and temporally far from the geological context of the Borborema Province basins. São Luís Basin had its origin in Aptian-Albian time, during the opening of the Atlantic margin in the equatorial region of Brazil. The outcrop area of the São Luís Basin comprises Upper Cretaceous (Cenomanian) reddish sandstones, siltstones, shales, and mudstones that are grouped into the Itapecuru Group. The environmental interpretation of outcrop lithofacies shows environments such as estuarine, nearshore, and shallow marine environments affected by both tidal and storm process (Klein and Ferreira, 1979; Rossetti, 1994, 1996a). Dinosaur footprints are found in a sandy tidal plain area, cut by freshwater and tidal channels.

The following environmental settings present track-bearing strata in northeast Brazilian basins:

Alluvial Fan—Braided Fluvial System

The alluvial fans are characterized by coarse detrital sediments, immature, poorly sorted, built up by a mountain stream at the base of a mountain front. The coarsest and thickest deposits occur near the fan head area, decreasing rapidly toward the base of the alluvial fan deposit. These may be found associated with braided river deposits, depending upon the topographical and climatic conditions. The braided river facies comprises braid bars of coarse material developed in mountainous streams and that ones of fine-grained material developed in rivers with large seasonal discharge and sediment load in the lower reaches of the river (Reineck and Singh, 1986). These kind of environments present extremely oxidizing conditions, and organic matter is rare. The coarse-grained facies assemblages susceptible to reworking and scour presumably reflect a low preservation potential in these areas (Lockley and Conrad, 1991). Despite the low preservation potential of alluvial fans and braided fluvial systems, dinosaur tracks and trackways are found in this context at Sousa, Uiraúna-Brejo das Freiras, Araripe, Cedro, Malhada Vermelha and Lima Campos basins (Carvalho, 1989, 1996; Carvalho and Leonardi, 1992; Carvalho et al. 1993a, b, 1995a, b). The grain size of the sediments that formed the substrate over which the dinosaurs traveled, was probably the main limiting factor on the footprint preservation.

In Sousa Basin footprints are found in the Antenor Navarro and Piranhas Formations preserved only in fine sediments that accumulated as subaerial sandy bars (Fig. 2). In Uiraúna-Brejo das Freiras Basin they are also present in the Antenor Navarro Formation, in a sequence of interbedded medium- to fine-grained sandstones and siltstones. The footprints would have been made during periodic breaks of sedimentation when channel sand bars became subaerial owing to discharge fluctuations. The same interpretation is proposed to the track-bearing strata of Cariri Formation (Araripe Basin), Tacaratu Formation (Cedro Basin), Quixoá Formation (Lima Campos Basin), and Malhada Vermelha Formation (Malhada Vermelha Basin).

A conspicuous aspect of the footprints from these areas is that they are always preserved as convex hyporelief with a coarser grain-size than the surrounding matrix and red color pigmented by iron oxides. The Antenor Navarro Formation footprints at Serrote do Letreiro (Sousa Basin) are a good example of this preservation mode. Small theropod footprints are reddish in color and sometimes filled with coarse sandstones, contrasting with the surrounding substrate. Such aspects have already been analyzed by Kuban (1991a) in his study of the footprints from Glen Rose Formation (Lower Cretaceous, U.S.A.). This author considered that the color differences on footprints and matrix result from secondary sediment infilling of the original track depression and differential oxidation of iron on the surface of the infilling material. Although some tracks do not show any textural differences with the surrounding substrate, they are reddish color, contrasting with the pavement where they occur. This could be related to a differential packing of the sediments where footprints are present, a factor that allowed distinct iron concentrations due to fluid percolation during diagenesis.

