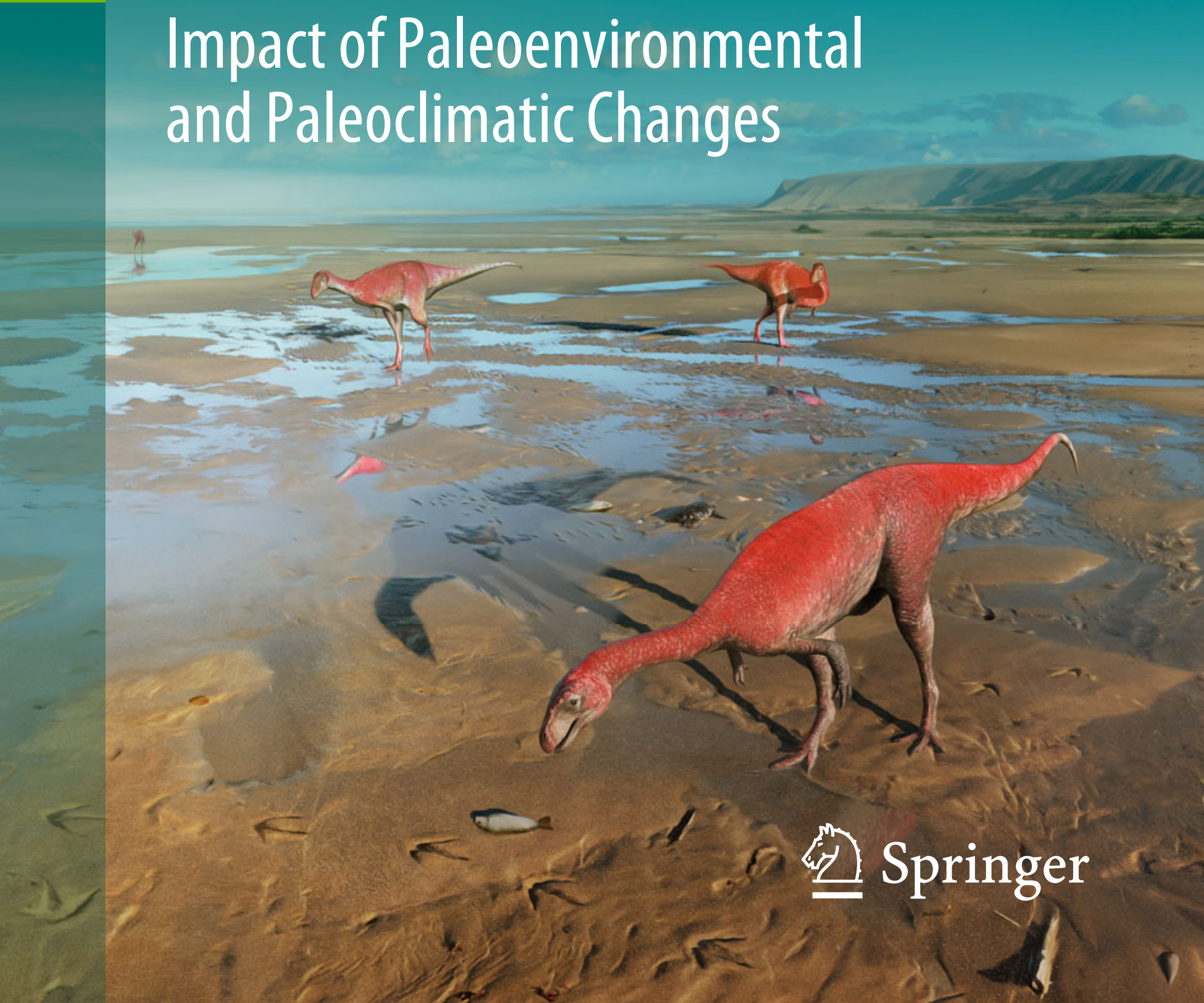
Ismar de Souza Carvalho
Giuseppe Leonardi *Editors*

Dinosaur Tracks of Mesozoic Basins in Brazil

Impact of Paleoenvironmental and Paleoclimatic Changes



Springer

Chapter 6
The Cretaceous Araripe Basin Dinosaur Tracks and Their Paleoenvironmental Meaning

Ismar de Souza Carvalho, Giuseppe Leonardi, and Jaime Joaquim Dias

6.1 Introduction

During the Mesozoic in South America, the terrestrial ecosystems were remodeled due to changes in the configuration of continents and oceans, particularly the opening of the South Atlantic Ocean by the Gondwana supercontinent rifting process (Matos 1992; Assine 1992, 2007; Marques et al. 2014). Within this context, continental depressions were formed analogous to pull-apart basins, with their genesis by transcurrent tectonics along faults during the opening of the Atlantic Ocean (Matos 1992). The Araripe Basin is the largest among these interior sedimentary basins in northeastern Brazil (Fig. 6.1), covering an approximate area of 12,200 km^2 in the southern part of the Ceará State, and portions of the Pernambuco and Piauí states (Carvalho et al. 2012; Fambrini et al. 2020; Dias et al. 2022). The Araripe Basin is not only important for understanding the environment and climate of the Brazilian Mesozoic but also stands out for the high quantity and quality of its fossils, including dinosaur footprints found in four lithostratigraphic units: Mauriti, Rio da Batateira, Crato, and Exu formations (Carvalho et al. 1995, 2018, 2019a, b, 2021a, b, 2022, 2023).

I. S. Carvalho (✉) · G. Leonardi · J. J. Dias
CCMN/IGEO, Departamento de Geologia, Universidade Federal do Rio de Janeiro, 21.910-200
Cidade Universitária, Ilha do Fundão, Rio de Janeiro, Estado do Rio de Janeiro, Brazil
e-mail: ismar@geologia.ufrj.br

I. S. Carvalho
Centro de Geociências, Universidade de Coimbra, Rua Sílvio Lima, 3030-790 Coimbra, Portugal

G. Leonardi
Istituto Cavanis, Dorsoduro 898, 30123 Venezia, Italy

J. J. Dias
CCMN/IGEO, Departamento de Geologia, Universidade Federal do Rio de Janeiro, 21.910-200
Cidade Universitária, Ilha do Fundão, Rio de Janeiro, Estado do Rio de Janeiro, Brazil

I. S. Carvalho and G. Leonardi (eds.), *Dinosaur Tracks of Mesozoic Basins in Brazil*,
https://doi.org/10.1007/978-3-031-56355-3_6

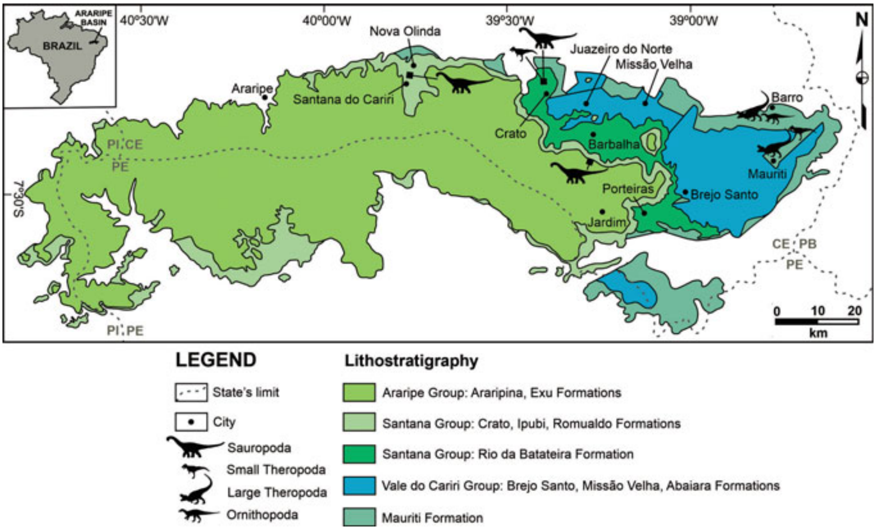


Fig. 6.1 Geological map of the Araripe Basin and the location of the dinosaur footprints ichnosites. The geochronological data, lithostratigraphic unit's limits and nomenclature were based in Ponte and Appi (1990), Fambrini et al. (2011), Rios-Netto et al. (2012), Assine (2007) and Arai and Assine (2020)

The footprints in the Araripe Basin are imprints in the upper bedding surface or even as structural deformations only visible in cross section. They allow the evaluation of substrate consistency besides the potential trackmaker identification. The environmental contexts of the dinosaur footprints from the Araripe Basin include the dinosaur trampling in fluvial sand bars, floodplains, deltas, and saline-alkaline lake borders. Then these footprints permit us to evaluate the diversity of the Cretaceous biota in this region and also discuss the environmental changes throughout the early and beginning of the Late Cretaceous in this region.

6.2 Geological Context

The sedimentary filling of the Araripe Basin begins with a controversial Paleozoic sequence (Carvalho et al. 2024), followed by three Mesozoic super sequences known as Pre-Rift, Rift, and Post-Rift (Ponte and Appi 1990; Assine 2007; Assine et al. 2014). The full sedimentary succession of the basin (Fig. 6.2) rests unconformably on the igneous and metamorphic rocks of the Precambrian Piancó-Alto Brígida Terrain, part of the Transversal Zone of the Borborema Province (Brito-Neves et al. 2000).

The Mauriti Formation footprints occur in two ichnosites: Milagres (Milagres County) and Mauriti (Mauriti County), both in the Ceará State, in a succession of coarse and fine-grained sandstones. The unit is constituted of conglomerate and

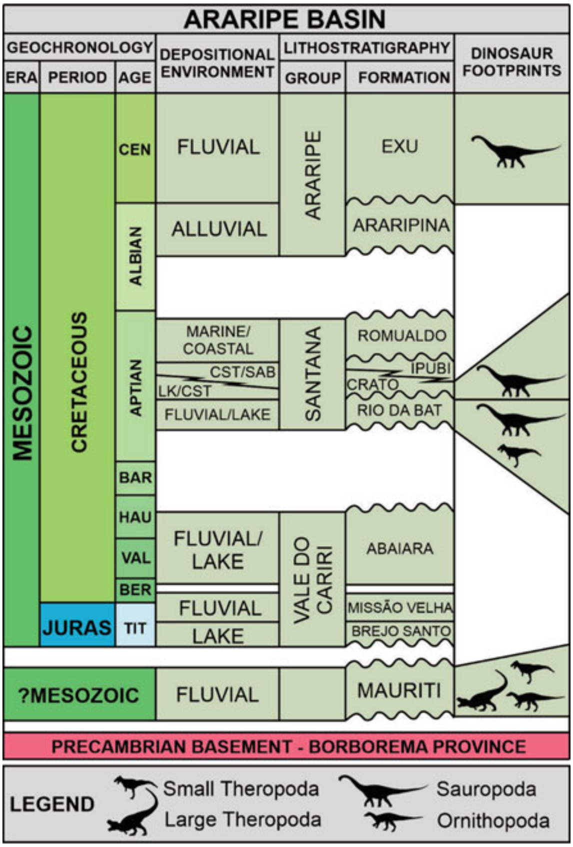


Fig. 6.2 Araripe Basin stratigraphical chart and the lithostratigraphic units with dinosaur footprints. Abbreviations: JURAS: Jurassic; TIT: Tithonian; BER: Berriasian; VAL: Valanginian; HAU: Hauterivian; BAR: Barremian; CEN: Cenomanian; LK: Lake; CST: Coastal environment; SAB: Sabhka; RIO DA BAT: Rio da Batateira Formation. The geochronological data and nomenclature of the lithostratigraphic units were based in Ponte and Appi (1990), Fambrini et al. (2011), Rios-Netto et al. (2012), Assine (2007) and Arai and Assine (2020)

pebbly sandstone that grades into medium-to coarse-grained sandstone towards the top in a sedimentary succession interpreted as a braided fluvial system during a hot and dry climatic context. The fossil record is marked only by the presence of invertebrates and vertebrate ichnofossils, such as dinosaur footprints (Ponte and Appi 1990; Assine 1992; Carvalho et al. 1994, 1995, 2023, 2024; Batista et al. 2012; Cerri et al. 2022).

Initially designated as Cariri Formation, of Neocomian age (Beurlen, 1962), it was renamed as Mauriti Formation (Gaspary and Anjos, 1964) and has been interpreted as indicative of an initial depositional event in the Lower Paleozoic, Upper Ordovician to Lower Devonian, based on lithostratigraphic correlation with the Serra Grande Group (Parnaíba Basin) and the Tacaratu Formation of the Jatobá Basin (Ponte and Appi 1990; Assine 1992). Sedimentologic, stratigraphic, detrital zircon U–Pb dating and provenance approaches based on trace elements in detrital rutile established that the sedimentation of the Mauriti Formation started after the Late Cambrian, probably extending through the Ordovician (Cerri et al. 2022). However, the identification of theropod and possibly ornithopod tracks in the Milagres and Mauriti ichnosites may indicate a Neojurassic to Early Cretaceous age for the Mauriti Formation, suggesting that the beginning of deposition in the Araripe Basin was restricted to the last part of the Mesozoic (Carvalho et al. 1995, 2023). This Mesozoic age is also supported by tectonic and sedimentary analyses (Berthou 1990; Mabesoone 1990).

