Ismar de Souza Carvalho
Giuseppe Leonardi *Editors*

Dinosaur Tracks of Mesozoic Basins in Brazil

Impact of Paleoenvironmental and Paleoclimatic Changes

Springer

Chapter 5
The Dinosaur Footprints in the Cretaceous Aeolian Deposits of Sanfranciscana Basin

Ismar de Souza Carvalho and Senira Kattah

5.1 Introduction

The Sanfranciscana Basin is one of the Brazilian intracratonic basins, located in central-eastern Brazil, oriented in the N–S direction with approximately 1,100 km long and 200 km wide (Cabral and Mescolotti 2021), occurring in the states of Minas Gerais, Goiás, Bahia, Tocantins, Piauí and Maranhão (Fig. 5.1). It covers 220,000 km^2 of the São Francisco Craton with Paleozoic (Santa Fé Group, Permo-Carboniferous) and Mesozoic rocks, ranging from the Late Jurassic to the Late Cretaceous (Campos and Dardenne 1997a; Sgarbi et al. 2001) and encompasses the Abaeté (south) and Urucuia (north) sub-basins (Campos and Dardenne 1997b). The Cretaceous sedimentary record is constituted by the Areado (Lower Cretaceous), Mata da Corda (Upper Cretaceous), and Urucuia (Upper Cretaceous) groups, deposited from Barremian to Maastrichtian and is one of the extensive events of Gondwanan continental sedimentation (Carmo et al. 2004; Mescolotti et al. 2019; Nascimento et al. 2022; Sgarbi et al. 2001).

The dinosaur footprints from the Sanfranciscana Basin are found in the Lower Cretaceous aeolian deposits of the Areado Group that is constituted by the Abaeté, Quiricó and Três Barras formations. The Abaeté Formation is composed of matrix-supported and clast-supported conglomerates, resulted from gravity-controlled processes in alluvial fans and wadi in desert conditions (Campos and Dardenne 1997a; Sgarbi et al. 2001). The Quiricó Formation is composed of mudstone and

I. S. Carvalho (✉)
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

Centro de Geociências, Universidade de Coimbra, Rua Sílvio Lima, 3030-790 Coimbra, Portugal

S. Kattah
3128 Edgewater Drive, Austin, TX 78733, USA

I. S. Carvalho and G. Leonardi (eds.), *Dinosaur Tracks of Mesozoic Basins in Brazil*,
https://doi.org/10.1007/978-3-031-56355-3_5

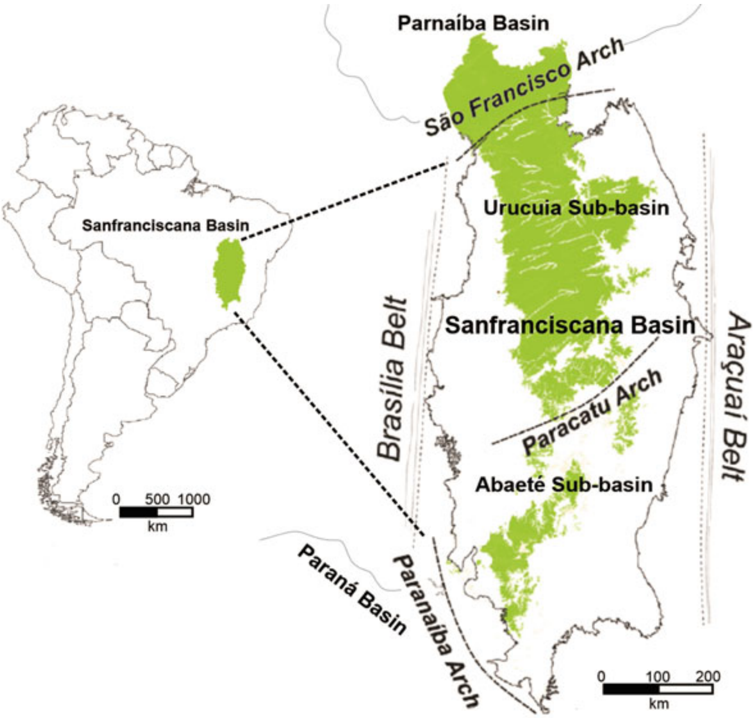

Fig. 5.1 Geographic context of Sanfranciscana Basin in Central-East Brazil. Structural archs and subdivision into the Urucuia and Abaeté sub-basins. 2022 Modified from Cardoso and Basilici (2022)

heterolithic facies (Mescolotti et al. 2019) interpreted as deposited in lacustrine, fluvial and aeolian environments (Campos and Dardenne 1997b). The Três Barras Formation is comprised mainly of sandstones, with associated conglomerate and fine-grained deposits resulted from fluvial-aeolian processes (Campos and Dardenne 1997a; Sgarbi et al. 2001). This unit was divided by Mescolotti et al. (2019) in two depositional units. The Lower Unit (Barremian/Aptian) encompasses a wet aeolian system composed of dunes, interdunes, and ephemeral alluvial deposits. In the upper part of the Lower Unit a continuous paleosol records dune stabilization and the end of aeolian accumulation. Follows a stratigraphic gap (Cenomanian to Coniacian) that coincides with the Cretaceous Thermal Maximum. The Upper Unit (Santonian?/ Campanian) comprises dune fields of a dry aeolian system capped by volcanic rocks (Mescolotti et al. 2019).

The footprints from the Sanfranciscana Basin occur in the aeolian deposits, interpreted as interdune deposits, an adequate area to flourish life, especially due the moister environment and the availability of water. The footprints are found in the Três Barras Formation and they are in the same environmental context of the Botucatu Formation and Caiuá Group (Paraná and Bauru basins), where also occur similar theropod footprints.

5.2 Geological Context

The Lower Cretaceous rock successions registered extremely arid conditions in the Gondwana. In the Paraná Basin there are the deposits of the most extensive paleodesert of Earth history—the Botucatu Paleodesert, where fossil footprints are found in the Botucatu Formation. The Cretaceous deposits of the Sanfranciscana Basin (mainly the Areado Group, Fig. 5.2) also record semi-arid to desert settings associated to the hot and dry climatic conditions (Grossi Sad et al. 1971; Suguio and Barcelos 1983).

The Três Barras Formation (Areado Group) is dominantly composed of sandstones that interfinger and conformably overlie the deposits of Quiricó Formation and it is overlain by the Upper Cretaceous volcanic alkaline rocks of Mata da Corda Group (~80 Ma, Sgarbi et al. 2004). Ten sedimentary facies were recognized in the Três Barras Formation by Mescolotti et al. (2019), including: Medium- to coarse-grained trough cross-bedded sandstone; meter-scale trough cross-bedded sandstone; planar cross-bedded sandstone; parallel-laminated sandstone; climbing