Meandering Fluvial Flood Plain— Lacustrine Environments

The flood plain of meandering fluvial rivers presents the finest grain of all the alluvial sediments, generally fine silt and clay, finely laminated, interrupted by some sandy intercalation. Perennial and temporary lakes may develop in the flood plain area. In hot climates little or no organic matter is incorporated into flood basin deposits, and if the water flow is sluggish, it is possible to have the establishment of saline lakes. Mud cracks, raindrops, bioturbation, and other surface features are widespread because of repeated exposure (Reineck and Singh, 1986). This is a favorable environment for fossil track preservation. There are a wide distribution area, many track-bearing strata, and it is possible to have detailed footprint morphology impressions, such as that ones found in the Sousa Formation (Sousa Basin).

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 structures, ripple marks, climbing ripples, rain prints, and vertebrate and invertebrate bioturbation.

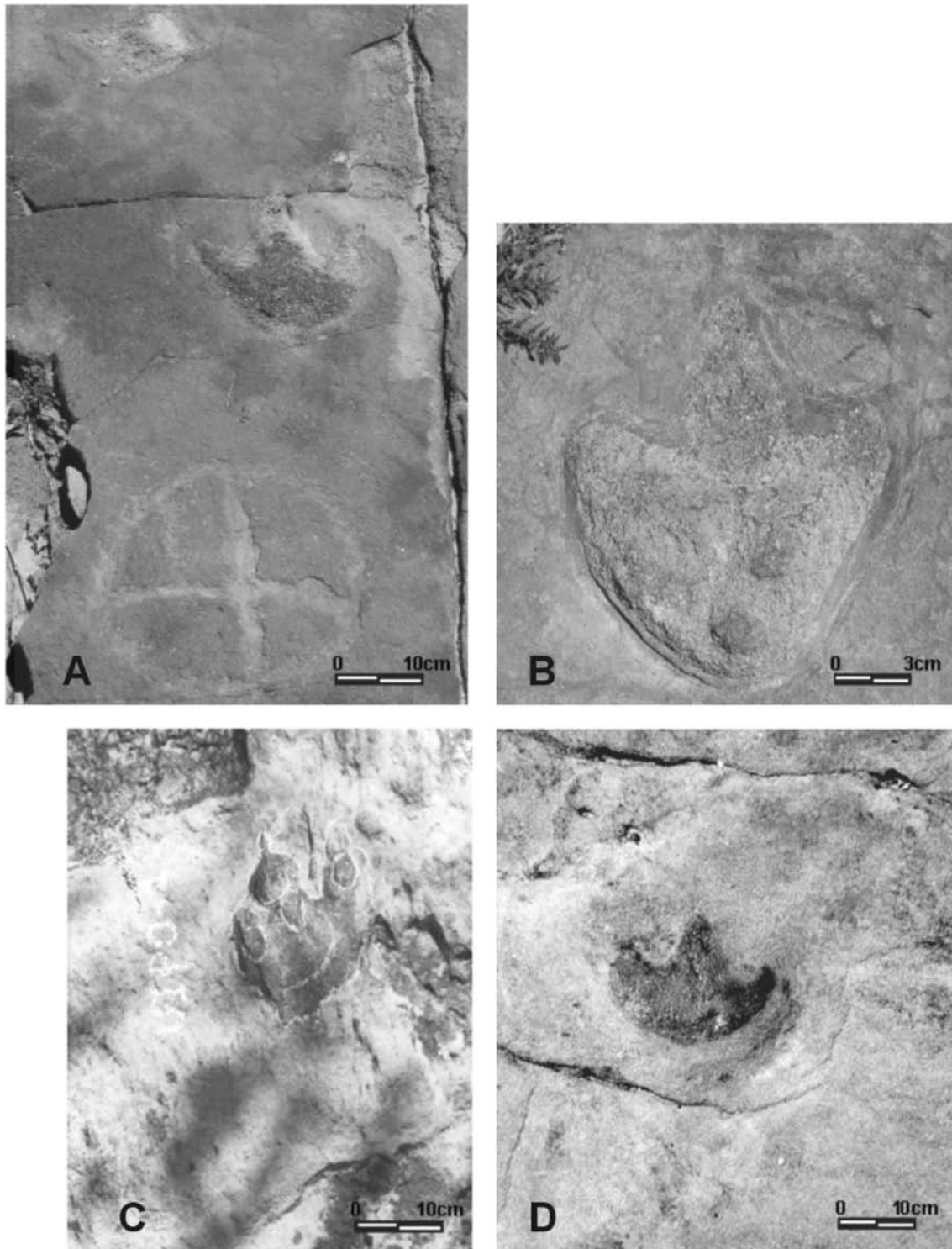


FIG. 2. Dinosaur footprints from alluvial fan and braided fluvial systems. (A) A theropod footprint associated with an ancient native rock engraving (astronomical observation point) and (B) a probable theropod footprint from Serrote do Letreiro, Sousa Basin. (C) A theropod footprint from Uiraúna Basin (Antenor Navarro Formation). (D) An isolated ornithopod footprint from Araripe Basin.

There are 13 ichnofossiliferous sites in at least 60 levels that include approximately the following ichnofauna: 220 large theropods, 29 small theropods; 11 sauropods; 15 graviportal ornithopods; 1 small quadrupedal ornithischian; a number of unclassifiable or uncertain dinosaurian tracks; 1 batrachopodid set; and a large number of small chelonian tracks. The total recorded dinosaurian individuals number more than 276 (Leonardi and Carvalho, 2002; Leonardi et al., 1987a, b, c). The domain of theropod footprints is attributed to an ecological zonation of the dinosaurian biota and a taphonomic artifact. The theropods probably had a preferential distribution in the low floodplain areas, where is higher the preservational possibilities in the fine-grained sediments. The sauropods otherwise were far from these regions. They lived in the higher areas of the basin near its borders, where there is a lower potential to the track preservation due the coarse nature of the substrate sediments.