The Upper Jurassic Pre-Rift super sequence of the Araripe Basin (Assine 2007; Assine et al. 2014), consists of the Brejo Santo and Missão Velha formations, which include shales, mudstones, and locally conglomeratic sandstones interpreted as alluvial and lacustrine sedimentary systems (Ponte and Appi 1990; Assine 1992, 2007; Fambrini et al. 2011, 2013). Furthermore, the Rift super sequence is characterized by the facies of the Abaiara Formation, which was formed in shallow lakes and braided channel fluvial plains associated with the rifting of Gondwana in the Early Cretaceous (Assine 1992, 2007).

The Santana Group indicates the beginning of the Aptian Post-Rift I super sequence (Assine 2007; Assine et al. 2014), and consists of the Rio da Batateira, Crato, Ipubi, and Romualdo formations that encompass the Brazilian Alagoas local stage. The Rio da Batateira Formation (also called Barbalha Formation by Assine et al., 2014) presents sandstones, micro conglomerates, siltstones, carbonates, and bituminous shales of fluvial-lacustrine and deltaic origin (Chagas et al., 2007; Paula-Freitas et al. 2007; Paula Freitas and Borghi 2011). The multiproxy approach elaborated by Varejão et al. (2021a) includes sedimentological, paleontological, ichnological, and chemo-stratigraphic analyses through the upper portion of the Rio da Batateira Formation, the entire Crato Formation, and the lower portion of the Ipubi Formation. These authors recorded the first marine influence in the Araripe Basin through the uppermost portion of the Rio da Batateira Formation (also referred to as Barbalha Formation), in which syn-rift fluvial channels, and overbank deposits with sedimentary transport from north-west to south-east, were bounded upward by bayhead deltas, commonly developed in the innermost part of bays and estuaries in transgressive coastlines. The Fundão Member (Rios-Netto et al. 2012), comprises a very fossiliferous horizon in the Rio da Batateira Formation, in which algal laminations, coprolites (possibly from fish), ostracods, conchostracans, fish, amber, plant fragments, and dinosaur tracks (sauropods and theropods) are recorded (Hashimoto et al. 1987; Rios-Netto et al. 2012; Carvalho et al. 2021a).

During the deposition of the Crato Formation, there is a wide variety of continental and transitional environments, also with records of marine incursions (Neumann and Cabrera 2002a, b; Varejão et al. 2021a; Ribeiro et al. 2021). Within the lacustrine hypersaline succession (Varejão et al. 2021a), there are abundant and diverse exquisite preserved fossils that give the Lagerstätte status for the unit (Martill 2007; Selden and Nudds 2012). The Crato Biota, as referred by Dias et al. (2022), is characterized by fungi, plants, arthropods, fish, frogs, lizards, turtles, pterosaurs, non-avian dinosaurs, and birds living in a wetland-type ecosystem influenced by climatic oscillations between wetter and drier periods (Ribeiro et al. 2021). The marine influence in the Crato Formation is attested by tide-dominated bay facies, and confined bay with typical facies deposited in foreshore to upper shoreface conditions with storm deposits (hummocky cross-stratified sandstones). The maximum flooding surface is a dark shale below these foreshore-to-shoreface facies, marking the beginning of the Highstand Systems Tract that culminates with the deposition of the evaporites from the Ipubi Formation (Varejão et al. 2021a). The presence of micro foraminiferal linings in the transition between the Crato and Ipubi formations suggests that these evaporites from the Ipubi Formation may have been putatively precipitated by the evaporation of marine waters (Goldberg et al. 2019).

Although there is the influence of marine environments in other facies association (Varejão et al. 2021a, b) the dinosaur footprints of the Aptian in the Araripe Basin occur in floodplain areas of meandering rivers and low-energy lake deposits, without evidence of a marine influence. In the Rio da Batateira Formation, the tracks occur in fluvial siliciclastic successions (Carvalho et al. 2019a, b, 2021a). In the Crato Formation, however, the footprints are restricted to the locality of Três Irmãos mine in the carbonate deposits formed in hypersaline alkaline lakes and microbial-induced(Carvalho et al. 2021a).

The Aptian in the Araripe Basin also includes the Ipubi and Romualdo formations (Assine et al. 2014). In diastemic contact with the Crato Formation, the Ipubi Formation includes evaporite intercalations (gypsum and anhydrite) and green and/or pyrobituminous shales. They were deposited in a shallow and saline coastal environment, under a warmer climate with precipitation from brines (Assine et al. 2014; Bobco et al. 2017). The Alagoas local stage sedimentation of the Araripe Basin ends with the lagoonal and marine deposits of the Romualdo Formation, consisting of conglomerates, sandstones, marls, shales, and limestones. This unit also preserves an abundant and diverse biota, including foraminifera, palynomorphs, corals, mollusks, arthropods, echinoids, fishes, turtles, crocodyliforms, pterosaurs, dinosaurs, and plants (Abreu et al. 2020; Araripe et al. 2021; Lopes and Barreto 2021; Dias et al. 2022; Santana et al. 2022).

The Cretaceous sedimentation of the Araripe Basin finishes during the late Albian to early Cenomanian. This is recorded by the deposits of the Araripe Group, constituted by the Araripina and Exu formations (Assine 1992, 2007). The Araripina Formation are cyclic distal plain deposits of alluvial fan systems, while the Exu Formation is essentially fine-grained quartz sandstones with siltstones and occasional mudstones deposited in a fluvial environment (Assine 2007; Carvalho et al. 2021b, 2022). The dinosaur footprints are recorded in the fluvial floodplains and sand sheets of the Exu Formation, during episodes of hot climate (Carvalho et al. 2021b, 2022).

6.3 Footprints: Diversity and Paleobiological Interpretation

Although dinosaur tracks are commonly found in the surrounding basins of Sousa, Uiraúna-Brejo das Freiras, Malhada Vermelha, and Lima Campos, they are still rare in the Araripe Basin (Leonardi 1994; Leonardi and Spezzamonte 1994; Carvalho 2000; Carvalho et al. 2021a, b, 2022, 2023). The footprints from the Araripe Basin are found in four stratigraphic units: Mauriti, Rio da Batateira, Crato, and Exu formations, which were deposited in very distinct temporal, paleogeographical, and environmental contexts.

In the Mauriti Formation, the Milagres ichnosite (Fig. 6.3) presents theropod and ornithopod tracks. The theropod tracks are three isolated footprints (ARMI 01, ARMI 02, ARMI 04) and a short trackway with three footprints (ARMI 05). All of them are tridactyl, mesaxonic, with pointed digits, some of them with claw impressions. The rear borders of the footprints are V-shaped or angular (Fig. 6.4). The sandstone filling of the footprints is similar to the surrounding matrix. The footprints are large, ranging from 28–40 cm in length and 20–30 cm in width (Carvalho et al. 1995). The probable trackmakers are large theropods related to the groups that are already known in the Cretaceous deposits of the basin, such as the Spinosauridae *Angaturama limai* or *Irritator challengeri* (Kellner and Campos 1996; Martill et al. 1996). However, the footprints from Milagres ichnosite are certainly older than the Aptian-Albian age of these fossils. There is also an isolated footprint related to an ornithopod (ARMI 03). It is a tridactyl and mesaxonic footprint with rounded extremities of the three digits and wide concave hypexes (Fig. 6.3b). The digits II and IV are 5 cm in length and digit III is longer showing 10 cm in length. The footprint is 20 cm in width and its length is also 20 cm. The rear portion of the footprint shows an extrusion rim, with a rounded and wide crescent shape. Its color is more reddish than the surrounding matrix. The absence of claws, the wide concave hypexes, and the wide width allowed its interpretation as an ornithopod footprint (Carvalho et al. 1995). Osteological elements of this group are unknown in the Araripe Basin, although tracks are found in the surrounding Rio do Peixe basins.

The Mauriti ichnosite (Fig. 6.5), Maurity county, presents at least seven isolated footprints. There are four tridactyl, mesaxonic footprints with pointed (?theropod) and rounded digits (?ornithopod). The other imprints are rounded depressions with no clear digit impressions. The partial sandstone filling of the footprints is similar to the surrounding matrix. They range from 30–48 cm in length and 25–48 cm in width. The trackmakers of the theropod footprints could be the large theropods related to those already known in the Araripe Basin's Cretaceous formations (Carvalho et al. 2023).

The Rio da Batateira Formation tracks (Aptian) are observed as cross-section casts (Figs. 6.6 and 6.7). They are three-dimensional casts in cross-section, as pillar-like morphologies, small- and large-sized concave-up and sub-cylindrical structures. They allow examination of the deformation of the underlying layers and also how the footprints were filled by the sediments deposited afterward. The casts may also be presented as amorphous bulges or sedimentary layers deformed and downfolded, reaching one meter below the depositional surface.

The dinosaur tracks of the Rio da Batateira ichnosite (Fig. 6.6a) can seem to be simple load casts; however, they are interpreted as dinosaur trampling, and more in detail an association of distinct groups of dinosaurs. These load structures, interpreted as dinosaur footprints, measure 15–120 cm in length and 20–100 cm in depth, in fine-grained siliciclastic beds, such as shales, siltstones, and fine sandstones. The depth penetration, which can reach 100 cm, probably is due to the higher plasticity of the substrate, similar to some sauropod tracks from the Upper Jurassic of Spain

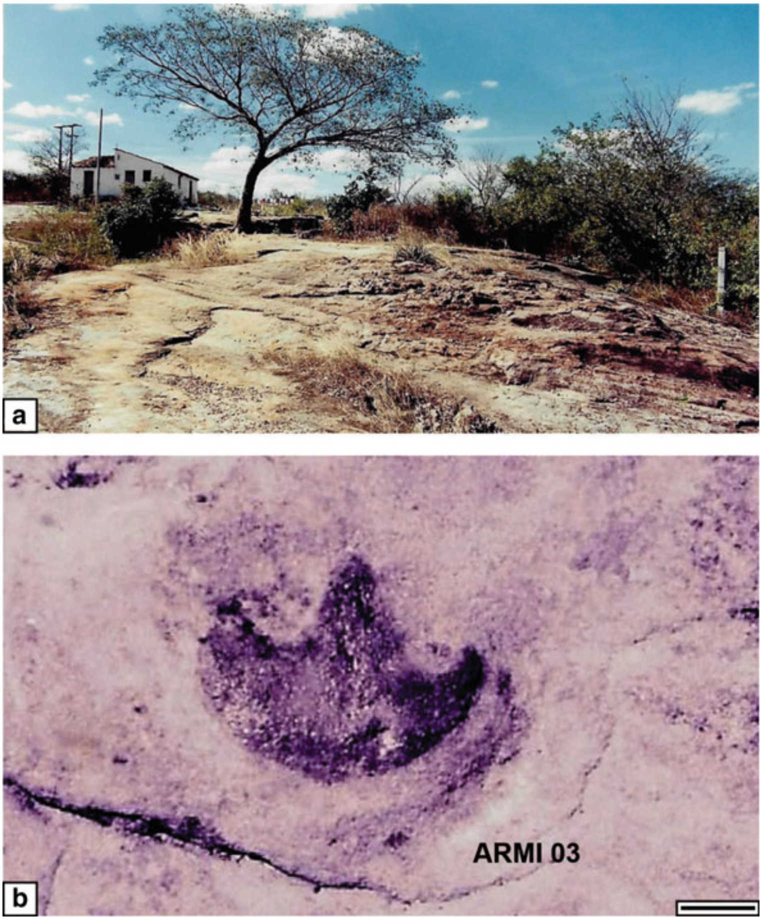


Fig. 6.3 Milagres ichnosite, in the Milagres ranch. **a** Outcrop of the Mauriti Formation, where the dinosaur tracks are found. **b** An isolated ornithopod footprint (ARMI 03) showing a contrasting color with the surrounding matrix. Scale bar: 5 cm

(Valenzuela et al. 1988; García-Ramos et al. 2006). In Rio da Batateira ichnosite it is also possible to observe the digit impressions in some of the casts (Fig. 6.6b), enabling their interpretation as belonging to bipedal or quadruped dinosaurs (Fig. 6.6b–e). The largest footprints are produced in an exposed waterlogged substrate or in a flooded area, where was possible the liquefaction of the sediments of sauropod trackmakers (Fig. 6.7). The smaller ones present a “V-shaped” cross-section with the evidence of a more prominent digit that exerts a higher pressure on the substrate, conducting a greater deformation in the central area of the cast. It probably corresponds to digit III of small theropods, like *Mirischia asymmetrica* or *Santanaraptor placidus* (Naish et al. 2004; Kellner 1999) or some small ornithopod. The interpretation of these tracks indicates the presence of quadrupedal (probably sauropod) and bipedal