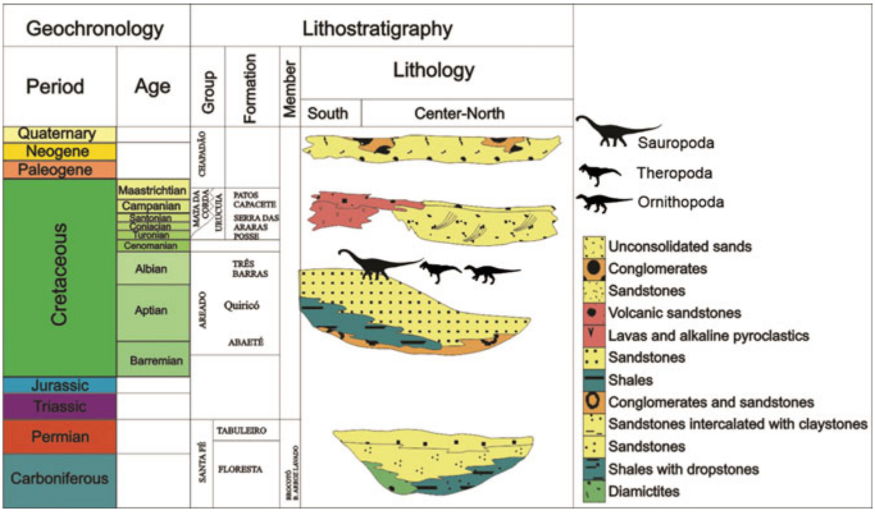

Fig. 5.2 Stratigraphic chart of the Sanfranciscana Basin (modified from Leite and Carmo 2021)

ripple cross-laminated sandstone; sandstone with deformational structures; paleosol; massive mudstone; laminated mudstone; and interlaminated fine-grained sandstones and mudstones with heterolithic lamination.

The fossils of the Areado Group are restricted to the Quiricó and Três Barras Formation (Carvalho et al. 1994). The mudstones, shales, siltstones and carbonates of Quiricó Formation (?Hauterivian-Aptian) are a mixed siliciclastic–evaporitic succession interpreted as fluvio-lacustrine and playa lake paleoenvironment (Cardoso et al. 2022, 2023). They contain palynomorphs, leaves of gymnosperms and angiosperms, annelids, insects, ostracods, spinicaudatans, elasmobranchs, actinopterygians, coelacanthiforms and dinosaur bones (Scorza and Santos 1955; Barbosa 1965; Duarte, 1968; Barbosa et al. 1970; Santos 1971; Lima 1979; Duarte 1985a, b; Santos 1985; Carvalho et al. 1994, 1995; Arai et al. 1995; Duarte 1997; Barbosa et al. 1997; Delício et al. 1998; Carmo et al. 2004; Gallego and Martins-Neto 2006; Carvalho and Maisey 2008; Zaher et al. 2011, 2020; Leite et al. 2018; Fragoso et al. 2019; Brito et al. 2020; Bittencourt and Brandão 2021; Bittencourt et al. 2015, 2018; Ribeiro et al. 2018; Coimbra 2020; Carvalho and Santucci 2021; Leite and Carmo 2021). The shales of Quiricó Formation can be organic-rich locally, and temporally record permanent dysoxic/anoxic environments. The succession is characterized by mudstones with scattered grains of fine sand and desiccation cracks, evaporites interpreted as ephemeral shallow lakes with events of subaerial exposure and rapid modifications of the water chemistry (Mescolotti et al. 2019; Cardoso et al. 2022). In the Três Barras Formation (Barremian-Albian), silexilite units occur in association with sandstones and mudstones. In these silica-rich rocks, radiolarians and other marine fossils are present (Kattah 1992; Kattah and Koutsoukos 1992). The Três Barras Formation (Fig. 5.3) comprises siliciclastic deposits interpreted as fluvial, deltaic, marine and aeolian sedimentation. The presence of dinoflagellates, radiolarians, spicules of sponges, carapaces of foraminifera and possible acritarchs in silexilite levels were interpreted as indicative of marine environments (Kattah 1991; Kattah and Koutsoukos 1992; Pessagno and Dias-Brito, 1996; Pessagno et al. 1997; Dias-Brito et al. 1999) such as restricted platform (Kattah 1992), marine transitional marginal (Castro 1996) and neritic or oceanic environments (Arai 1999; Dias-Brito et al. 1999; Arai 2009, 2014a, b). Carvalho and Kattah (1998) described eleven dinosaur footprints in the Três Barras Formation. They are in deposits of an aeolian facies of a humid interdune environment (Kattah 1993; Carvalho and Kattah 1998). Other footprints were identified as cross-section structures, concave-upward and asymmetric soft-sediment deformation structures, interpreted as produced in wet interdune facies, in the interdune-dune contact and in dune foresets (Mescolotti et al. 2019).

5.3 Footprints: Diversity and Paleobiological Interpretation

The fossil footprints are found in two distinct ichnosites: João Pinheiro and Presidente Olegário, both in the homonymous municipalities of the Northwest of the state of Minas Gerais, microregion Paracatu. There are eleven dinosaur footprints in the João

Fig. 5.3 Outcrop of the Três Barras Formation where occur the footprints of the João Pinheiro ichnosite

Pinheiro ichnosite preserved as epireliefs filled with a fine to coarse-grained reddish sandstone similar to the surrounding matrix. Three smaller of them are part of a short trackway (Carvalho and Kattah 1988). There are also cross-section footprints observed as concave upward deformation structures and narrow shaft straight borders from the Presidente Olegário ichnosite (Mescolotti et al. 2019).

5.3.1 João Pinheiro Ichnosite

The short track of three consecutive footprints (JPAR 01, JPAR 02 and JPAR 03) shows an oblique pace of 60 cm and step angle of 155º. The stride is 112.5 cm long. These footprints are tridactyl, mesaxonic and digitigrade with evidence of claws, with 15 cm of width and length. The hypexes angles between digits II-III and III-V are acute, with an average value of 30º. Footprint JPAR 01 is preserved as convex epirelief and footprints JPAR 02 and JPAR 03 as concave epirelief. Two footprints from this short track (JPAR 01 and JPAR 02) show a projection on the rear border that could correspond to digit I. The digits are tapered and the extremities of footprints JPAR 01 and JPAR 03 show claw imprints (Figs. 5.4 and 5.5).