The footprints are preserved as concave epirelief, sometimes with detailed morphology, such as claws, digital pads, sole pads, and interdigital web. The essentially microclastic sequence allowed such preservation (Fig. 3). Lockley and Conrad (1991) presented many examples from distal fluvial flood plain environments and lake borders, where there are diversity, abundance, and wide distribution of dinosaur footprints. The lakes in the Sousa Basin are developed in the depocenters areas and are characterized by clastic sediments. They result from fluvial systems that grade into fluvio-lacustrine complexes. 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. This aspect of the lakes, along whose margins dinoturbation was significant, was discussed by Carvalho and Carvalho (1990) and Carvalho (1993). The dominance were of small temporary lakes, hot and shallow, in which the chemical conditions had an alkaline character (pH between 7 and 9). There were large amounts of nutrients and chemical ions such as calcium and phosphorous, an ecological optimum to flourish life.

The cyclic succession of mudstones, siltstones and fine-grained sandstones in fluvial-lacustrine environments, a product of periodic flooding and a lake's shoreline changing, allowed the establishment of many successive surfaces adequate to footprint preservation. This can be observed in recent environments as described by Cohen et al. (1991) in Lake Manyara (Tanzania). They observed that a strong shoreline-parallel zonation of environmental variation correlates with differences in track preservation style. Texture, composition, and moisture regulate the probability of initial track registration and depth of penetration. Also in paleolakes a cyclic pattern of deposition occurs as presented by Prince and Lockley (1991). They mapped bedding plane exposures of the Morrison Formation (Jurassic, Colorado, USA) that revealed hundreds of dinosaur footprints in a package of cyclic lacustrine sediments at the top of the shoreline facies beds. In Sousa Basin, Leonardi (1991, 1994) recognized at Sousa Formation (Piau locality) 25 levels with dinosaurian ichno-populations. These different levels rep-

resent the cyclic deposition on a Cretaceous shoreline's lake. Similarly, Paik et al. (2001) analyzed the dinosaur track-bearing deposits in 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.