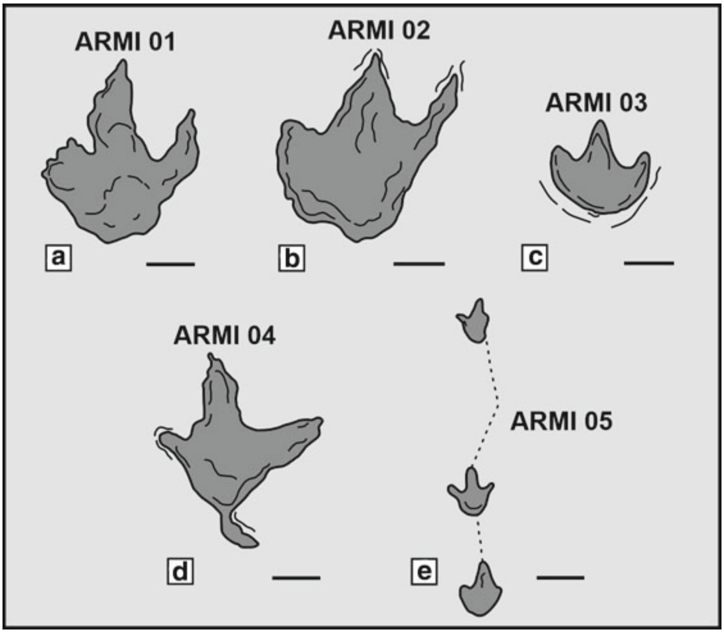


Fig. 6.4 Footprints from the Mauriti Formation, Milagres ichnosite. **a**, **b**, **d** Isolated theropod footprints (ARMI 01, ARMI 02, ARMI 04) with sharp pointed digits; **c** Ornithopod isolated footprint (ARMI 03); **e** Short track (ARMI 05) with three sequencial tridactyl footprints interpreted as a theropod trackway. ARMI—Araripe Basin, Milagres ichnosite. Scale bars: **a**–**d** 10 cm; **e** 30 cm

(theropod and ornithopod) dinosaurs (Carvalho et al. 2019a, b, 2021a). These tracks are an important tool for the reconstruction of the terrestrial Cretaceous ecosystem in the context of the Araripe Basin. It is noteworthy that no sauropod body fossils were so far found either in this or other lithostratigraphic units of the Araripe Basin (Carvalho et al. 2019b).

In the Crato Formation (Nova Olinda County, Ceará State), in the Três Irmãos ichnosite, the dinosaur tracks are found in fine-grained sandstones, intercalated with shales and laminated carbonates (Fig. 6.8). They range from 35 to 100 cm in length and 30–50 cm in depth. The pressure that occurred during the contact of dinosaur feet and the substrate led to the deformation of the upper surface of the sediments, with the origin of load structures accompanying a concave aspect with successive lamina deformation. Tracks may occur as isolated or superimposed casts in cross-section, as pillar-like or concave-up morphologies, but casts are more commonly irregularly cylindrical to "U" shaped (with a larger basal diameter than at the top, as usually occurs with undertracks). Undulating forms that grade into load casts may be recognized as tracks when they occur along the same bedding plane adjacent to recognizable tracks, and when they have relief and dimensions similar to those of associated distinct tracks. The substrate should be soft and moist, with a relatively high cohesiveness (Carvalho et al. 2018) allowing for the deformation of successive

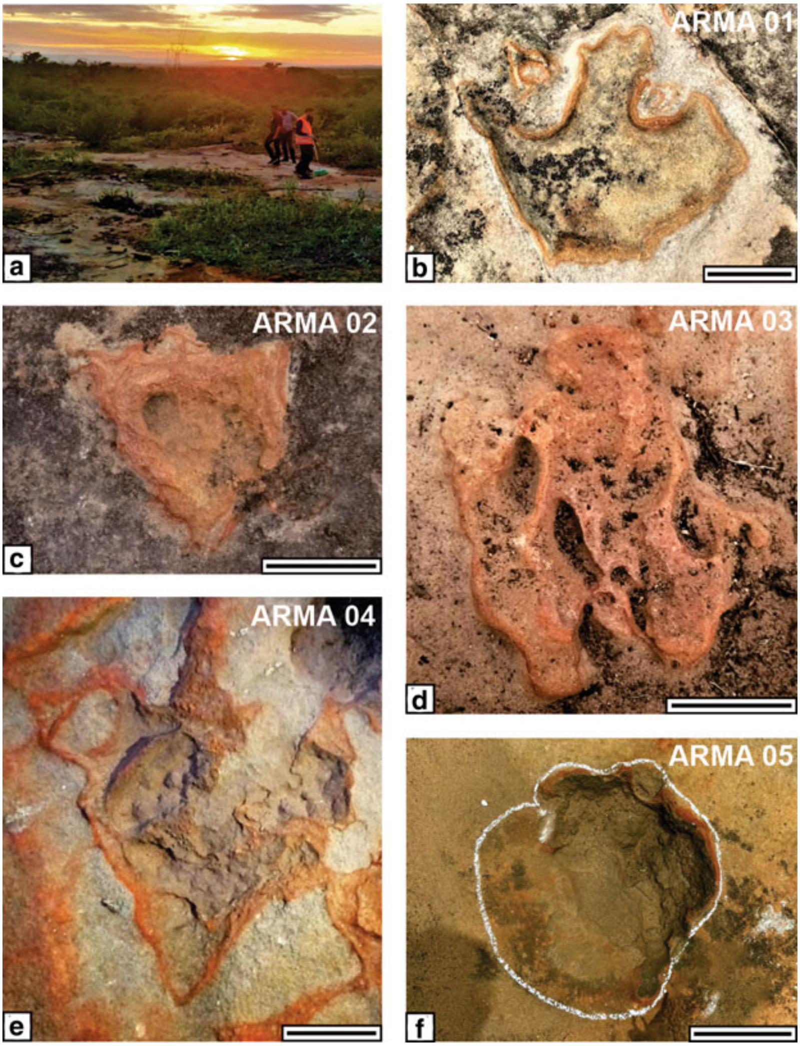


Fig. 6.5 Footprints from the Mauriti Formation, Mauriti ichnosite. **a** Outcrop of the Mauriti Formation with the dinosaur footprints; **b**–**e** Isolated footprints of small and large theropods (ARMA 01, ARMA 02, ARMA 03, ARMA 04). ARMA—Araripe Basin, Mauriti ichnosite. Scale bars: **b**–**e** 10 cm; **f** 20 cm

layers and developing undertracks. The dinoturbation index was defined as the degree of dinosaur trampling (Lockley and Conrad 1989) and its intensity over a surface (light: 0–33%, moderate: 34–66%, and heavy: 67–100%). In the Rio da Batateira Formation, the dinoturbation index can be considered heavy, while in the Crato Formation, it is light (Carvalho et al. 2021a).

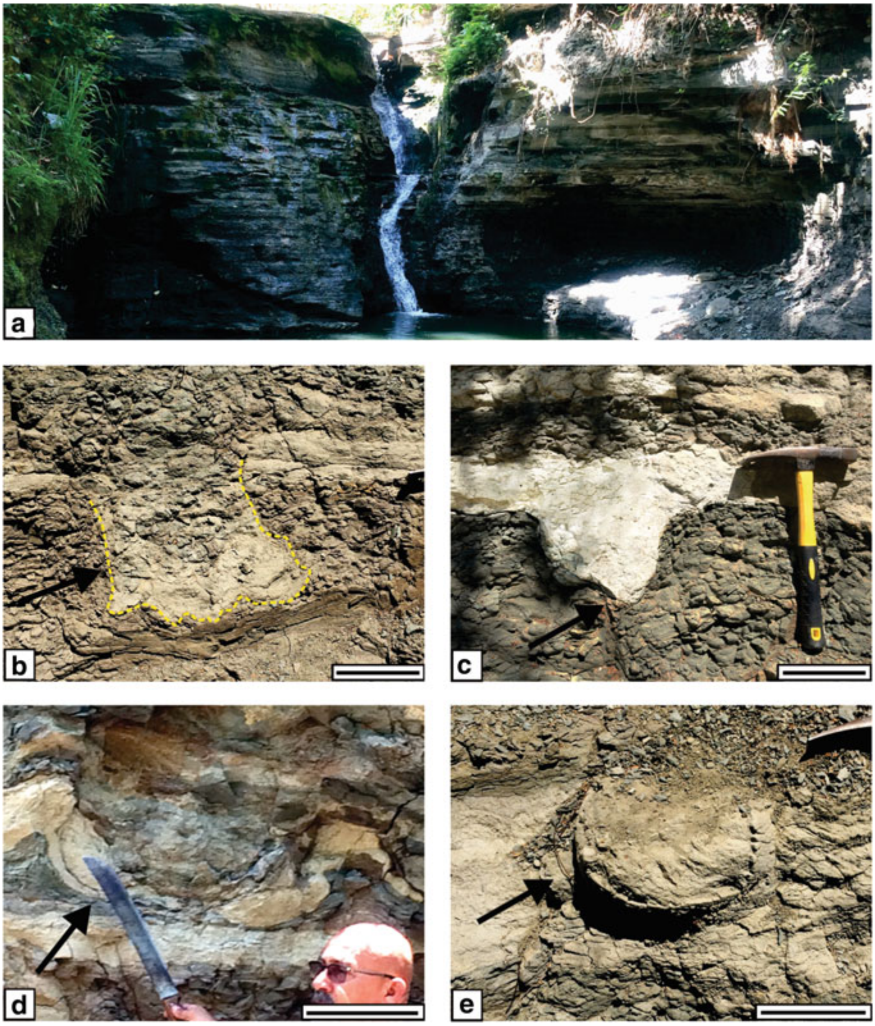


Fig. 6.6 Footprints from the Rio da Batateira Formation, Rio da Batateira ichnosite. **a** Riacho da Batateira outcrop, Cascatinha locality where are found the cross-section footprints; **b** Section of a track cast with the digit imprints in the lower portion, indicating a probable sauropod track. Dashed line indicates the limits of the foot contact with the sediment, the original surface stepped on; **c** Digit III (indicated by an arrow) exerts a higher pressure on the substrate, conducting to a greater deformation in the central area of the cast, feature common in theropod footprints; **d** A large flattened depression, bordered by displacement rims (high declivity borders) interpreted as a footprint of a quadrupedal dinosaur, probably a sauropod; E. Cross-section of a small footprint with a rounded outline, showing the distinct patterns of deformation of the substrate by the dinosaur trampling. Scale bars: **b** 15 cm; **c** 10 cm; **d** 20 cm; **e** 10 cm

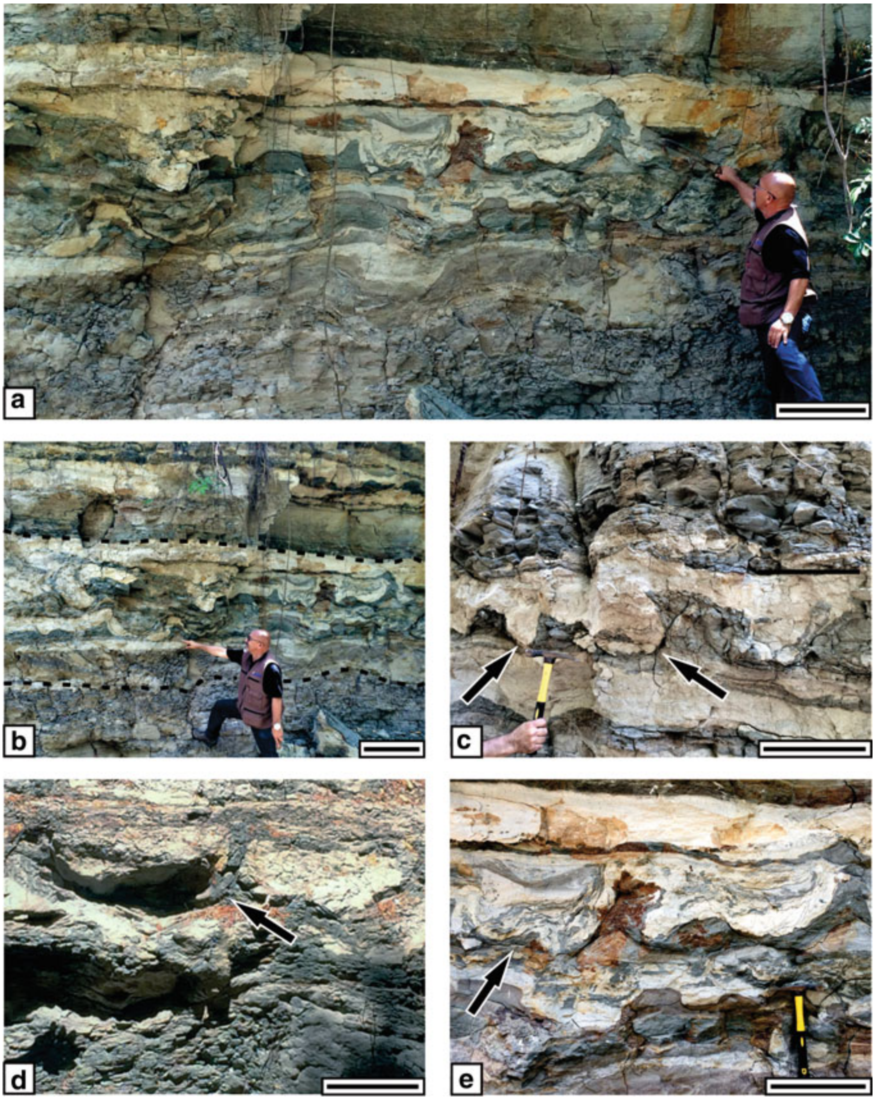


Fig. 6.7 Footprints from the Rio da Batateira Formation, Rio da Batateira ichnosite. **a** Outcrop with dinoturbation structures in the margins of Riacho da Batateira. **b** Disturbed layers resulted from the vertebrate trampling; **c** The cross-section through dinosaur tracks displays large structural and dimension variations indicated by arrows; **d** The high-water content induces the deformation by the foot impact up to one meter below the surface; **e** High deformation of the substrate including fluidization (indicated by an arrow) induced by the dinosaur trampling. Scale bars: 30 cm