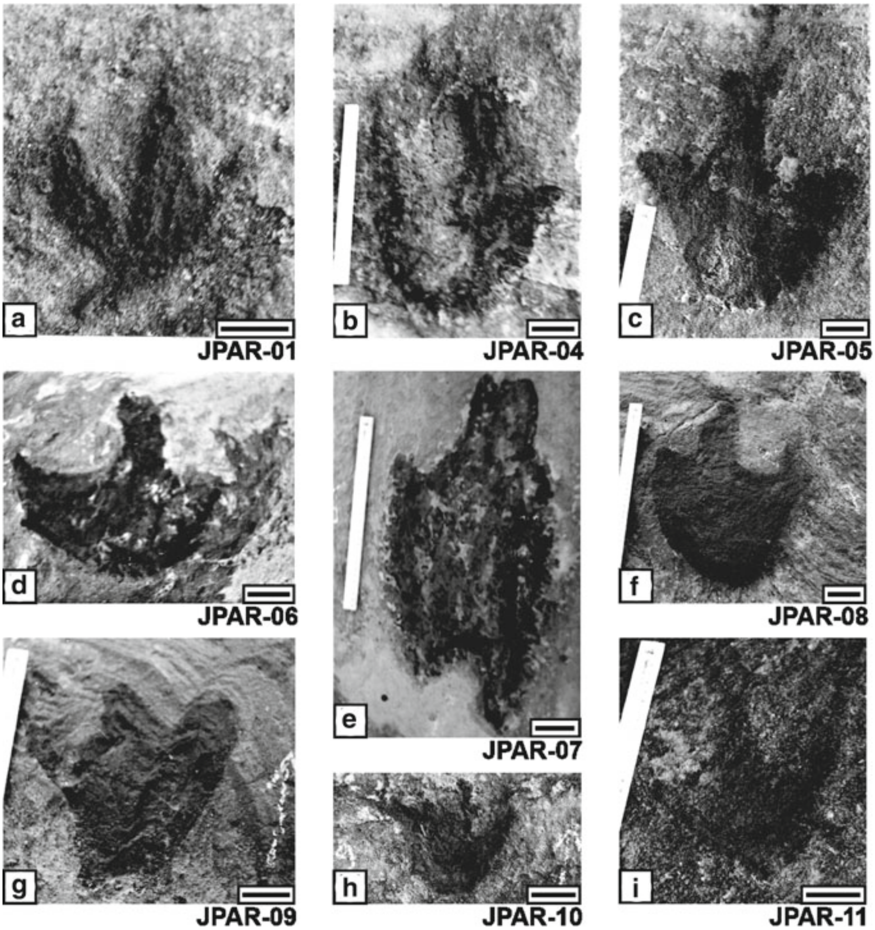

Fig. 5.4 Footprints from the João Pinheiro ichnosite that are interpreted as tracks of small and large-sized theropods and ornithopod trackmakers preserved in the Três Barras Formation, Areado Group. JPAR—João Pinheiro County, Areado Group. Footprints in dark color due the use of water to highlight them. Scale bar: 5 cm

The isolated footprints are bigger than these last ones. They are also tridactyl, mesaxonic and with digit III projecting more than digits II and IV (JPAR 04, JPAR 05, JPAR 07, JPAR 08, JPAR11) or presenting almost the same size (JPAR 06, JPAR 09, JPAR 10).

The footprint JPAR 04 is isolated, tridactyl and mesaxonic preserved in concave epirelief without clear morphological details. The footprint shows 25 cm in width and 30 cm in length. Digit III is the bigger, very large in its base and pointed in the anterior extremity. The two other digits show almost the same size, shorter and more pointed, suggesting the presence of claws. The hypexes between digits II-III and III-IV are acute (35º).

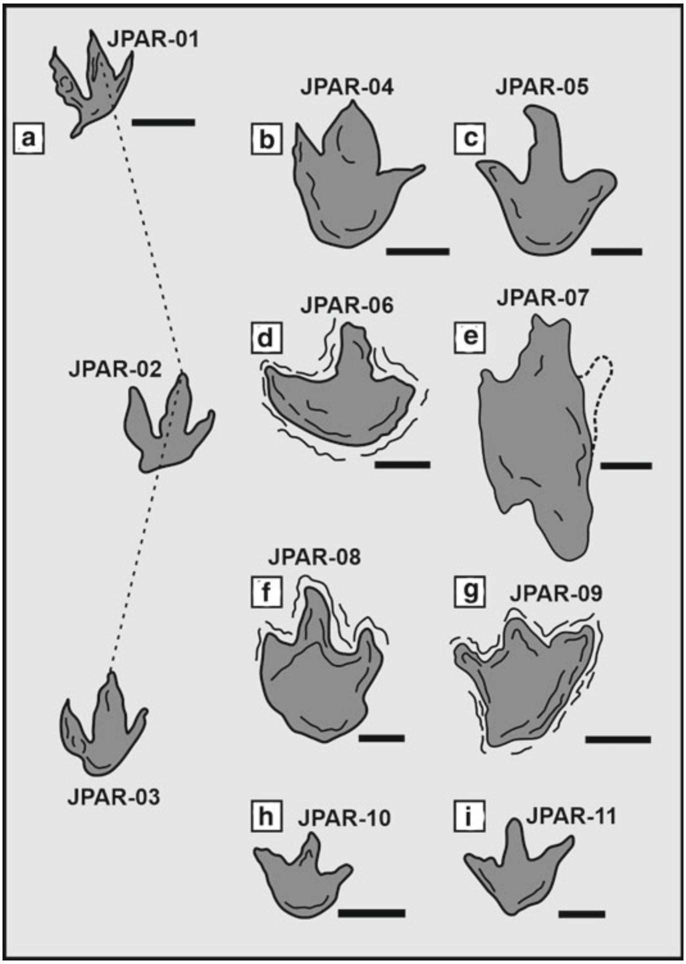

Fig. 5.5 Morphological aspects of the dinosaur footprints from the João Pinheiro ichnosite. **a** Small-sized theropod footprints in a short trackway (JPAR 01, JPAR 02, JPAR03); **b** (JPAR 04), **c** (JPAR 05) theropod footprints; **d** (JPAR 06), an isolated ornithopod footprint; **e** (JPAR 07), a dubious trackmaker (ornithopod or large-sized theropod) due the preservation conditions of the footprint; **f** (JPAR 08), **g** (JPAR 09) and **h** (JPAR 10) probable theropod footprints; **i** (JPAR 11), an isolated large-sized theropod footprints probably related to Abelisauroidea; Modified from Carvalho and Kattah (1998). JPAR – João Pinheiro County, Areado Group. Scale bar: 10 cm

The footprint JPAR 05 is preserved as concave epirelief. It is an isolated footprint, tridactyl and mesaxonic with 26 cm in width and 30 cm in length. Digit III is the longest in size, slightly curved in the anterior region. Digits II and IV show the same size, while digit III is the most pointed. The hypexes are acute, with 30º of angular value between digits II-III and III-IV. The rear border of the footprint is well defined and rounded.

JPAR 06 is also an isolated footprint, tridactyl and mesaxonic, preserved as concave epirelief, with 38 cm in width and 24 cm in length. The index l/w is here 0.63, a rare condition. It is, in fact, a very short and wide footprint, perhaps because of the collapse effect. Surrounding the digits and the rear border there is the deformation of the sediments with a crenulation aspect. It corresponds to a fluidization process related to the load of the trackmaker over the substrate. Digit IV is not preserved. Digit II is pointed, showing bigger dimensions than the other two digits. Only the lower portion of digit III is partially preserved. The hypex between digits II-III is wide and rounded and the III-IV angle is 40º. The rear border of the footprint is a wide continuous curve.

JPAR 07 is an isolated footprint, 20 cm in width and 48 cm in length, preserved as concave epirelief, without clear morphological details and contour. Digits II and III are partially preserved, with a wide elongation of the posterior margin of the footprint. The interdigital angle between digits II-III is 35º and the hypex is parabolic.

JPAR 08 is an isolated tridactyl and mesaxonic footprint preserved as a convex epirelief. There is also as in JPAR 06 the deformation of the sediments, with a crenulation aspect, surrounding the digits. It is an evidence of fluidization induced by the trackmaker load. The footprint is 25 cm width and 38 cm in length with a rounded rear outline. The digits show a larger lower portion and a pointing aspect in the distal region. They present almost the same size, although digit III is slightly longer (10 cm in length) than the others and shows a small curvature in the distal extremity. The angular value is 30º between digits II-III and 50º between digits III–IV.

JPAR 09 is an isolated tetradactyl and mesaxonic footprint preserved as a convex epirelief. It measures 24 cm in width and 24 cm in length. Surrounding the footprint there are crenulated deformations, especially on the borders of digit IV. The three digits present almost the same length (12 cm) with a larger lower portion. The distal ends are more pointed. The hypexes are wide, with 50º between digits II-III and 40º between digits III-IV. The rear margin presents a short spur, probably corresponding to digit I.