The footprints and undertracks in the basins in northeastern Brazil were produced in subaerial and subaqueous settings. It is possible to identify footprints with well-defined morphologies or progressively loosing their clarity due to their relationship with mud cracks, fluidization, convolute, and radial structures. Those ones with impressions of claws, nails, and soft tissue such as the sole and phalangeal pads are considered to be produced in mud sediments with high plasticity and low water content, probably in a subaerial setting of floodplains and marginal lakes areas. This context is easily recognized by the association of the footprints with raindrops and mud cracks that sometimes has its origin related to the contour of the track or as extension of the digits. The dehydration of the muddy sediments produces structures similar to those ones described by Lockley et al. (1989). If the geological setting of the footprint is the alluvial fan sediments, although it was also produced in a subaerial setting, their morphology is always restricted to the contour. In this case the track is related to a disruption of the depositional surface and can be considered as a dinoturbation structure. There are some exceptions as in the case of Antenor Navarro Formation footprints from Serrote do Letreiro that show well defined contours due the differential iron oxidation on the surface of the infilling material. In subaqueous environments, there is the decrease of the morphological details of the footprints such as nails, claws, pads and sole marks.

Estuarine-Nearshore Marine Environments

The footprints in this environmental setting in northeastern Brazil are found in rocks of Cenomanian age at São Luís Basin, Maranhão State (Figs. 4 and 5). The environmental scenery during the Cenomanian in this area comprises many sub environments associated with an estuary that occupied a low-gradient coastal plain. Distinct dinosaur communities are found in this geological context (Carvalho and Pedrão, 1998). In the outcrops of the São Luís Basin, Rossetti (1994; 1996a, b) recognized two depositional intervals. The footprint bearing-strata are found in the upper succession that have been interpreted as the product of tidal-dominated deposits attributed to channel, sand flat, delta, and bay fill depositional settings of an estuary. At São Luís Basin dinosaurian footprints bearing strata are found in six localities of São Luís and Alcântara counties: Ponta da Guia, Ponta do Farol, Praia do Boqueirão, Ilha do Medo, Praia da Baronesa, and Ilha do Cajual. The best preserved footprint localities are at Ponta da Guia and Praia da Baronesa (Carvalho, 1994, 1995, Carvalho and Gonçalves, 1994; Carvalho and Araújo, 1995).