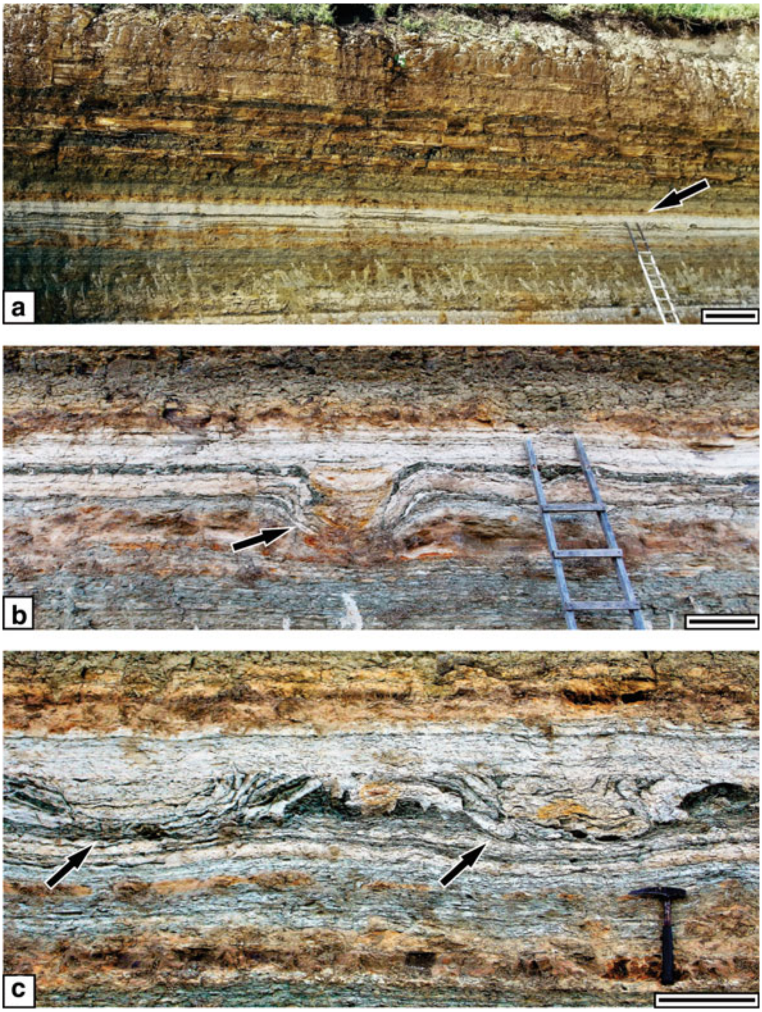


Fig. 6.8 Footprints from the Crato Formation, Três Irmãos ichnosite. **a** Outcrop of Crato Formation, Três Irmãos Quarry, showing the succession of laminated carbonates and the level with cross-section tracks; **b** A cast of the true track with surrounding strongly bent and downfolded layers indicate a deformation due to a foot impact of a sauropod or a large quadrupedal dinosaur; **c** Concave deformations induced by the foot load pression. The cross-section footprints are eroded in its upper surface before the following deposition of fine sandstones. Arrows indicate the position of the footprints. Scale bars: **a** 1 m; **b**–**c** 30 cm

Marty (2011) and Marty et al. (2006) indicated that, after the foot impact, some structures are apparent on the surface (true track, overall track, underprint) and others are hidden within the substrate (undertrack, deep track). The types of deformation indicate that theropods adopted many walking strategies at different times, resulting in the formation of a stacked succession of undertracks that gradually becomes wider, shallower, and less detailed downward (Milàn et al. 2006). The deformation structures in a vertical section allow obtaining additional details about the walking kinematics that rarely could be available from the true track at the surface (Milàn and Bromley 2006), usefulness for the correct interpretation of the trackmaker and the substrate consistency (Milàn et al. 2004, 2006). Laboratory track simulations presented by Manning (2008) enabled the analysis of the magnitude and distribution of load acting on surface sediments, transmitting through and deforming subsequent layers. This aspect is clear in the tracks at the Rio da Batateira and Crato formations, due to the deformation produced in the lower sedimentary levels after the footprint impact (Carvalho et al. 2021a).

The Exu Formation footprints (Barbalha County, Ceará State), Barbalha ichnosite, are about 20 cm in height and 30 cm wide (Fig. 6.9). They are evident on a vertical cross-section of a sandstone bed as concave-up deformations of the lamina-set. Digit impressions or other morphological features of the footprints are not preserved (Carvalho et al. 2021b, 2022). Therefore, the geometry and dimensions of these structures allow us to interpret them as similar to dinoturbation structures produced by sauropods. These dinosaur footprints enhance the understanding of the genetic interpretation of deformational structures and paleoenvironmental scenarios of the Late Cretaceous from Northeastern Brazil.

6.4 Paleogeographical Distribution of the Footprints

The dinosaur footprints of the Araripe Basin are recorded in three unquestionably Cretaceous lithostratigraphic units (Rio da Batateira, Crato, and Exu formations), and one with controversial age but adopted as Jurassic-Cretaceous based on its dinosaur tracks (Mauriti Formation). Thus, the paleogeographic context during the Late Jurassic and Early Cretaceous of the Araripe Basin is linked to the rifting process of the Gondwana supercontinent, with distinct tectonic evolution during the pre-rift, rift, and post-rift phases, which influenced the pattern of biota dispersal and speciation processes.

The Mauriti Formation footprints of the Milagres and Mauriti ichnosites (Carvalho et al. 1994, 1995, 2023, 2024) present a temporal inconsistency, as the Mauriti Formation is frequently considered part of an Early Paleozoic depositional cycle (Ponte and Appi 1990; Assine 1992, 2007; Cerri et al. 2022). The NW paleoflow indicates that the main source areas for the Mauriti fluvial system are located in the Transversal and Southern zones of the Borborema Province (Cerri et al. 2022). Meanwhile, the presence of dinosaur footprints in the Mauriti Formation suggests that it is certainly a Mesozoic unit (Carvalho et al. 1995, 2023). Due to the geographical proximity with

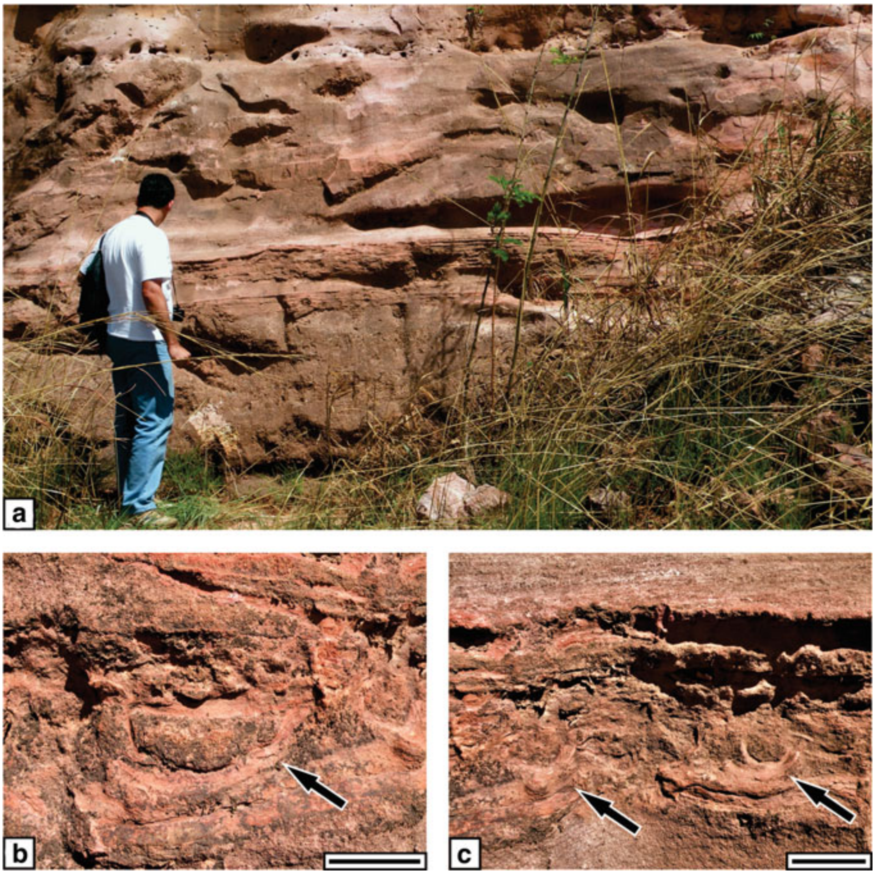


Fig. 6.9 The Cenomanian Exu Formation and its footprints, Barbalha ichnosite. The Exu Formation is the last Cretaceous sedimentation cycle in the Araripe Basin, composed of coarse to fine-grained reddish sandstones. **a** Outcrop of the Exu Formation with a succession of channel cross-stratification and laminated bimodal sandstones; **b** Concave-up deformation of the lamina-set, 20 cm height and 30 cm wide, observed on a vertical cross-section. Digit impressions or other morphological features of the footprints are not preserved; **c** Deformations as concave-up features interpreted as dinoturbation structures observed in cross-section. Arrows indicate the position of the footprints. Scale bars: **c** 20 cm; d 30 cm

Rio do Peixe basins, that present similar dinosaur tracks, probably Early Cretaceous age is suggested (Carvalho et al. 2023, 2024). The importance of these two ichnosites confirms the need to revise the age of the Mauriti Formation and the paleogeographical context of these footprints, establishing a new stratigraphic framework for the lower successions of the Araripe Basin (Carvalho et al. 2023, 2024). If the Jurassic-Cretaceous age was confirmed, the paleogeography of the Mauriti Formation would not be related to the Western Paleozoic Gondwana, as indicated by Cerri et al. (2022), but with the Mesozoic Gondwana supercontinent evolution during the Jurassic and Cretaceous, as the others lithostratigraphic units of the Araripe Basin.

The break up between the South American and African continents occurred predominantly due to east-west divergent tectonic, during the Jurassic. The rupture began in the southern part of Gondwana and progressively extended northward throughout the Early Cretaceous, shaping itself along pre-existing weakness zones (Françolin and Szatmari 1987). Valuable paleobiogeographic data from Maisey (2011) show that in the pre-rift stage, there were no individual depocenters in the Brazilian sedimentary basins, resulting in low diversity of the Gondwanan biota at the genus and species levels. In Western Gondwana, Brazil and West Africa was a single continuous landmass, sometimes referred to as the Afro-Brazilian Depression, allowing for extensive taxa dispersion. This distinct pre-rift biota is Gondwanan, with a Pangaean origin, and various groups of vertebrates such as mawsoniid coelacanths, notosuchian crocodiles, and dinosaurs, diversified within Gondwana before the breakup (Maisey 2011). Within this context, the dinosaur footprints of the Mauriti Formation are included, and the large theropods and an ornithopod as probable trackmakers, would be in this terrestrial scenario of a single continuous continental mass before the rifting process of the Gondwana.

The Brazilian Alagoas local stage is associated with the breakup of the Gondwana supercontinent in the Mesozoic. This interval has special importance to the correlation of sub-aerial exposition surfaces throughout the basin. The Aptian dinosaur tracks from the Araripe Basin occur in the Rio da Batateira Formation (Fundão Member) and Crato Formation, in the Ceará State. They can be observed only in cross-section, as three-dimensional natural structures in siliciclastic and carbonate successions.

During the Gondwana breakup, rift valleys were formed and subsequently flooded by epicontinental seas during the Aptian, which separated Northeast Brazil from the rest of South America, but remained contiguous with Africa (Maisey 2011). The Aptian epicontinental seas were formed before the complete detachment process of South America and Africa. As a result, these marine incursions do not necessarily correspond to tectonic boundaries of rifting but rather represent distinct biogeographic provinces created through intracontinental vicariance processes due to land separations caused by the marine incursions (Maisey 2011). Within this context, the biotas of the Aptian formations in the Araripe Basin are included, such as Rio da Batateira and Crato, which feature small theropods and sauropods as possible trackmakers.