The footprint JPAR 10 is isolated, tridactyl and mesaxonic, 15 cm in width and in length, preserved as concave epirelief. The posterior margin is rounded and shows a continuous curve between digits II and IV. The digits are pointed, almost with the same length (7 cm), and a probable claw impression in digit III. The hypexes are acute, and the angle value between digits II-III and III-IV is 40º.

JPAR 11 is an isolated, tridactyl and mesaxonic footprint preserved as concave epirelief. The footprint measures 22 cm in width and 22 cm in length. Although the three digits are pointed they show rounded extremities, without the presence of claw marks. The hypices between II-III and III-IV are acutes and they show the same angle value (45º). The rear margin of the footprint is narrow and slightly pointed.

The trackmaker interpretation of the footprints from the João Pinheiro ichnosite is difficult. There is only one theropod based on osteological data described to the Sanfranciscana Basin, the Abelisauroidea *Spectrovenator ragei* (Zaher et al. 2020) from the Quiricó Formation. Other dinosaur remains (bone fragments and teeth) were preliminarily attributed to Abelisauridae, Dromaeosauridae (Carvalho et al. 2012; Santucci et al. 2014), Abelisauroidea (Bittencourt and Langer 2011; Zaher et al.

2011; Pires-Domingues 2009) and Noasauridade (Silva 2013). The short track with three small fooprints is classified as a small biped dinosaur. In these footprints it is possible to observe claws in the digits II, III and IV (JPAR 01, JPAR 02 and JPAR 03) and a digit I (hallux) in the rear border. The general morphology allows attributing these footprints to a small-sized theropod. Carvalho and Kattah (1998) suggested to this track an origin "coelurosauriform" (term that had another meaning, at that time), and the Aptian small theropods from the Araripe Basin, similar to *Mirischia asymmetrica* Naish et al. (2004), probably a coelurosaurid or *Santanaraptor placidus* Kellner (1999), classified as coelurosaurid or as a noasaurids (Naish et al. 2004; Kellner 1999), could be good examples of trackmakers.

The footprints from the Três Barras Formation present similarities with some footprints found in the Botucatu Formation, Paraná Basin (Leonardi and Godoy 1980; Leonardi and Lima 1990). There are also features in common with footprints from China (Zhen et al. 1991) that show a wide posterior margin (*Zhengichnus jinningensis* Zhen et al. 1986 and *Xiangxipus chenxiensis* Zeng 1982), in addition to those that present a well-defined metatarsal region, similarly to the Sanfranciscana Basin footprints JPAR 06 and JPAR 07. The tracks are generally of small, cursorial theropod, related to Gondwanan clades such as noasaurids or velocisaurids. Leonardi (1977) and Langer et al. (2019) interpreted the recurrence of a similar desert-dwelling fauna based on similar tracks from the Botucatu Formation that are also found in the Caiuá Group. These authors also observed that the functionally monodactyl theropod footprints from the Botucatu Formation, Caiuá Group (Paraná Basin) and La Matilde Formation (Argentina; Casamiquela 1964) are consistent with the foot morphology of the noasaurid *Vespersaurus paranaensis*. Noasauridae is a clade of theropod dinosaurs nested within Abelisauroidea mainly known by rather incomplete records from the Cretaceous of Gondwana. They are small to medium-sized dinosaurs with necks, arms, and skulls relatively longer than those of other abelisauroid clades (Carrano et al. 2011; Barbosa et al. 2023) and a species such as *Vespersaurus paranaensis* was not a top predator, having a possibly generalist diet and an opportunistic feeding strategy (Barbosa et al. 2023).

The footprints JPAR 10 and JPAR 11, that show an acute rear border and bigger dimensions than the short track (JPAR 01, JPAR 02 and JPAR 03), are related to large-sized theropod dinosaurs such as the Abelisauroidea. The same classification is assigned to the footprints JPAR 04, JPAR 05, JPAR 08 and JPAR 09, with pointed digits and digit III (JPAR 04, JPAR 05, JPAR 08) longer than the others. In the Sanfranciscana Basin the unique possible comparison could be with *Spectrovenator ragei* (Zaher et al. 2020). Although it is an Abelisauridae from the Quiricó Formation (Aptian) it is correlative in time to these footprints from the Três Barras Formation. There are few postcranial remains of *Spectrovenator* to estimate its length: an astragalus is fused to the calcaneum; astragalar ascending process is tall and laminar and lacks the fusion with the fíbula; the metatarsus is gracile, lacking the reduced width of metatarsal II present in noasaurids; the pedal unguals have proximally bifurcated grooves (Y-shaped) and a flexor tubercle with an associated ventral depression (Zaher et al. 2020). It is a medium-sized Abelisauridae (2.5 m in length), which general dimensions fit in the larger isolated footprints proportions (20–28 cm in width and 23–48 cm in length) of the Três Barras Formation.

The footprint JPAR 06 is the one with the most distinct morphological pattern among the Sanfranciscana Basin footprints. The rear border and the obtuse angled hypex between digits II-III suggest an autopodium with a digital membrane as identified by Reynolds (1991) and Zhen et al. (1991). Therefore Reynolds (1991) suggested that the large width of the footprint could be related to a locomotor response to the sand surface where the trackmaker walked, and not necessarily related to the presence of a digital membrane between digits. The absence of sharp claws indicates that the footprints can be assigned to the ornithopods described and illustrated by Leonardi (1994).

Concerning footprint JPAR 07, the stretching of the rear border could represent very distinct groups. The impression of a metatarsal, which is common in Lower Jurassic ornithopods (Thulborn 1990; Ellenberger 1970) such as *Anomoepus scambus* and *Moyenisauropus natator*, is also present in Triassic and Cretaceous theropods (Lockley and Gillette 1991). Kuban (1991) considered that the metatarsal impression in biped dinosaurs could be a behavioral response to the unstable condition of the substrate or a posture change of the trackmaker during the walk.

5.3.2 Presidente Olegário Ichnosite

The footprints from the Presidente Olegário ichnosite are preserved as cross-section structures concave-upward, symmetric and asymmetric deformation structures, and a narrow shaft structure in the facies meter-scale trough cross-bedded sandstone (St2) proposed by Mescolotti et al. (2019). The concave-upward footprints range 55–60 cm in width and 20 cm in penetration depth, despite the depth of the bedding deformation reach 75 cm. The narrow shaft shows straight borders, without the bending of the surrounding sandstone beds. It is slightly curved and pointed in the lower border. It has 36 cm in width and 80 cm in depth. The load of the trackmakers induced a successive deformation in the lower levels of reddish sandstones, fine- to medium grained. In the case of the large concave-upward footprints there isn't the rupture of the lower strata. Instead, the narrow shaft shows a clear rupture of the substrate lamina succession with the association of microfaults. The environment where these tracks were preserved was interpreted as the migration of large sinuous-crested aeolian dunes, sometimes with sand liquefaction at the base of foresets due to gravitational instability, in a context of wet interdune facies (Mescolotti et al. 2019) (Fig. 5.6).