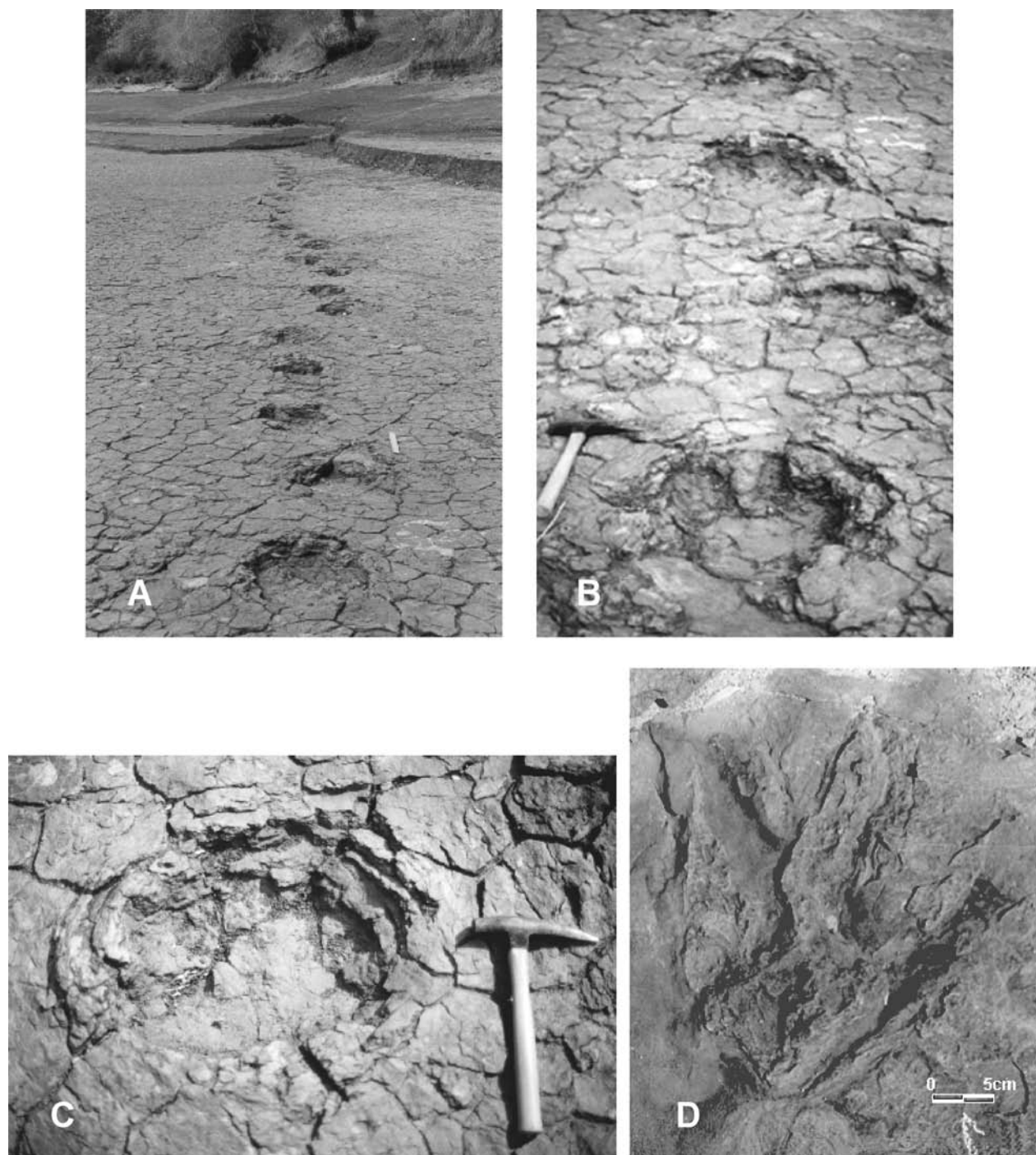


FIG. 3. The meandering fluvial flood plain and the lacustrine environments present a large amount of tracks, such as that ones found at Passagem das Pedras (A, B, C) and Fazenda Caiçara-Piau (D) in the Sousa Basin (Sousa Formation).