Taxonomic studies of ostracod fossils from the Rio da Batateira Formation were a subsidy for the understanding of the beginning of the opening of the South Atlantic Ocean during the Aptian in the Araripe Basin (Santos Filho et al. 2023). The ostracod assemblage from the Santo Antônio section presents nine typically brackish-marine species, associated with the first marine ingression in the interior of the continent during the beginning of the formation of the Atlantic Ocean (Tomé et al. 2022). Fauth et al. (2023) present three marine incursion events in the Batateiras unit (two of them in the Fundão Member), defined by benthonic and planktonic foraminifera, calcareous nannofossils, dinocysts, serpulid tubes, and a mass mortality event of mixohaline ostracods. The integration of paleontological, sedimentological, and ichnological data by Varejão et al. (2021a) also indicates the deposition under marine influence in the upper portion of the Rio da Batateira Formation. The stratigraphic architecture and paleocurrents data suggest that marine waters reached the basin from the south, with marine ingressions of an incipient South Atlantic Ocean over the interior basins of northeastern Brazil (Varejão et al. 2021a). Other sedimentary and stratigraphic studies of the Aptian in the Araripe Basin point to a more complex scenario, with distinct marine pulses from different directions (Custódio et al. 2017; Bom et al. 2021). However, the Tethyan origin of a wide variety of vertebrates, invertebrates, and microfossils groups recorded in the Araripe Basin and other chrono-related basins of Northeast Brazil suggest marine ingressions from North to South (Arai 2014; Pereira et al. 2017; Araripe et al. 2021; Lindoso and Carvalho 2021; Kroth et al. 2021).

Although the dinosaur footprints are still not recorded in the Aptian Romualdo Formation of the Araripe Basin, the unit contains five species of theropod dinosaurs (see Kellner and Campos 1996; Martill et al. 1996, 2000; Kellner 1999; Aureliano et al. 2018; Sayão et al. 2020) and one possible Ornithischia (Leonardi and Borgomanero 1981), later considered as a theropod bone (Batista and Kellner 2007). The Romualdo Formation records the last marine ingression within the Cretaceous interior basins of Northeastern Brazil, with, at least, two distinct pulses of marine incursions associated with the formation of a proto-Atlantic Ocean (Assine et al. 2014; Custódio et al. 2017; Teixeira et al. 2017; Fürsich et al. 2019; Bom et al. 2021; Kroth et al. 2021). The marine ingressions that reached the Araripe Basin during the late Aptian formed a vast epicontinental sea in Northeast Brazil, with an area much larger than the current Araripe Basin (Arai, 2014). These interior seas are characterized by water masses that rest directly on the continental crust and are commonly formed by short-term variations in sea level, resulting in abrupt fluctuations in water salinity, temperature, and oxygenation (Kroth et al. 2021) recorded in the Rio da Batateira, Crato, Ipubi, and Romualdo formations.

While the sedimentary succession of the Santana Group represents a transgressive–regressive cycle associated with sea-level variations during the Aptian, the sedimentary deposits of the Araripe Group (which includes the Araripina and Exu Formations) indicate a differentiated tectonic uplift during the late Albian and early Cenomanian (Assine 2007). During the Cenomanian, there was the establishment of oceanic crust with the separation of the South American and African continents (Maisey 2011). The last record of dinosaur footprints in the Araripe Basin occurs in the Exu Formation, a Cenomanian fluvial succession (Carvalho et al. 2021b, 2022) that represents the return to the strictly continental conditions in the Araripe Basin, not being directly related to the marine influence of the opening of the South Atlantic Ocean.

6.5 Paleoenvironmental and Paleoclimatic Contexts

6.5.1 Mauriti Formation

The paleoenvironmental interpretation of the deposits where the Mauriti Formation footprints are found is coalescent alluvial fans and a braided fluvial system with high energy (Fig. 6.10), formed in a hot and more arid climatic context (Ponte and Appi 1990; Carvalho et al. 1995; Batista et al. 2012; Carvalho et al 2024). The few isolated footprints and trackways in the Milagres and Mauriti ichnosites of the Mauriti Formation may reflect the time between periods of sediment accumulation and the nature of the substrate. It is possible that the high energy of the environment contexts, grain size, low water content, and lack of sediment plasticity did not allow the preservation of a large number of footprints, indicating a potential preservation bias (Carvalho et al. 1995, 2023, 2024).

6.5.2 The Aptian Rio da Batateira and Crato formations

The Aptian records of dinosaur tracks in the Araripe Basin occurred in a moment of environmental changes of transitional siliciclastic to carbonate environments related to the deposition in an endorheic lake, also during a hot and arid climate. As demonstrated by Moratalla et al. (1995) Avanzini et al. (2000), Leonardi and Mietto (2000), Marty (2008), Santos et al. (2013), and Campos-Soto et al. (2017), carbonate environments are important for the preservation of fossil tracks.

The Rio da Batateira sequence is interpreted as fluvial and clastic lake shore environments, including floodplain areas of meandering rivers and low-energy lacustrine environments. The stratigraphic data interpretation shows that the interval was subject to tectonic control (Paula Freitas 2010; Rios-Netto and Regali 2007; Rios-Netto et al. 2012). The low-energy lacustrine paleoenvironment was subjected to water level fluctuations and anoxic events (Assine et al. 2014). Although Varejão et al. (2021a) recorded a bayhead delta facies association deposited under a marine influence in the upper portion of the Rio da Batateira Formation, the dinosaur footprints recorded in this unit occur in fine sandstones and shale successions associated with floodplain areas of meandering rivers and low-energy lakes, without evidence of a marine influence (Fig. 6.11).

The footprints of the Rio da Batateira Formation were produced in an exposed waterlogged substrate or in a flooded area, where the sediments' liquefaction was possible. The evaluation of these tracks and their relationship with the substrate, allow the understanding of the deformation due to a foot impact, and the construction of a model for the cross-section track formation. They also show behavioral insights into the trackmaker biology, substrate properties, interaction among the producer, and environmental factors (Carvalho et al. 2019b; 2021a, b). The preservation of these dinosaur footprints is enhanced by specific environmental and more arid climatic

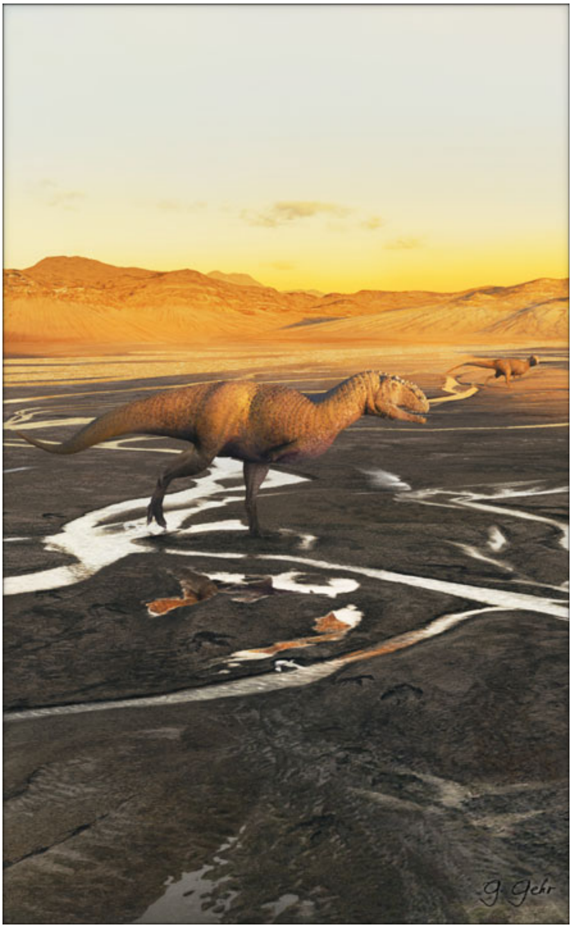


Fig. 6.10 Reconstruction of the environmental scenery of the Mauriti Formation and the dinosaur trackmakers. Exposed channel bars of braided rivers in a context of arid climate allowed the preservation of theropod and ornithopod footprints (Art by Guilherme Gehr)

conditions, which may have a biogenic component associated. Rapid and significant sedimentation with the track coating favors the preservation, thus, footprints are most commonly preserved in environments with cyclic sedimentation (Carvalho et al. 2021a), including water-level fluctuations, as described for the Rio da Batateira Formation depositional environments.

A key point for the final preservation of fossil vertebrate tracks in laminated sediments has been explained by the biostabilization process of the sediment surface by microbial mats (Carvalho et al. 2013). In the Lower Cretaceous Rio do Peixe Group in the Sousa Basin, also in the northeast of Brazil, microbial mats developed in the temporary and shallow lacustrine environments, during warm climate conditions. According to Carvalho et al. (2013), the footprint consolidation and its early lithification probably occurred due to the presence of microbial mats, which provided a more cohesive substrate, preventing the footprints from being eroded. The sediments were initially biostabilized by early cementation and the covering of the

Fig. 6.11 Reconstruction of the environmental scenery of the Rio da Batateira Formation and the dinosaur trackmakers. Trampling by dinosaurs in a floodplain area of meandering rivers and lacustrine environments induced the deformation of the substrate. The climate was hot and more humid as observed through the palynological assemblages (Art by Guilherme Gehr)

microbial mats over the footprints. Subsequent successive floods and the influx of sediments allowed the preservation of a large number of layers with dinosaur footprints. This same mechanism was discussed for the invertebrate trace fossil preservation in the Sousa Basin by Carvalho et al. (2017), giving light to the biostabilization process by microbial mats as one of the main responsible factors for the ichnofossils preservation. In this case, petrographic analysis showed microbially induced sedimentary structures (MISS), such as small pits, bumps, and crinkles, associated with microbiolaminations and dispersed microbial filaments (Carvalho et al. 2017).

Drawing a parallel with the similar proposed paleoenvironment for the Early Cretaceous Rio da Batateira Formation, it is plausible that these microbes also could have influenced the dinosaur footprints' preservation. So far, there are records of algal laminations in the bituminous shales of the Fundão Member, established by Rios-Netto et al. (2012). In the 3-D casts of the Rio da Batateira dinosaur tracks, there is a section that shows evidence of digits, indicating the high plasticity of the substrate where the track was produced (Carvalho et al. 2021a). This ductility of the substrate may have been provided by the extracellular polymeric substance (EPS) secreted by the microbial mats, which gives a plastic nature to the sedimentary substrate through mucilage production. The presence of these microbial communities could be enhanced by the drier climatic context and the oscillatory character of the environment. A possible future perspective of paleoichnological studies in Brazil is the investigation of the microbial role in the fossilization of the Rio da Batateira dinosaur tracks, in the same way as described for the dinosaur tracks and invertebrate ichnofossils of the Sousa Basin.

During the Aptian, alkaline lakes were one of the main depositional environments in the Araripe Basin, representing the Lagerstätte succession of the Crato Formation. Although there are records of marine facies association (Varejão et al. 2021a, b) the dinosaur footprints of the Crato Formation are recognized in deposits from the margins of alkaline and hypersaline lakes, where other exceptionally preserved fossils (Fig. 6.12) of vertebrates, invertebrates, plants, and even fungi are also found (Martill et al. 2007; Carvalho et al. 2021a; Dias et al. 2022, 2023). The tracks of the Crato Formation occur in the Três Irmãos Quarry, Nova Olinda County, which is mainly composed of micritic limestone, with levels of marls and fine-grained siliciclastic beds (Neumann and Cabrera 2002a, b). This Lagerstätte succession of the Crato Formation represents a hypersaline lacustrine environment based on the presence of evaporitic features (halite hoppers, gypsum beds, and isolated gypsum crystals), predominant terrestrial fossil fauna and flora content, absence of bioturbation, and presence of several structures that points to the microbial nature of the carbonates, such as peloids, amorphous organic matter, coccoid and filamentous cells embedded in EPS, and horizons of microbialites (Heimhofer et al. 2010; Catto et al. 2016; Warren et al. 2017; Varejão et al., 2019). The vertical passage from the underlying ephemeral lake and river-dominated delta facies association to the overlying hypersaline lacustrine deposits indicates an increase in the dry condition (Varejão et al. 2021a).

In shallow, perennial, and closed lacustrine water bodies, as proposed for the Lagerstätte succession of the Crato Formation, the register of climate oscillations is expected. These climatic variations have been suggested by Neumann et al. (2003), Osés et al. (2017), Gomes et al. (2021), Guerra-Sommer et al. (2021), and Dias and Carvalho (2022). During drier periods, there is a greater proliferation of microbial mats and carbonate precipitation (Varejão et al. 2019, 2021a; Dias and Carvalho 2020, 2022). In wetter periods, increased productivity in the water column can also generate thick carbonate layers, although without a significant influence of microbial mats on the genesis of these rocks (Heimhofer et al. 2010). Consequently, Dias and Carvalho (2022) and Dias et al. (2023) suggested a possible climate control influencing fossil preservation, which probably affected the record of the dinosaur footprints, both in the Aptian Rio da Batateira and Crato formations.