There are also concave-upward symmetric and asymmetric cross-section tracks in the interdune-dune contact. They range from 25–45 cm in width and 32–37 cm penetration depth, despite the depth of the bedding deformation reaches 65 cm. They are found in fine- to medium-grained parallel laminated sandstones with two-fold grain size segregation, arranged in 0.5- to 2-m-thick horizontal to low angle (less than 5°) strata (SI facies, Mescolotti et al. 2019). The paleoenvironment is interpreted as

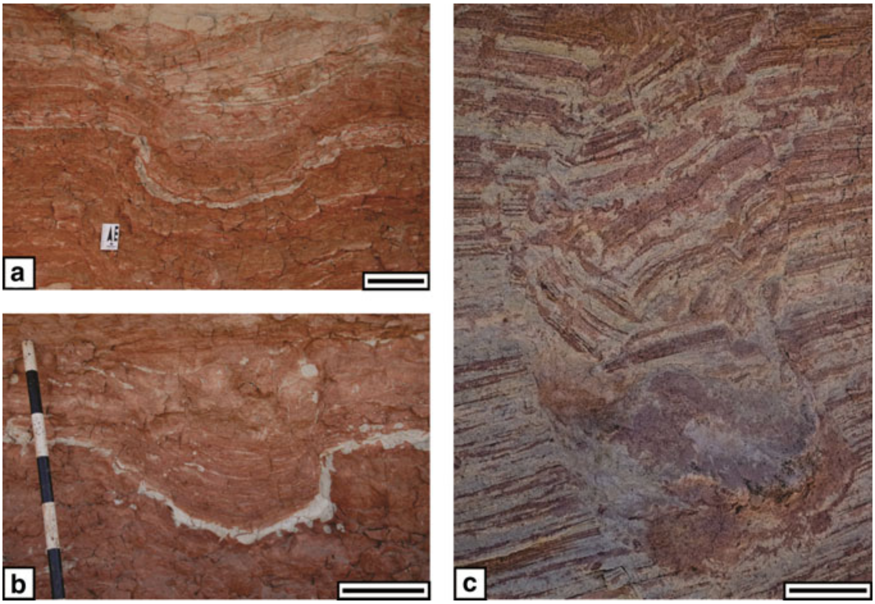

Fig. 5.6 Cross-section footprints from the wet aeolian system of Três Barras Formation, Presidente Olegário ichnosite. **a, b** Concave upward deformation structures with bedding deformation interpreted as a sauropod footprint in the wet interdune facies; **c** Narrow shaft structures, with a pointed lower extremity, this last being interpreted as the impression of a theropod digit III in the dune foresets. Facies St2—meter-scale trough cross-bedded sandstone. Photographs courtesy by Patricia Colombo Mescolotti. **a** Scale bar: 20 cm; **b** Scale bar: 2 cm; **c** Scale bar: 5 cm

protodunes migration across deflation sand flats under high ratio of wind velocity/ sedimentary supply (Mescolotti et al. 2019).

The cross-section concave-upward footprints (Fig. 5.7) from the Presidente Olegário ichnosite were interpreted as produced by sauropods, considering the morphology and dimensions of similar occurrences (Avanzini 1998; Gatesy 2003; Romano and Whyte 2003; García-Ramos et al. 2006; Falkingham et al. 2016; Sanz et al. 2016; Campos-Soto et al. 2017; Díaz-Martínez et al. 2018; Mescolotti et al. 2019; Carvalho et al. 2021a). The trackmaker could be a large sauropod similar to *Tapuiasaurus macedoi*, a Titanosauria of the family Nemegtosauridade found in the Aptian of Quiricó Formation (Zaher et al. 2011). The other cross-section footprint that is a narrow shaft, slightly curved with a pointed impression is related to a tridactyl trackmaker, in which digit III supported a greater load and consequently its marked impression in the substrate. The medium-sized Abelisauroidea *Spectrovenator ragei* from the Quiricó Formation (Zaher et al. 2020) could be a good example of trackmaker to this footprint morphology. In bipedal dinosaurs, the digit III exerts a higher pressure on the substrate, conducting to a greater deformation in the central area of the cast as suggested by Gatesy et al. (1999), Milàn and Bromley (2006), Falkingham

Fig. 5.7 Two cross-section concave upward footprints in the interdune-dune contact. The probable trackmaker is a sauropod. Facies Sl—parallel-laminated sandstone. Photograph courtesy by Patricia Colombo Mescolotti

and Gatesy (2014) and Milàn et al. (2004, 2006) that analyzed the sediment deformation induced by theropod foot movements during a stride. Besides, as proposed by Delcourt et al. (2024) the distribution of abelisaurids was driven by climatic conditions because they were well adapted to semi-arid conditions and diversified in size and number of species.

5.4 Paleogeographical Distribution of the Footprints

At the end of the Jurassic and beginning of the Cretaceous, a region of great aridity was established in the interior of the Gondwana continent. The eolic and fluvial sandstones found in Rio Grande do Sul State (Guará Formation, Late Jurassic), indicate a semi-arid climate (Scherer and Lavina 2005, 2006). At the beginning of the Cretaceous (Scherer 2000, 2002; Scherer et al. 2002), there was a change in climate, with hyperarid conditions, establishing a wide desert known as the Botucatu Paleodesert (Almeida 1953; Bertolini et al. 2021). The origin of the Botucatu Paleodesert (Botucatu Formation) resulted from the geographic configuration defined from the end of the Permian, with the origin of Pangea. The area occupied by this paleodesert reached about 1,300,000 km^2, covering central-southern Brazil, northern Uruguay, eastern Paraguay and eastern Argentina. The ichnofauna of the Botucatu Formation is an endemic fauna of an extremely arid environment (Leonardi and Sarjeant 1986) including “coelurosaurs”, “carnosaurs”, ornithopods, and mammals trackmakers (Leonardi 1980; Leonardi 1981a, b; Leonardi 1991; Leonardi and Godoy 1980). The presence of conchostracans indicates the existence of temporary lakes (Cardoso 1965).

The paleogeographical position of continental landmasses, the low eustatic sea level and atmospheric currents, defined a climate of great aridity during almost all of the Mesozoic (Almeida and Carneiro 1998). This climate changed after the breakup of Gondwana during the Cretaceous, which led to a modification in the atmospheric and oceanic currents, humidity and temperature and, therefore, to the disappearance of this great desert.

During the Late Cretaceous, regional arid conditions are still persistent as observed in the deposits of the Caiuá Group. It is a quartz and feldspathic sandstones succession, fine to-medium grained size, reddish in color, with large cross stratifications presenting an ichnofauna of theropods and mammals (Leonardi 1977; Leonardi 1981a, b; Leonardi 1991). The dinosaur tracks in this unit are few, with only one large theropod trackway, one trackway and an isolated footprint of a "coelurosauriform". None of these are similar to those found in the Sanfranciscana Basin. Their morphologies are masked by a wide deformation zone on the surrounding sandy matrix, not allowing clearly recognizing the contours of the footprints and their digits.

The stratigraphic levels of the Sanfranciscana Basin (Três Barras Formation) where the fossil footprints are found are indicative of humid interdunes areas, with subordinated deflationary pavements (Kattah 1991). The footprints with a clear morphology would indicate the moments of greater wetness of the substrate, while without clear morphology would have formed in conditions of dryness. During the living time (Barremian-Albian) of the trackmakers occurred great environmental changes related to the South Atlantic opening (Mescolotti et al. 2019), especially a more humid climate and the first marine ingressions from the Equatorial region.