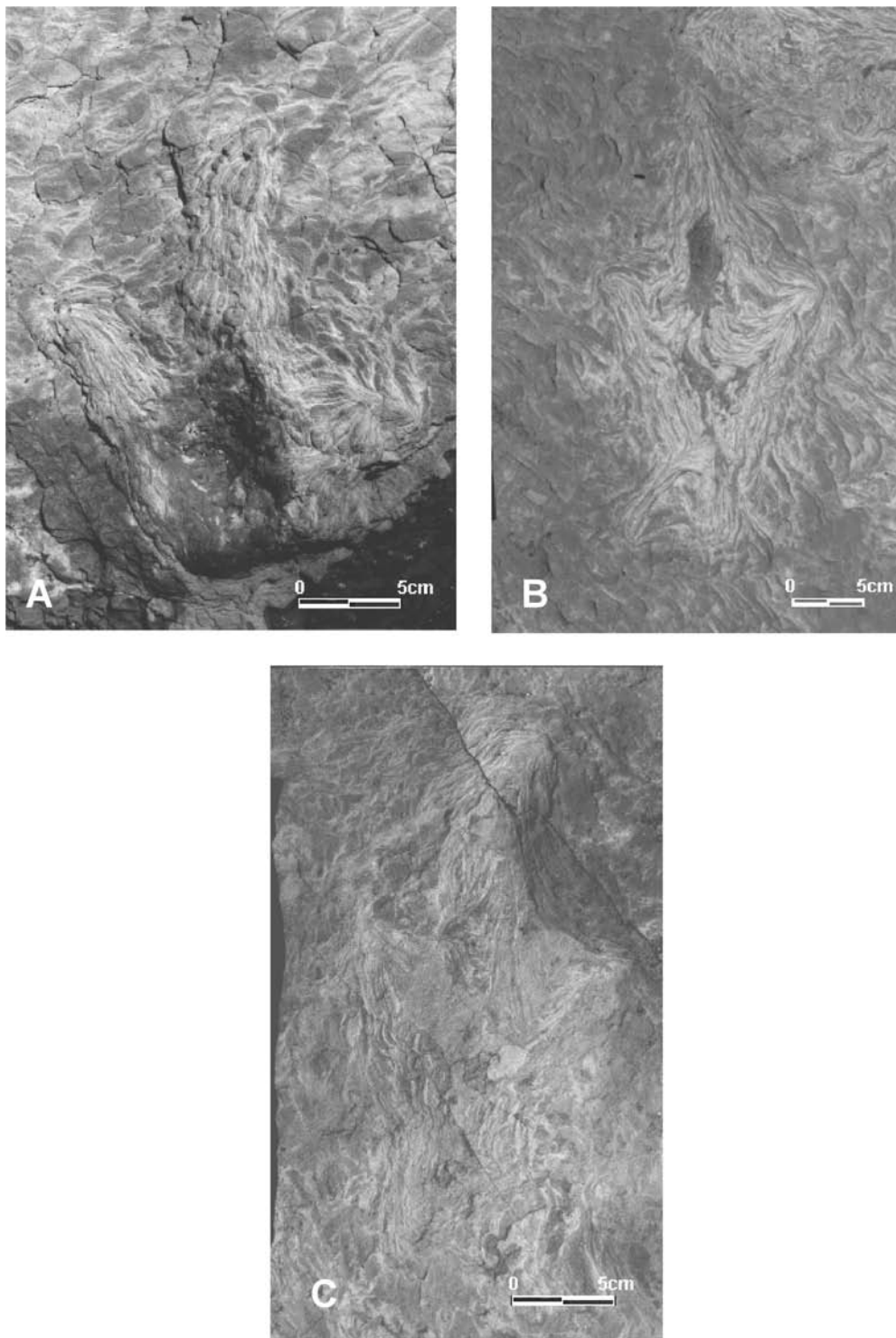


FIG. 4. Cenomanian theropod footprints with fluidization structures from nearshore marine environments. São Luís Basin, Itapecuru Group (Alcântara County, Praia da Baronesa).