Distinctly of the Rio da Batateira Formation, the microbial role in the carbonate genesis and fossilization process in the Crato Formation is already been well-discussed (Catto et al. 2016; Osés et al. 2016, 2017; Warren et al. 2017; Varejão et al. 2019; Dias and Carvalho 2020, 2022; Iniesto et al. 2021; Prado et al. 2021;

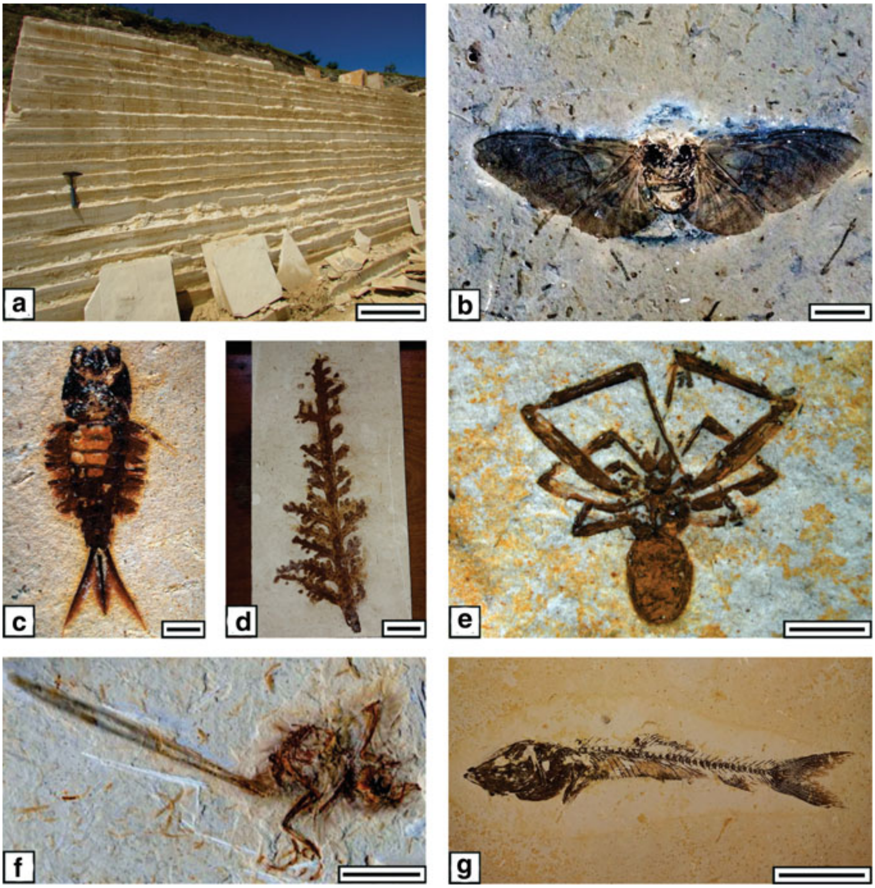


Fig. 6.12 The fossils variety from Crato Formation. **a** Outcrop of fine laminated carbonates where occur the exquisite Aptian fossils, Três Irmãos Quarry; **b** Insect of the Hemiptera order (UFRJ-DG 1163 Ins); **c** Insect larvae of the Ephemeroptera order (UFRJ-DG 441 Ins); **d** *Brachyphyllum obesum* (UFRJ-DG 2424 Pb), a Coniferophyta; **e** Arachnid of the Araneae order (UFRJ-DG 42 Ac); **f** *Cratoavis cearensis* (UFRJ-DG 31 Av), an Enantiornithes; **g** The fish *Dastilbe crandalli* (UFRJ-DG 1898 P). Scale bars: **a** 50 cm; **b** 1 cm; **c** 2 mm; **d** 3 cm; **e** 2 mm; **f** 2 cm; **g** 4 cm

Dias et al. 2023). The high degree of morphological fidelity of fossils has been mainly attributed to the influence of microbial mats in the fossilization process, particularly in the covering and mineralization of organic remains when they reach the lacustrine substrate (Varejão et al. 2019; Dias and Carvalho 2020, 2022; Iniesto et al. 2021; Dias et al. 2023).

The dinosaur footprints of the Crato Formation probably could be included in this fossilization scenario (Fig. 6.13), since this same mechanism of track preservation mediated by the microbial mats has already been described for the Sousa Basin (Carvalho et al. 2013). Just as a microbial mat enhances the chance of preservation by covering the carcass of an organism and creating physicochemical conditions conducive to the mineralization of organic remains (Dias et al. 2023), the coverage of a dinosaur track by the mats could favor exquisite preservation.

In Vermelha Lagoon (Rio de Janeiro State), a hypersaline lagoon from the Quaternary of Brazil, there is extensive development of microbial mats, MISS (microbially induced sedimentary structures), and microbialites. On the margins of this environment, desiccation tracks and wrinkle marks are associated with the preservation of wave marks and already lithified footprints of humans wearing sneakers. on the substrate (Guedes et al. 2022; Dias et al. 2023). During the Early Cretaceous in the Araripe Basin, the preservation of these dinosaur footprints occurs especially in the lacustrine margins, where there is more development of microbial mats, the same way observable for the Vermelha Lagoon. The sealing effect after covering the track, and the microbial sarcophagus created by the microorganisms, are key factors for the

Fig. 6.13 Reconstruction of the environmental scenery of the Crato Formation and the dinosaur trackmakers. The footprints are found in a context of carbonate environments related to the deposition in an endorheic lake, during a hot and arid climate. Episodes of more humid events allowed the increase of life diversity (Art by Guilherme Gehr)

preservation. This biogenic influence is directly correlated with environmental and climatic controls, with fossil preservation associated with shallow and hypersaline lacustrine environments, during more hot and arid contexts.

According to Pérez-Lorente (2015), the bearing capacity in which a foot can sink into sediment occurs when the resistance to penetration of the foot is equal to the pressure applied, directly related to the substrate plasticity and consistency. Falkingham et al. (2011, 2014) discuss different substrate models on track formation potential. As the walls of some of the Crato Formation tracks are vertical, it is interpreted that the original substrate was soft, yet cohesive and competent. The foot could enter deeply, but the sediment stayed together leaving sharp walls. Otherwise, in the Rio da Batateira Formation footprints, the deformation can reach 100 cm depth as the result of the foot impact in a less firm substrate (Carvalho et al. 2021a).

Besides the microbial component in the fossilization, other factors are also important for the dinosaur track preservation in the fossil record. For Carvalho et al. (2021a), the abundance of vertebrate bioturbation depends upon rates of trampling, texture, and plasticity of the substrate, and also the subsequent permanent burial with a low reworking rate. The small grain size, consistency, plasticity, and water content of the sediments are determinants for the preservation of anatomical details.

6.5.3 The Cenomanian Exu Formation

The succession of the Exu Formation is interpreted as channel bars of ephemeral streams and floodplains under a more arid to semiarid climate during the Cenomanian. The sediments in the sand bars of the dry channel streams could be reworked by winds resulting in bimodal sandstone deposits (Carvalho et al. 2021b, 2022). The opening of the South Atlantic Ocean during the Cenomanian and the return to continental conditions in the Araripe Basin at this age were likely accompanied by an increase in aridity and average temperature of terrestrial ecosystems due to the continentalization process.

In the Exu Formation (Barbalha ichnosite), the digit impressions or other morphological features of the footprints are not recognized. Probably, the substrate where the tracks were produced was not as plastic as the substrate with footprints in the Aptian Rio da Batateira and Crato formations. The absence of more delicate features of the Exu footprints could be a preservation bias due to the environmental conditions (Fig. 6.14).

6.6 Conclusions

The dinosaur footprints found in the Araripe Basin are temporal markers of subaerial exposition surfaces throughout the basin, recording cyclical changes in the environments and climate. These footprints vary across four distinct lithostratigraphic units:

Fig. 6.14 Reconstruction of the environmental scenery of the Exu Formation (Cenomanian) and the dinosaur trackmakers. Channel bars of ephemeral streams and sand sheets in floodplains were reworked by the feet load of dinosaurs. The climate during this moment was hot and dry with more humid events (Art by Guilherme Gehr)

Mauriti, Rio da Batateira, Crato, and Exu formations, each associated with different environmental settings. The tracks in the Mauriti Formation are located in alluvial fans and braided river deposits, formed during a hot and arid climate. This environmental context limited the preservation of a larger number of footprints. In contrast, the Aptian dinosaur footprints of the Rio da Batateira and Crato Formations, which developed in fluvial-lacustrine settings under arid conditions, have better-preserved records. This preservation may have been influenced by the presence of microbial mats during the fossilization process. Other studies conducted with arthropod fossils from the Crato Formation highlight the significant role of these microbes in the coverage, sealing, and mineralization of organic remains. Extrapolating this mechanism for preserving dinosaur tracks offers valuable insights for future paleoichnological studies in the Araripe Basin. Finally, the dinoturbations observed in the Cenomanian Exu Formation do not exhibit the features seen in the Aptian record of the same basin. This discrepancy is likely due to preservation biases caused by the more unstable environment, similar to the Mauriti Formation.

References

Abreu D, Viana MSS, Oliveira PV, Viana GF, Borges-Nojosa DM (2020) First record of an amniotic egg from the Romualdo Formation (Lower Cretaceous, Araripe Basin, Brazil). Revista Brasileira de Paleontologia 23(3):185–193

Arai M (2014) Aptian-Albian (Early Cretaceous) paleogeography of the South Atlantic: a paleontological perspective. Braz J Geol 44(2):339–350

Arai M, Assine ML (2020) Chronostratigraphic constraints and paleoenvironmental interpretation of the Romualdo Formation (Santana Group, Araripe Basin, Northeastern Brazil) based on palynology. Cretac Res 116:104610

Araripe RC, Oliveira DHD, Tomé METR, Moura de Mello R, Barreto AMF (2021) Foraminifera and ostracoda from the Lower Cretaceous (Aptian-lower Albian) Romualdo Formation, Araripe Basin Northeast Brazil: Paleoenvironmental Inferences. Cretac Res 122:104766

Assine ML (1992) Análise estratigráfica da Bacia do Araripe, Nordeste do Brasil. Revista Brasileira de Geociências 22(3):289–300

Assine ML (2007) Bacia do Araripe. Boletim de Geociências da Petrobrás 15(2):371–389

Assine ML, Perinotto JAJ, Custódio MA, Neumann VH, Varejão FG, Mescolotti PC (2014) Sequências deposicionais do Andar Alagoas da Bacia do Araripe, Nordeste do Brasil. Boletim de Geociências da Petrobrás 22(1):3–28

Aureliano T, Ghilardi AM, Buck PV, Fabbri M, Samathi A, Delcourt R, Fernandes MA, Sander M (2018) Semi-aquatic adaptations in a spinosaur from the Lower Cretaceous of Brazil. Cretac Res 90:283–295

Avanzini M, Frisia S, Rinaldo M (2000) I Lavini di Marco nel Giurassico inferiore: la riconstruzione di um antico ambiente di vita. In: Leonardi G, Mietto P (eds) Dinosauri in Italia, Accademia Editoriale. Pisa-Roma, p 245–272

Batista EB, Kellner AWA (2007) Reavaliação da suposta ocorrência de Ornithischia na Formação Santana (Cretáceo Inferior), Bacia do Araripe, Nordeste Brasil. Anuário do Instituto de Geociências 30(1):224

Batista ZV, Valença LMM, Fambrini GL, Silva SM, Neumann VHML, Santos CA, Barros CL (2012) Análise de fácies da Formação Cariri, Bacia do Araripe Nordeste do Brasil. Estudos Geológicos 22(1):3–20

Berthou PY (1990) Le bassin d'Araripe et les petits bassins intracontinentaux voisins (N.E. du Brésil): formation et évolution dans le cadre de l'ouverture de l'Atlantique Equatorial. Comparaison avec les bassins ouest-Africains situés dans le même context. In: Simpósio sobre a Bacia do Araripe e Bacias Interiores do Nordeste, 1, Crato, pp 113–134

Beurlen K (1962) A geologia da Chapada do Araripe. An Acad Bras Ciênc 34(3):365–370

Bobco FER, Goldberg K, Bardola T (2017) Modelo deposicional do Membro Ipubi (Bacia do Araripe, Nordeste do Brasil) a partir da caracterização faciológica, petrográfica e isotópica dos evaporitos. Pesquisa em Geociências 44(3):431–451

Bom MHH, Ceolin D, Kochhan KGD, Krahl G, Fauth G, Bergue CT, Savian JF, Strohschoen Junior O, Simões MG, Assine ML (2021) Paleoenvironmental evolution of the Aptian Romualdo formation, Araripe Basin Northeastern Brazil. Glob Planet Chang 203:103528

Brito-Neves BB, Santos EJ, Van Schmus WR (2000) Tectonic history of the Borborema Province, Northeastern Brazil. In: Cordani UG, Milani EJ, Thomaz Filho A, Campos DA (eds) Tectonic evolution of South America, 31 International Geological Congress, p 151–182