5.5 Paleoenvironmental and Paleoclimatic Contexts

The more diverse biologic activity in deserts occurs in interdune areas. The parameters controlling the kind of activity in those settings are moisture, sedimentation rate, and the size of surrounding dunes. Especially in the interdune environments, such as the wadi, there is a high potential to the preservation of the fossil footprints. The maintenance of tracks in aeolian sandstones is directly related to the cohesion of the sand, related to a high humidity, when the trackmaker induces the deformation of the substrate (Ahlbrandt et al. 1978). Furthermore the fast burial also plays an important role in the preservation, especially in the leeward and interdune areas, which are the most conducive to preserving footprints.

The origin of the wetness in the sand dunes that allow the footprints preservation is controversy. Leonardi (1980) considered that the preservation of footprints in the Botucatu Paleodesert would be related to a higher humidity (because of dew) of the sandy surface during the night, when the footprints would be produced and at dawn there would be their subsequent covering by dry sand. Another possibility would be the existence of a high groundwater level, which would allow a greater wetness of the sediments and, consequently, the preservation of the footprints even in the dunes foreset. However, the predictive model of Winkler et al. (1991), of restricting occurrences of fossil footprints to interdune areas, is the most common. Interdune deposits represent a complex sedimentation of aeolian and non-aeolian environments ranging from deflation surfaces to ephemeral lakes. Due to the high local sedimentation rate and grain size of the surrounding active dunes, the potential for fossil footprints preservation in interdune areas is high. In addition, observation of current environments demonstrates that the wetness conditions in these areas allow the proliferation of a diverse biota (Carvalho and Kattah 1998).

In this way, the lack of fossils in deposits adjacent to the interdunes would reflect the low original biological productivity and the low diversity of large animals in an area of active dunes. Winkler et al. (1991) postulated that the presence of fossil tracks and fossils of large vertebrates in the interdune deposits of the Navajo Sandstone (Middle Jurassic, Arizona, USA) would imply the existence of a complex food chain, and may even represent temporal intervals not typical of the hyper aridity of deserts, a moment where the dunes are most active. Leonardi (1991) considered that the dinosaur tracks in the desert paleoenvironments of South America generally belong to bipedal and small-sized forms. The frequency of theropods is high (87%) with a predominance of "coelurosauriforms", absence of sauropods and rare ornithopods, which possibly would have been the largest dinosaurs in arid environments. A similar conclusion was also reached by Lockley and Conrad (1991) in the study of the Glen Canyon and San Rafael groups (Jurassic, USA), in which most of the fossil footprints in desert paleoenvironments are those produced by theropods. There would be a preferential distribution of these in the playa lake and interdune fluvial deposits, when compared with the paleoenvironments that represent the dune fields.

The footprints of the Três Barras Formation (João Pinheiro ichnosite) are in a context of sandstones with fine to medium grain size, poorly selected. There is intercalation of centimetric levels of coarse-grained sandstones, claystones and siltstones. The color is pink to reddish. Under the microscope, crystals of calcite and dolomite are observed in the siltstones. The sedimentary structures are dissecation cracks, symmetrical and climbing wavy ripples, and channel cross-bedding. The pavement on which the footprints are found is poor selected quartz sandstone, locally with ripple marks and tabular cross-stratifications. Above the level of footprints there is conglomeratic sandstone with faceted pebbles. Kattah (1991) interpreted this stratigraphic level as indicative of an area of humid interdunes, with subordinated deflationary pavements. Most footprints preserved on this surface do not have clear morphological details, which must be related to a very loose sandy substrate. However in some cases (JPAR 01 and JPAR 03) the anatomical details such as claws and phalangeal pads are quite evident. Reynolds (1991) and Lockley (1991) consider that this fact results from fluctuations in the hydrostatic level during the formation of footprints. The footprints with a clear morphology would indicate the moments of greater moisture of the substrate. The others would have formed in conditions of greater aridity, when the groundwater is lower. Drier sand would not have been cohesive enough to allow for better footprint preservation.

The fossil footprints from the João Pinheiro ichnosite were recognized by morphological data from the autopodia on the bedding plane. Otherwise the footprints from the Presidente Olegário ichnosite reach many sedimentary levels beyond the surface and they are preserved as deformation structures which can be observed in cross-sections. They are directly related with the trampling by terrestrial vertebrates and the pressure generated during the contact between a tetrapod autopodium and the substrate, leading to the origin of load structures with successive laminae deformation (Carvalho et al. 2021a, b, 2022). Deformation of the print-bearing surface, by the dinosaur trampling, favors the preservation of underprints and transmitted prints on bedding planes beneath the primary footprint-bearing surface as "undertracks" or "ghost prints" (Sarjeant and Leonardi 1987). The stratigraphic analysis of Mescolotti et al. (2019) considered a wet aeolian system including a wet interdune facies, interdune-dune contact and dune foresets as the environments where these footprints were preserved (Fig. 5.8).

5.6 Conclusions

The desert environment is a challenging geological context to the preservation of footprints. The dry sands, the low humidity, the inconstancy and fast changes in the substrate, the deflation, generally destroy the tracks or just allow a deformation structure in the contact between the trackmaker's feet and the superficial layers. Despite these restrictions, some environmental settings especially in the wet interdune areas, where there is a more diverse biologic activity in deserts, present a high potential to the preservation of the footprints. Interdune deposits represent a complex sedimentation of aeolian and non-aeolian environments ranging from deflation surfaces to ephemeral lakes. Due to the high local sedimentation rate and grain size of the surrounding active dunes, the potential for fossil footprints preservation in the interdune areas is high. In addition, observation of current environments demonstrates that the moisture conditions in these areas allow the proliferation of a diverse biota. Then, the maintenance of tracks in aeolian sandstones is directly related to a high humidity that allows the cohesion of the sand. The fast burial also plays an important role in the preservation, especially in the leeward and interdune areas, which are the most conducive to preserving footprints.

The footprints from the Sanfranciscana Basin are found in two localities where the Três Barras Formation outcrops: João Pinheiro and Presidente Olegário ichnosites. There are eleven dinosaur footprints in the João Pinheiro ichnosite preserved as concave epilelief with infilling of fine to coarse-grained reddish sandstone similar to the surrounding matrix. In the Presidente Olegário ichnosite the footprints are observed as cross-section concave upward deformation structures and narrow shaft straight borders. These two sets of footprints indicate small and medium-sized theropods, ornithopods and sauropods. Aptian age deposits of the Sanfranciscana Basin (Quiricó Formation) present osteological remains of Abelisauroidea (Noasauridae and Abelisauridae), Dromaeosauridae and Titanosauria (Nemegtosauridae) that could be related to some of the trackmakers of João Pinheiro and Presidente Olegário ichnosites.