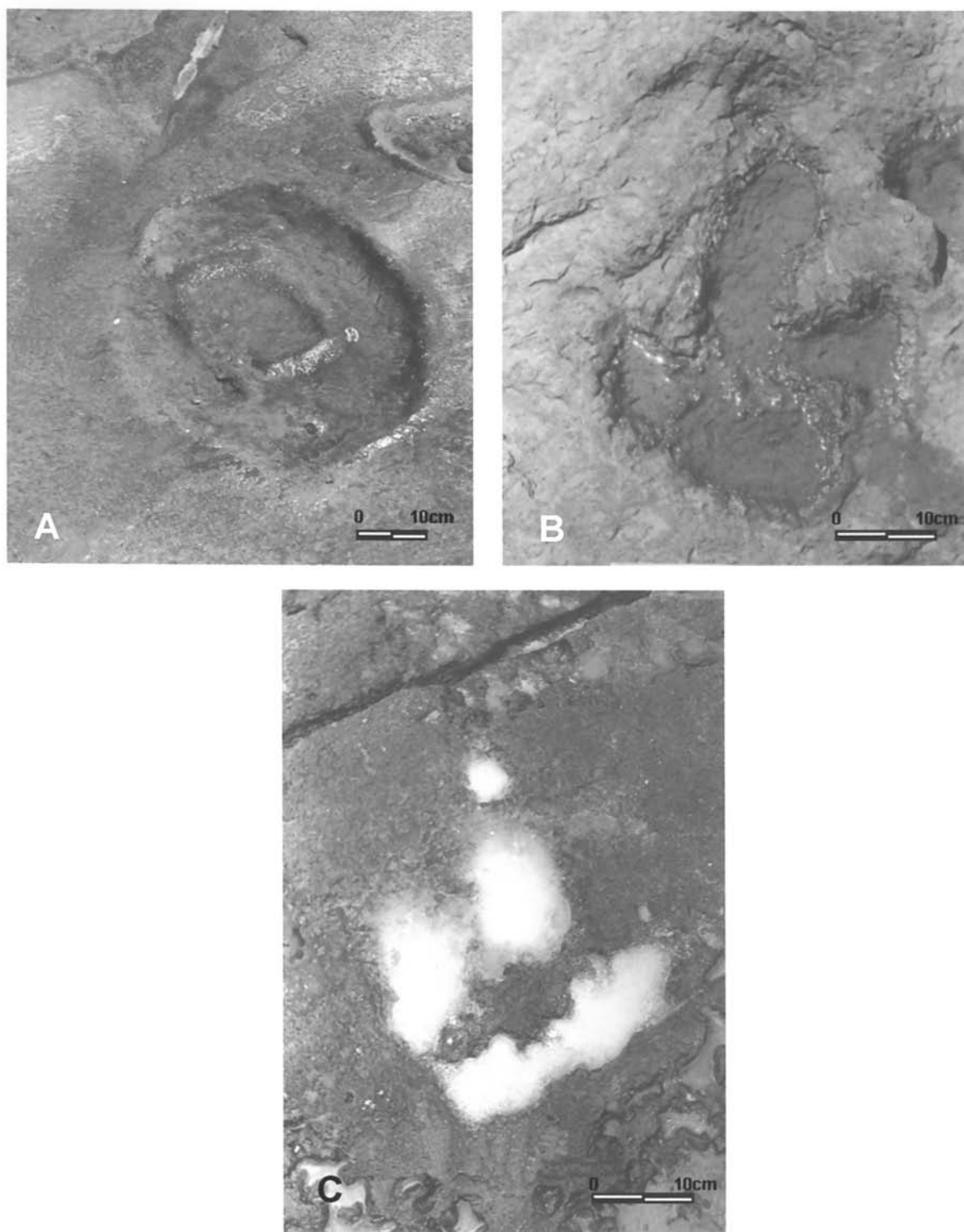


FIG. 5. (A) Sauropod (?) track and (B, C) theropod footprints from the Cenomanian of São Luís Basin, Itapecuru Group. (A) Prefeitura locality and (B) Praia da Baronesa, both at Alcântara County. (C) Ponta da Guia locality, São Luís County.

The estuary and delta are characterized by a complex of fluvial and shallow marine environments. In regions with marked tidal ranges, the estuarine sediments are laterally associated with tidal flats or salt marshes. If the estuarine or delta mouth is partly closed by a barrier-beach and dune ridge complex, lagoons may develop (Reineck and Singh, 1986). Preservation of footprints in these environments is possible because of the sedimentological aspects, fine-grained sediments such as clay and carbonate, found in seasonally flooded areas. They are generally found on the inter and supratidal sediments as presented by Avanzini and Frisia (1996) and Dalla Vecchia et al. (2001).

The dinosaur footprints in São Luís Basin are found associated with fossils of mollusks, fishes (Dipnoi, Elasmobranchia, and Actinopterygii) and reptiles (Dinosauria, Crocodylomorpha, and Chelonia). The geological context of their occurrences are estuarine, nearshore and shallow marine environments affected by both tidal and storm processes. The architectural distribution of some deposits of the Itapecuru Group revealed a prograding barred coast, probably in the distal (seaward) portion of a wave-dominated estuarine system (Rossetti, 1994, 1996a, 1997).