Cerri RI, Warren LV, Spencer CJ, Varejão FG, Promenzio P, Luvizotto GL, Assine ML (2022) Using detrital zircon and rutile to constrain sedimentary provenance of Early Paleozoic fluvial systems of the Araripe Basin, Western Gondwana. J S Am Earth Sci 116:103821

Campos-Soto S, Cobos A, Caus E, Benito MI, Fernández-Labrador L, Suarez-Gonzalez P, Quijada IE, Mas R, Royo-Torres R, Alcalá L (2017) Jurassic coastal park: a great diversity of palaeoenvironments for the dinosaurs of the Villar del Arzobispo Formation (Teruel, eastern Spain). Palaeogeogr Palaeoclimatol Palaeoecol 485:154–177. https://doi.org/10.1016/j.palaeo.2017.06.010

Carvalho IS (2000) Geological environments of dinosaur footprints in the intracratonic basins from Northeast Brazil during South Atlantic opening (Early Cretaceous). Cretac Res 21:255–267. https://doi.org/10.1006/cres.1999.0194

Carvalho IS, Viana MSS, Lima Filho MF (1994) Dinossauros do Siluriano: um anacronismo crono-geológico nas bacias interiores do Nordeste? In: 38º Congresso Brasileiro de Geologia, Camboriú, vol 3. Boletim de Resumos Expandidos, Camboriú, Santa Catarina, SBG,pp 213–214

Carvalho IS, Viana MSS, Lima Filho MF (1995) Os icnofósseis de dinossauros da Bacia do Araripe (Cretáceo Inferior, Ceará–Brasil). An Acad Bras Ciênc 67(4):433–442

Carvalho IS, Freitas FI, Neumann V (2012) Chapada do Araripe. In: Hasui Y, Carneiro CD, Almeida FFM, Bartorelli A (eds) Geologia do Brasil. Beca, São Paulo, pp 510–513

Carvalho IS, Borghi L, Leonardi G (2013) Preservation of dinosaur tracks induced by microbial mats in the Sousa Basin (Lower Cretaceous), Brazil. Cretac Res 44:112–121

Carvalho IS, Borghi L, Fernandes ACS (2017) Microbial mediation in invertebrate trace fossil preservation in Sousa Basin (Early Cretaceous), Brazil. Cretac Res 69:136–146

Carvalho IS, Melo BGV, Borghi L, Rios-Netto AM, Andrade JAFG, Freitas FI (2018) Dinosaur tracks from the Aptian (Early Cretaceous) of Araripe Basin, Brazil. In: 4º Simpósio Latino-Americano de Icnología. Santa Marta, Colombia, Resúmenes, p 69

Carvalho IS, Rios-Netto AM, Borghi L, Leonardi G (2019a) Dinoturbation structures from the Aptian of Araripe Basin, Brazil, as tools for stratigraphic correlation. In: 3rd International Stratigraphic Congress, Strati 2019. Milano, Italy, p 262

Carvalho IS, Rios-Netto AM, Borghi L, Paula Freitas A, Leonardi G, Andrade JA (2019b) Dinosaur trampling from the Rio da Batateira Formation—Lower Cretaceous of Araripe Basin, Brazil. In: Paleo Falls, Livro de Resumos, Évora, Portugal, p 21

Carvalho IS, Leonardi G, Rios-Netto AM, Borghi L, Paula Freitas A, Andrade JA, Freitas, FI (2021a) Dinosaur trampling from the Aptian of Araripe Basin, NE Brazil, as tools for paleoenvironmental interpretation. Cretacous Res 117:104626. https://doi.org/10.1016/j.cretres.2020.104626

Carvalho IS, Leonardi G, Andrade JAFG, Freitas FI, Borghi L, Rios-Netto AM, Figueiredo SMD, Cunha PP (2021b) Dinoturbation in the Exu Formation (Cenomanian, Upper Cretaceous) from the Araripe Basin, Brazil. In: 3rd Virtual Paleontological Congress, 2021. Book of Abstracts 3rd Paleontological Virtual Congress, vo1 1. pp 193–193

Carvalho IS, Neto, JX, Leonardi G, Andrade JAFG, Freitas FI, Borghi L, Rios-Netto AM, Figueiredo SMD, Cunha PP (2022). Estruturas de Dinoturbação do Cretáceo Superior da Bacia do Araripe (Formação Exu), Brasil. In: 27º Congresso Brasileiro de Paleontologia, Cuiabá, 2022. Paleontologia em Destaque, 37 (Ed. Especial), p 133. https://doi.org/10.4072/paleodest.2022.37.ed.especial

Carvalho IS, Silva DS, Andrade JAFG, Borghi L, Viana MSS, Lima Filho MF, Silva RS, Rios-Netto AM, Figueiredo SD, Costa GT (2023) A new dinosaur tracksite in the ‘Early Paleozoic’, Mauriti Formation, Araripe Basin, Brazil In: 4th Paleontological Virtual Congress, 2023, Espanha. Book of abstracts of 4th paleontological virtual congress, 2023, 1:162–162

Carvalho IS, Dias JJ, Silva DS, Borghi L, Andrade JAFG, Viana MSS, Lima Filho MF, Schmitt RS, Rios Netto AM (2024) A new dinosaur tracksite from the Araripe Basin (Brazil) and the Putative Early Paleozoic age for the Mauriti Formation. In: Taylor LH, Raynolds RG and Lucas SG 2024, Vertebrate Paleoichnology: A Tribute to Martin Lockley. New Mexico Museum of Natural History and Science Bulletin 96: 339–344

Catto B, Jahnert RJ, Warren LV, Varejão FG, Assine ML (2016) The microbial nature of laminated limestones: lessons from the Upper Aptian, Araripe Basin, Brazil. Sed Geol 341:304–315

Chagas DB, Assine ML, Freitas FI (2007) Fácies sedimentares e ambientes deposicionais da Formação Barbalha no Vale do Cariri, Bacia do Araripe, Nordeste do Brasil. Geociências 26:512–521

Custódio MA, Quaglio F, Warren LV, Simões MG, Fürsich FT, Perinotto JAJ, Assine ML (2017) The transgressive-regressive cycle of the Romualdo Formation (Araripe Basin): sedimentary archive of the Early Cretaceous marine ingression in the interior of Northeast Brazil. Sed Geol 359:1–15

Dias JJ, Batista DL, Corecco L, Carvalho IS (2022) Bacia do Araripe: Biotas do Cretáceo do Gondwana. In: Corecco L (ed) Paleontologia do Brasil: Paleoecologia e Paleoambientes. Interciência, Rio de Janeiro, pp 129–190

Dias JJ, Carvalho IS (2020) Remarkable fossil crickets' preservation from Crato Formation (Aptian, Araripe Basin), a Lagerstätte from Brazil. J S Am Earth Sci 98:102443

Dias JJ, Carvalho IS (2022) The role of microbial mats in the exquisite preservation of Aptian insect fossils from the Crato Lagerstätte, Brazil. Cretacous Res 130:105068

Dias JJ, Carvalho IS, Buscalioni ÁD, Umamaheswaran R, López-Archila AI, Prado G, Andrade JAFG (2023) Mayfly larvae preservation from the Early Cretaceous of Brazilian Gondwana: Analogies with modern mats and other Lagerstätten. Gondwana Res 124(2023):188–205

Falkingham PL, Hage J, Bäker M (2014) Mitigating the Goldilocks effect: the effects of different substrate models on track formation potential. R Soc Open Sci 1:140225. https://doi.org/10.1098/rsos.140225

Falkingham PL, Bates KT, Margetts L, Manning PL (2011) The 'Goldilocks' effect: preservation bias in vertebrate track assemblages. J R Soc Interface 8(61):1142–1154. https://doi.org/10.1098/rsif.2010.0634

Fambrini GL, Lemos DR, Tesser S Jr, Araújo JT, Silva-Filho WF, Souza BY, Neumann VH (2011) Estratigrafia, Arquitetura Deposicional e Faciologia da Formação Missão Velha (Neojurássico-Eocretáceo) na Área-Tipo, Bacia do Araripe, Nordeste do Brasil: Exemplo de Sedimentação de Estágio de Início de Rifte a Clímax de Rifte. Revista do Instituto de Geociências - USP 11(2):55–87

Fambrini GL, Neumann VH, Barros CL, Silva SM, Galm PC, Filho JA (2013) Análise estratigráfica da Formação Brejo Santo, Bacia do Araripe, Nordeste do Brasil: implicações paleogeográficas. Revista do Instituto de Geociências - USP 13(4):3–28

Fambrini GL, Silvestre DC, Barreto Junior AM, Silva-Filho WF (2020) Estratigrafia da Bacia do Araripe: estado da arte, revisão crítica e resultados novos. Geologia USP Série Científica 20(4):169–212

Fauth G, Kern HP, Villegas-Martín J, Mota MAL, Santos Filho MAB, Catharina AS, Leandro LM, Luft-Souza F, Strohschoen O Jr, Nauter-Alves A, Tungo EJF, Bruno MDR, Ceolin D, Baecker-Fauth S, Bom MHH, Lima FHO, Santos A, Assine ML (2023) Early Aptian marine incursions in the interior northeastern Brazil following the Gondwana breakup. Sci Rep 13:6728

Françolin JBL, Szatmari P (1987) Mecanismo de rifteamento da porção Oriental da margem Norte brasileira. Revista Brasileira de Geociências 17(2):196–207

Fürsich FT, Custódio MA, Matos AM, Hethke M, Quaglio F, Warren LV, Assine ML, Simões MG (2019) Analysis of a late Aptian (Cretaceous) high-stress ecosystem: the Romualdo Formation of the Araripe Basin, Northeastern Brazil. Palaeogeogr Palaeoclimatol Palaeoecol 95:268–296

García-Ramos JC, Piñuela L, Lires JL (2006) Atlas del Jurásico de Asturias. Oviedo. Ediciones Nobel.

Gaspary J, Anjos NFR (1964) Estudo hidrogeológico de Juazeiro do Norte–Ceará. Série Hidrogeologia 3, SUDENE, Grupo de Estudos do Vale do Jaguaribe, Departamento de Recursos Naturais, p 25

Goldberg K, Premaor E, Bardola T, Souza PA (2019) Aptian marine ingressions in the Araripe Basin: implications for paleogeographic reconstruction and evaporite accumulation. Mar Petrol Geol 107:214–221

Gomes JMP, Rios-Netto AM, Borghi L, Carvalho IS, Filho JGM, Sabaraense LD, Araújo BC (2021) Cyclostratigraphic analysis of the early Cretaceous laminated limestones of the Araripe Basin, NE Brazil: estimating sedimentary depositional rates. J S Am Earth Sci 112(1):103563

Guedes CB, Arena MC, Santos HN, Valle B, Santos JA, Favoreto J, Borghi L (2022) Sedimentological and geochemical characterization of microbial mats from Lagoa Vermelha (Rio de Janeiro, Brazil). J Sediment Res 92:591–600

Guerra-Sommer M, Siegloch AM, Degani-Schmidt I, Santos ACS, Carvalho IS, Andrade JAFG, Freitas FI (2021) Climate change during the deposition of the Aptian Santana Formation (Araripe Basin, Brazil): Preliminary data based on wood signatures. J S Am Earth Sci 111:103462

Hashimoto AT, Appi CJ, Soldan AL, Cerqueira JR (1987) O Neo-Alagoas nas bacias do Ceará, Araripe e Potiguar (Brasil): caracterização estratigráfica e paleoambiental. Revista Brasileira de Geociências 17(2):118–122

Heimhofer U, Ariztegui D, Lenniger M, Hesselbo SP, Martill DM, Rios-Netto AM (2010) Deciphering the depositional environment of the laminated Crato fossil beds (Early Cretaceous, Araripe Basin, North-eastern Brazil). Sedimentology 57:677–694

Iniesto M, Gutiérrez-Silva P, Dias JJ, Carvalho IS, Buscalioni AD, López-Archilla AI (2021) Soft tissue histology of insect larvae decayed in laboratory experiments using microbial mats: taphonomic comparison with Cretaceous fossil insects from the exceptionally preserved biota of Araripe, Brazil. Palaeogeogr Palaeoclimatol Palaeoecol 564:110156

Kellner AWA (1999) Short note on a new dinosaur (Theropoda, Coelurosauria) from the Santana Formation (Romualdo Member, Albian), Northeastern Brazil. Boletim do Museu Nacional 49:1–8

Kellner AWA, Campos DA (1996) First Early Cretaceous theropod dinosaur from Brazil. Newues Jahrbuch Für Geologie Um Paläontologie 199(2):151–166

Kroth M, Borghi L, Bobco FER, Araújo BC, Silveira LF, Duarte G, Ferreira LO, Guerra-Sommer M, Mendonça JO (2021) Aptian shell beds from the Romualdo Formation (Araripe Basin): Implications for paleoenvironment and paleogeographical reconstruction of the Northeast of Brazil. Sed Geol 426:106025

Leonardi G (1994) Annotated Atlas of South America Tetrapod Footprints (Devonian to Holocene) with an appendix on Mexico and Central America. CPRM (Serviço Geológico do Brasil), Brasília, Brasil