Fig. 5.8 Environmental reconstruction of the wet aeolian system of Três Barras Formation, Sanfranciscana Basin, and the dinosaur trackmakers (Art by Guilherme Gehr)

References

Ahlbrandt TS, Andrews S, Gwyne DT (1978) J Sediment Petrol 48(3):839–848

Almeida FFM (1953) Botucatu, a Triassic desert of South America. In: 19th International Geological Congress, Argel, 1953. Comptes Rendus, XIX Sessão, fasc. VII. p 9–24

Almeida FFM, Carneiro CDR (1998) Botucatu: o grande deserto brasileiro. Ciência Hoje 24(143):36–43

Arai M (1999) A transgressão marinha Mesocretácea: sua implicação no paradigma da reconstituição paleogeográfica do Cretáceo no Brasil In: 5º Simpósio sobre o Cretáceo do Brasil, Boletim, Serra Negra, Sociedade Brasileira de Geologia, p 577–582

Arai M (2009) Paleogeografia do Atlântico Sul no Aptiano: um novo modelo a partir de dados micropaleontológicos recentes. Boletim de Geociências da Petrobrás 17:331–351

Arai M (2014a) Aptian/Albian (Early Cretaceous) paleogeography of the South Atlantic: a paleontological perspective. Braz J Geol 44(2):339–350. https://doi.org/10.5327/Z2317-4889201400020012

Arai, M (2014b) Reconstituições paleo-oceanográfica e paleoclimática do Oceano Atlântico no Cretáceo, baseadas em dinoflagelados. In: Carvalho IS, Garcia MJ, Lana CC, Strohschoen Jr O (eds) Paleontologia: Cenários de Vida - Paleoclimas. 1ed., vol 5. Rio de Janeiro: Editora Interciência. pp 45–62

Arai M, Dino R, Milhomem PS, Sgarbi GNC (1995) Micropaleontologia da Formação Areado, Cretáceo da Bacia Sanfranciscana: estudo dos ostracodes e palinologia. In: 14º Congresso Brasileiro de Paleontologia, Atas, Uberaba, Sociedade Brasileira de Paleontologia, pp 1–2

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

Barbosa EM, Delicio MP, Coimbra JC (1997) Conchostracans and ostracodes indicators of paleoenvironment in the Alto Sanfranciscana Basin, Olhos d'Agua Area, Northwest of Minas Gerais state Brazil. In: The first international conference application of micropaleontology in environmental sciences. Tel Aviv, pp 37–38

Barbosa GG, Langer MC, Martins NO (2023) Montefeltro FC (2023) Assessing the palaeobiology of *Vespersaurus paranaensis* (Theropoda, Noasauridae), Cretaceous, Bauru Basin - Brazil, using Finite Element Analysis. Cretac Res 150:105594. https://doi.org/10.1016/j.cretres.2023.105594

Barbosa O (1965) Geologia econômica e aplicada a uma parte do Planalto Central brasileiro. In: 19º Congresso Brasileiro de Geologia, Rio de Janeiro, Sociedade Brasileira de Geologia, Anais pp 1–11

Barbosa O, Braun OPG, Dyer RC, da Cunha CABR (1970) Geologia da região do Triângulo Mineiro. Boletim da Divisão de Fomento da Produção Mineral 136:1–140

Bertolini G, Marques JC, Hartley AJ, Basei MAS, Frantz JC (2021) Santos PR (2021) Determing sediment provenance history in a Gondwanan erg: Botucatu Formation, Northern Paraná Basin, Brazil. Sediment Geol. https://doi.org/10.1016/j.sedgeo.2021.105883

Bittencourt JS, Brandão NCA (2021) A segmented wormlike specimen from the Lower Cretaceous lacustrine shales of the Sanfranciscana Basin in southeast Brazil. J S Amn Earth Sci 111 (2021) 103488. https://doi.org/10.1016/j.jsames.2021.103488

Bittencourt JS, Langer MC (2011) Mesozoic dinosaurs from Brazil and their biogeographic implications. Anais da Academia Brasileira de Ciências 83 (1):23–60. ISSN 0001-3765

Bittencourt JS, Kuchenbecker M, Vasconcelos AG, Meyer KEB (2015) O registro fóssil das coberturas sedimentares do cráton do São Francisco em Minas Gerais. Geonomos 23(2):39–62

Bittencourt JS, Rohn R, Gallego OF, Monferra MD, Uhlein A (2018) The morphology and systematics of the clam shrimp *Platyestheria* gen. nov. *abaetensis* (Cardoso) (Crustacea, Spinicaudata) from the Lower Cretaceous of the Sanfranciscana Basin, southeast Brazil. Cretac Res 91:274–286

Brito PM, Figueiredo FJ, Leal MEC (2020) A revision of *Laeliichthys ancestralis* Santos, 1985 (Teleostei: Osteoglossomorpha) from the Lower Cretaceous of Brazil: Phylogenetic relationships and biogeographical implications. PLoS ONE 15(10):e0241009. https://doi.org/10.1371/journal.pone.0241009

Cabral VC, Mescolotti PC (2021) Varejão FG (2021) Sedimentary facies and depositional model of the Lower Cretaceous Quiricó Formation (Sanfranciscana Basin, Brazil) and their implication for the occurrence of vertebrate fauna at the Coração de Jesus region. J S Am Earth Sci 112:103632. https://doi.org/10.1016/j.jsames.2021.103632

Campos JEG, Dardenne MA (1997a) Estratigrafia e sedimentação da Bacia Sanfranciscana: uma revisão. Revista Brasileira de Geociências 27(3):269–282

Campos JEG, Dardenne MA (1997b) Origem e evolução tectônica da Bacia Sanfranciscana. Revista Brasileira de Geociências 27(3):283–294

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. https://doi.org/10.1016/j.palaeo.2017.06.010

Cardoso RN (1965) Sobre a ocorrência no Brasil de Monoleiolophinae e Afrograptidae, conchostráceos carenados. Divisão de Geologia e Mineralogia, Departamento Nacional da Produção Mineral, Boletim 221, 35p

Cardoso AR, Basilici G (2022) Silva, PAS (2022) Early diagenetic calcite replacement of evaporites in playa lakes of the Quiricó Formation (Lower Cretaceous, SE Brazil). Sed Geol 438:106212. https://doi.org/10.1016/j.sedgeo.2022.106212

Cardoso AR, Basilici G, Mesquita ÁF (2023) The Cretaceous palaeodesert of the Sanfranciscana Basin (SE Brazil): a key record to track dissolved evaporites in the West Gondwana. Cretac Res. https://doi.org/10.1016/j.cretres.2023.105788

Carmo DA, Tomassi HZ, Oliveira SBSG (2004) Taxonomia e distribuição estratigráfica dos ostracodes da Formação Quiricó, Grupo Areado (Cretáceo Inferior), Bacia Sanfranciscana, Brasil. Revista Brasileira de Paleontologia 7(2):139–149

Carrano MT, Loewen MA, Sertich JJW (2011) New materials of *Masiakasaurus knopfleri* Sampson, Carrano and Forster, 2001, and implications for the morphology of the Noasauridae. Smithson Contrib Paleobiol 95:1–53

Carvalho AB, Zaher H, da Silva RR, Nascimento PM (2012) Análise morfológica dos dentes de terópodes (Dinosauria: Saurischia) da Formação Quiricó, Eocretáceo da Bacia Sanfranciscana, estado de Minas Gerais. In: 8º Simpósio Brasileiro de Paleontologia de Vertebrados, Recife, Boletim de Resumos, p 109

Carvalho IS, Kattah SS (1998) As pegadas fósseis do Paleodeserto da Bacia Sanfranciscana (Jurássico Superior-Cretáceo Inferior, Minas Gerais). An Acad Bras Ciênc 70(1):53–67