The theropod and ornithopod footprints and associated bone fragments in the São Luís Basin are found in fine-grained quartzose sandstones, with large scale cross-stratification. Such lithofacies were interpreted by Rodrigues et al. (1990) as the result of deposition in nearshore environment submitted to tidal currents with subaerial exposure and aeolian reworking. Alongside the coastline of a shallow marine environment lived an abundant dinosaurian fauna, and during low-tide periods, subaerial exposure of the bedforms allowed them to suffer dino-turbation.

There is evidence of gregarious behavior among the theropods of São Luís Basin (Ponta da Guia locality), an aspect that has been observed in other Brazilian ichnofaunas from the Lower Cretaceous of Sousa Basin and Upper Jurassic of Parnaíba Basin (Carvalho and Leonardi, 1992; Godoy and Leonardi, 1985; Leonardi, 1980, 1991).

The track preservation occurred in two contexts: supra-tidal and exposed bars in a tidal-channel environment. In the first case, the tracks such as the ones of Ponta da Guia locality, are preserved in fine-grained sandstones interbedded with argillaceous siltstones, show small-sized channel and tabular cross-stratification, ripple-marks, mud-cracks and clay-balls, laid down in a sand flat depositional environment in the upper portion of a low-gradient tidal flat. The second situation—exposed bars in tidal channels—presents randomly oriented trackways and isolated footprints. They are always associated with fluidization structures and present superficial color stains (blue-gray, green, red). Carvalho (1994) considered that fluidization around the footprints was produced as the result of a “dinostatic pressure” in water-saturated and low cohesive sediments. Such substrate aspect is corroborated by the metatarsal impressions in many footprints. Kuban (1991b) considered that this preservational character could be indicative of a behavior re-

sponse to a soft substrate. The elongate plantigrade footprints would be explained by a low posture assumed whenever a dinosaur foraged in mud flats or shallow water for small food item, stalking large prey, or while approaching other dinosaurs. The aspect of contrasting color footprints in relation to the surrounding substrate was explained by Kuban (1991a) as the result of secondary sediment infilling on the original track depressions and oxidation of iron on the surface of infilling material.

The footprint-bearing strata of São Luís Basin are considered a megatracksite (Carvalho, 2001; Carvalho and Pedrão, 1998). The dominance of large-sized theropod footprints is detected in the southern area of the basin, which includes the Ponta da Guia region. To the north, ichnocoenoses such as Praia da Baronesa show medium and small theropod tracks. There was a probable ecologic “segregation” of large and small theropods. Its geological context—a low gradient coastal plain—probably allowed the establishment of specific dinosaur communities.

CONCLUSIONS

The distribution of dinosaur footprints in the interior and Atlantic Equatorial northeast Brazilian basins are found in many geological settings. The Lower Cretaceous basins of Sousa, Uiraúna-Brejo das Freiras, Araripe, Cedro, Malhada Vermelha, and Lima Campos present tracks and isolated footprints in the context of continental rift basins: alluvial fans, perennial and temporary lakes, braided, and meandering fluvial systems. The tracks are sparse in the alluvial fans and braided fluvial deposits, probably due the coarse nature of their sediments. In the borders of lakes and flood plain areas of the meandering rivers, there are a great amount of well-preserved tracks and isolated footprints in many successive stratigraphic levels.

The Late Cretaceous tracks of the São Luís Basin were also found in a rift basin. This basin had its origin related to the opening of the Atlantic margin in the equatorial region of Brazil. The dinosaur tracks are found in estuarine-nearshore marine environments, such as the upper portion of a low-gradient tidal flat and also in exposed bars of tidal channels. The footprints, in the first case, occur in argillaceous siltstones that in many cases allowed the complete preservation of the *autopodia* morphology. In the water saturated, fine-grained sands of the tidal channels, the footprints were preserved by superficial color stains and as fluidization structures.

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