Leonardi G, Mietto P (2000) Le piste liassiche di dinosauri dei Lavini di Marco. In: Leonardi G, Mietto P (eds) Dinosauri in Italia. Accademia Editoriale, Pisa-Roma, pp 169–246

Leonardi G, Borgomanero G (1981) Sobre uma possível ocorrência de Ornithischia na Formação Santana, Chapada do Araripe (Ceará). Revista Brasileira de Geociências 11(1):1–4

Leonardi G, Spezzamonte M (1994) New tracksites (Dinosauria: Theropoda and Ornithopoda) from the Lower Cretaceous of the Ceará, Brasil. Studi Trentini di Scienze Naturali, Acta Geologica 69(1992):61–70

Lindoso RM, Carvalho IS (2021) The Cretaceous fishes of Brazil: a paleobiogeographic perspective. In: Pradel A, Denton JSS, Janvier P (eds) Ancient fishes and their living relatives: a Tribute to John G. Maisey, Verlag Dr. Friedrich Pfeil, Germany, pp 233–238

Lockley M, Conrad K (1989) The paleoenvironmental context, preservation and paleoecological significance of dinosaur tracksites in the Western USA. In: Gillette DD, Lockley MG (eds) Dinosaur Tracks and Traces. Cambridge University Press, Cambridge, pp 121–134

Lopes GLB, Barreto AMF (2021) Paleoecological and biomechanical inferences regarding the paleoichthyofauna of the Romualdo Formation, Aptian-Albian of the Araripe Basin, state of Pernambuco, northeastern Brazil. J S Am Earth Sci 111:103444

Mabesoone JM (1990) Problemas sedimentológicos-estratigráficos das bacias interiores do Nordeste. In: Simpósio sobre a Bacia do Araripe e Bacias Interiores do Nordeste, 1, Crato, pp 135–141

Maisey JG (2011) Northeastern Brazil: Out of Africa? In: Carvalho IS, Srivastava NK, Strohschoen Jr O, Lana CC (eds) Paleontologia: Cenários de Vida, Interciência, vol 4. Rio de Janeiro, p 515–529

Manning PL (2008) *T. rex* speed trap. In: Carpenter K, Larson PL (eds) *Tyrannosaurus rex*; The Tyrant King. Indiana University Press, Bloomington, pp 204–231

Marques FO, Nogueira FC, Bezerra FH, Castro DL (2014) The Araripe Basin in NE Brazil: an intracontinental graben inverted to a high-standing horst. Tectonophysics 630:251–264

Martill DM, Bechly G, Loveridge RF (2007) The Crato fossil beds of Brazil: window into an Ancient World. Cambridge University Press, Cambridge, p 675p

Martill DM, Cruickshank ARI, Frey E, Small PG, Clarke M (1996) A new crested maniraptoran dinosaur from the Santana Formation (Lower Cretaceous) of Brazil. J Geol Soc 153:5–8

Martill DM, Frey E, Sues HD, Cruickshank ARI (2000) Skeletal remains of a small theropod dinosaur with associated soft structures from the Lower Cretaceous Santana Formation of northeastern Brazil. Can J Earth Sci 37:891–900

Marty D (2008) Sedimentology, taphonomy, and ichnology of Late Jurassic dinosaur tracks from the Jura carbonate platform (Chenevez—Combe Ronde tracksite, NW Switzerland): insights into the tidal-flat paleoenvironment and dinosaur diversity, locomotion and palaeoecology. GeoFocus 21:1–278

Marty D (2011) Formation, taphonomy, and preservation of vertebrate tracks. In: Dinosaur Tracks–Obernkirchen, April 14–17, Abstracts, p 37

Marty D, Meyer CA, Billon-Bruyat J-P (2006) Sauropod trackway patterns expression of special behaviour related to substrate consistency? An example from the Late Jurassic of northwestern Switzerland. Hantekeniana 5:38–41. ISSN 1219-3933

Matos RMD (1992) The northeast Brazilian rift system. Tectonics 11:766–791

Milàn J, Bromley RG (2006) True tracks, undertracks and eroded tracks, experimental work with tetrapod tracks in laboratory and field: palaeogeography. Palaeoclim Palaeoecol 231:253–264. https://doi.org/10.1016/j.palaeo.2004.12.022

Milàn J, Clemmensen LB, 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. https://doi.org/10.1080/00241160410002036

Milàn J, Avanzini M, Clemmensen LB, García-Ramos JC, Piñuela L (2006) Theropod foot movement recorded by Late Triassic, Early Jurassic and Late Jurassic fossil footprints. New Mex Mus Nat Hist Sci Bull 37:352–364

Moratalla JJ, Lockley MG, Buscalioni AD, Fregenal-Martínez MA, Meléndez N, Ortega F, Pérez-Moreno BP, Pérez-Asensio E, Sanz JL, Schultz RJ (1995) A preliminary note on the first tetrapod trackways from the lithographic limestones of Las Hoyas (Lower Cretaceous, Cuenca, Spain). Geobios 28(6):777–782

Naish D, Martill DM, Frey E (2004) Ecology, systematics and biogeographical relationships of dinosaurs, including a new theropod, from the Santana Formation (?Albian, Early Cretaceous) of Brazil. Hist Biol 18:1–14. https://doi.org/10.1080/08912960410001674200

Neumann VH, Cabrera L (2002a) A Tendência Expansiva do Sistema Lacustre Aptiano-Albiano do Araripe durante sua evolução: Dimensões e Morfologia. IG. Série B, Estudos e Pesquisas, Recife-PE 11:176–188

Neumann VH, Cabrera L (2002b) Características hidrogeológicas gerais, mudanças de salinidade e caráter endorréico do sistema lacustre Cretáceo do Araripe, NE Brasil. Revista de Geologia (UFC). Fortaleza 15:43–54

Neumann VH, Borrego AG, Cabrera L, Dino R (2003) Organic matter composition and distribution through the Aptian-Albian lacustrine sequences of the Araripe Basin, northeastern Brazil. Int J Coal Geol 54(1–2):21–40

Osés GL, Petri S, Becker-Kerber B, Romero GR, Rizzutto MA, Rodrigues F, Galante D, Silva TF, Curado JF, Rangel EC, Ribeiro RP, Pacheco MLAF (2016) Deciphering the preservation of fossil insects: a case study from the Crato Member, Early Cretaceous of Brazil. PeerJ 4:1–28

Osés GL, Petri S, Voltani CG, Prado GMEM, Galante D, Rizzutto MA, Rudnitzki ID, Silva EP, Rodrigues F, Rangel EC, Sucerquia PA, Pacheco MLAF (2017) Deciphering pyritization-kerogenization gradient for fish soft-tissue preservation. Sci Rep 7:1–15

Paula Freitas ABL (2010) Análise estratigráfica do intervalo siliciclástico Aptiano da Bacia do Araripe (Formação Rio da Batateira). Dissertação (Mestrado em Geologia). Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro

Paula Freitas ABL, Borghi L (2011) Fácies sedimentares e sistemas deposicionais siliciclásticos aptianos da Bacia do Araripe. Geociências 30(4):529–543

Paula-Freitas ABL, Borghi L, Carvalho IS (2007) Âmbar na Formação Rio da Batateira, Bacia do Araripe (Cretáceo Inferior, Brasil). In: Carvalho, IS, Cassab, RCT, Scwanke, C, Carvalho, MA, Fernandes, ACS, Rodrigues, MAC, Carvalho, MSS, Arai, M, Oliveira, MEQ (Eds) Paleontologia: Cenários de Vida, Editora Interciência, 1, Rio de Janeiro, pp 169–176

Pereira PA, Cassab RCT, Barreto AMF (2017) Paleoecologia e paleogeografia dos moluscos e equinoides da Formação Romualdo, Aptiano-Albiano da Bacia do Araripe, Brazil. Anuário do Instituto de Geociências 40:180–198

Pérez-Lorente F (2015) Dinosaur footprints and trackways of La Rioja. Bloomington, Indiana, Indiana University Press. ISBN 9780253015150

Ponte FC, Appi CJ (1990) Proposta de revisão da coluna litoestratigráfica da Bacia do Araripe. In: 36 Congresso Brasileiro de Geologia. Natal, Brasil, pp 211–226

Prado G, Arthuzzi JCL, Osés GL, Callefo F, Maldanis L, Sucerquia P, Becker-Kerber B, Romero GR, Quiroz-Valle FR, Galante D (2021) Synchroton radiation in palaeontological investigations: examples from Brazilian fossils and its potential to South American palaeontology. J S Am Earth Sci 108:102973

Ribeiro AC, Ribeiro GC, Varejão FG, Battirola LD, Pessoa EM, Simões MG, Warren LV, Riccomini C, Pojato-Ariza FJ (2021) Towards an actualistic view of the Crato Konservat-Lagerstätte paleoenvironment: a new hypothesis as an Early Cretaceous (Aptian) equatorial and semi-arid wetland. Earth Sci Rev 216:103573

Rios-Netto AM, Regali MSP (2007) Estudo bioestratigráfico, paleoclimático e paleoambiental do intervalo Alagoas (Cretáceo Inferior) da bacia do Araripe, nordeste do Brasil (Poço 1-PS-11-CE). In: Carvalho IS, Cassab RCT, Schwanke, C, Carvalho MA, Fernandes ACS, Rodrigues MAC, Carvalho MSS, Arai M, Oliveira MEQ (eds) Paleontologia: Cenários de Vida, 1 edn, vol 2. Rio de Janeiro, Editora Interciência, pp 479–488. ISBN 9788571931855

Rios-Netto AM, Regali MSP, Carvalho IS, Freitas FI (2012) Palinoestratigrafia do Intervalo Alagoas da Bacia do Araripe. Revista Brasileira de Geociências 42(2):331–342

Santana W, Tavares M, Martins CAM, Melo JPP, Pinheiro AP (2022) A new genus and species of brachyuran crab (Crustacea, Decapoda) from the Aptian-Albian (Cretaceous) of the Araripe Sedimentary Basin, Brazil. J S Am Earth Sci 116:103848

Santos Filho MAB, Ceolin D, Fauth G, Lima FHO (2023) Ostracods from the Barbalha and Crato Formations, Aptian of the Araripe Basin, northeast Brazil. Zootaxa 5319(3):332–350

Santos VF, Callapez PM, Rodrigues NPC (2013) Dinosaur footprints from the Lower Cretaceous of the Algarve Basin (Portugal): New data on the ornithopod palaeoecology and palaeobiogeography of the Iberian Peninsula. Cretac Res 40:158–169. https://doi.org/10.1016/j.cretres.2012.07.001

Sayão JM, Saraiva AÁF, Brum AS, Bantim RAM, de Andrade RCIP, Cheng X, Lima FJ, Silva HP, Kellner AWA (2020) The first theropod dinosaur (Coelurosauria, Theropoda) from the base of the Romualdo Formation (Albian), Araripe Basin, Northeast Brazil. Sci Rep 10(1):1–15

Selden P, Nudds J (2012) Evolution of fossil ecosystems. Manson Publishing, London, 288p

Teixeira MC, Mendonça Filho JG, Oliveira AD, Assine ML (2017) Faciologia orgânica da Formação Romualdo (Grupo Santana, Cretáceo Inferior da Bacia do Araripe): caracterização da matéria orgânica sedimentar e interpretação paleoambiental. Geologia USP Série Científica 17(4):19–44

Tomé ME, Araripe R, Oliveira D, Barreto A, Prado L, Pedrosa F, Pereira P, Nascimento LR, NG C (2022) Early Cretaceous Ostracoda (Crustacea) from south-central Araripe Basin, Brazil, with descriptions of seven new species. Zootaxa 5159 (4): 535–557

Valenzuela M, García-Ramos JC, de Centi CS (1988) Las huellas de dinosaurios del entorno de Ribadesella. Central Lechera Asturiana. ISBN: 84-404-2845-6

Varejão FG, Warren LV, Simões MG, Fürsich FT, Matos SA, Assine ML (2019) Exceptional preservation of soft tissues by microbial entombment: insights into the taphonomy of the Crato Konservat-Lagerstätte. Palaios 34:331–348

Varejão FG, Warren LV, Simões MG, Buatois LA, Mangano MA, Bahniuk AMR, Assine ML (2021a) Mixed siliciclastic-carbonate sedimentation in an evolving epicontinental sea: Aptian record of marginal marine settings in the interior basins of north-eastern Brazil. Sedimentology. https://doi.org/10.1111/sed.12846

Varejão FG, Silva VR, Assine ML, Warren LV, Matos SA, Rodrigues MG, Fürsich FT, Simões MG (2021b) Marine of freshwater? Accessing the paleoenvironmental parameters of the Caldas Bed, a key marker bed in the Crato Formation (Araripe Basin, NE Brazil). Braz J Geol 51(1):e2020009

Warren LV, Varejão FG, Quaglio F, Simões MG, Fürsich FT, Poiré DG, Catto B, Assine ML (2017) Stromatolites from the Aptian Crato formation, a hypersaline lake system in the Araripe Basin, northeastern Brazil. Facies 63(3):1–19