Carvalho IS, Bertolino LC, Borghi LF, Duarte L, Carvalho MSS, Cassab RCT (1994) Range charts of the fossils of the Cretaceous interior basins—the São Francisco Basin. In: Beurlen G, Campos DA, Viviers MC (eds) Stratigraphic range of Cretaceous mega- and microfossils of Brazil. UFRJ, Rio de Janeiro, pp 333–352

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. Cretac 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, vol 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 JC, Santucci RM (2021) New fish remains from the Quiricó Formation (Lower Cretaceous, Sanfranciscana Basin), Minas Gerais, Brazil. Journal of South American Earth Sciences 111:103430. https://doi.org/10.1016/j.jsames.2021.103430

Carvalho MSS, Campos DA, Dardenne MA, Sgarbi GNC, Campos JEG, Cartelle C (1995) Ocorrência de celacantídeo *Mawsonia* nos sedimentos lacustres da Bacia Sanfranciscana, noroeste do Estado de Minas Gerais. In: XIV Congresso Brasileiro de Paleontologia, Uberaba, p 35

Carvalho MSS, Maisey JG (2008) New occurrence of *Mawsonia* (Sarcopterygii: Actinistia) from the Early Cretaceous of the Sanfranciscana Basin, Minas Gerais, southeastern Brazil. Geol Soc Spec Pub 295:109–144

Casamiquela RM (1964) Estudios Icnológicos. Problemas y métodos de la Icnología con aplicación al estudio de pisadas mesozóicas (Reptilia, Mammalia) de la Patagónia. Buenos Aires, p 229, 26 plates

Castro JC (1996) O Cretáceo da porção sul da Bacia Sanfranciscana: uma breve revisão. In: 4º Simpósio sobre o Cretáceo do Brasil, Águas de São Pedro, Sociedade Brasileira de Geologia, Boletim pp 209–211

Coimbra JC (2020) The Genus *Cypridea* (Crustacea, Ostracoda) and the age of the Quiricó Formation, SE Brazil: a critical review. Revista Brasileira de Paleontologia 23(2):90–96. https://doi.org/10.4072/rbp.2020.2.02

Delcourt R, Brilhante N, Pires-Domingues RA, Hendrickx C, Grillo ON, Augusta BG, Maciel BS, Ghilardi AM, Ricardi-Branco F. (2024) Biogeography of theropod dinosaurs during the Late Cretaceous: evidence from central South America. Zool J Linn Soc XX:1–40. https://doi.org/10.1093/zoolinnean/zlad184

Delicio MP, Barbosa EM, Coimbra JC, Vilella RA (1998) Ocorrência de conchostraceos e ostracodes em sedimentos Pós-Paleozóicos da Bacia do Alto Sanfranciscana, Olhos d´Água, noroeste de Minas Gerais, Brasil. Acta Geologia Leopoldensia 46(47):13–20

Dias-Brito D, Pessagno Jr. EA, Castro JC (1999) Novas considerações cronoestratigráficas sobre silexito a radiolários do suI da Bacia Sanfranciscana, Brasil, e a ocorrência de foraminíferos planctônicos nestes depósitos. In: 5º Simpósio sobre o Cretáceo do Brasil, Boletim, Rio Claro, Sociedade Brasileira de Geologia, pp 567–575

Díaz-Martínez I, Cónsole-Gonella C, de Valais S, Salgado L (2018) Vertebrate tracks from the Paso Córdoba fossiliferous site (Anacleto and Allen formations, Upper Cretaceous), Northern Patagonia, Argentina: preservational, environmental and palaeobiological implications. Cretac Res 83:207–220. https://doi.org/10.1016/j.cretres.2017.07.008

Duarte L (1968) Restos vegetais fósseis da Formação Areado. In: 22º Congresso Brasileiro de Geologia, Belo Horizonte, Sociedade Brasileira de Geologia, Anais, p 68

Duarte L (1985a) Vegetais fósseis da Chapada do Araripe. In: Campos DA, Ferreira CS, Brito IM, Viana CF (eds) Coletânea de trabalhos paleontológicos. DNPM, Rio de Janeiro, pp 557–563

Duarte L (1985b) Vegetais fósseis da Formação Areado, município de Presidente Olegário, Minas Gerais. In: 9º Congresso Brasileiro de Paleontologia, Fortaleza, Sociedade Brasileira de Paleontologia, Resumos p 59

Duarte L (1997) Vegetais do Cretáceo Inferior (Aptiano) da Formação Areado, município de Presidente Olegário, Estado de Minas Gerais. An Acad Bras Ciênc 69:495–503

Ellemberger P (1970) Le niveaux paléontologiques de première apparition des mammifères primordiaux en Afrique du Sud e leur ichnologie. Establissement de zones stratigraphiques detaillées dans Le Stormberg du Lesotho (Afrique du Sud) (Trias Supérieur à Jurassique). In: Haughton SH (ed) Proceedings and papers of the Second Gondwana Symposium, South Africa, 1970. South African Council for Scientific and Industrial Research, Pretoria, pp 343–370

Falkingham PL, Gatesy SM (2014) The birth of a dinosaur footprint: subsurface 3D motion reconstruction and discrete element simulation reveal track ontogeny. PNAS 111(51):18279–18284

Falkingham PL, Marty D, Richter A (eds) (2016) Dinosaur tracks: the next steps. Indiana University Press, p 428. ISBN-10: 9780253021021

Fragoso LGC, Bittencourt JS, Mateus ALD, Cozzuol MA, Richter M (2019) Shark (Chondrichthyes) microremains from the Lower Cretaceous Quiricó Formation, Sanfranciscana Basin, Southeast Brazil Shark (Chondrichthyes) microremains from the Lower Cretaceous Quiricó Formation, Sanfranciscana Basin, Southeast Brazil. Historical Biology https://doi.org/10.1080/08912963.2019.1692830

Gallego OF, Martins-Neto RG (2006) The Brazilian Mesozoic conchostracan faunas: its geological history as an alternative tool for stratigraphic correlations. Geociências 25:231–239

García-Ramos JC, Piñuela L, Lires JL (2006) Atlas del Jurásico de Asturias. Oviedo. Ediciones Nobel. p 228. ISBN: 9788484596578
Gatesy SM (2003) Direct and Indirect tracks features: what sediment did a dinosaur touch? Ichnos 10:91–98
Gatesy SM, Middleton KM, Jenkins FA Jr, Shubin NH (1999) Three-dimensional preservation of foot movements in Triassic theropod dinosaurs. Nature 399(6732):141–144
Grossi Sad JH, Cardoso RN, da Costa MT (1971) Formações cretácicas em Minas Gerais: uma revisão. Revista Brasileira de Geociências 1:2–13
Kattah SS (1991) Análise faciológica e estratigráfica do Jurássico Superior/Cretáceo Inferior na porção meridional da bacia do São Francisco, oeste do estado de Minas Gerais. Universidade Federal de Outro Preto, Escola de Minas, Departamento de Geologia (Dissertação de Mestrado), p 227
Kattah SS (1992) Novas considerações sobre o Aptiano-Albiano da Bacia Sanfranciscana. In: 2° Simpósio sobre as Bacias Cretácicas Brasileiras, Rio Claro, UNESP, pp 118–119
Kattah SS (1993) A ocorrência de pegadas de dinossauros no Grupo Areado, porção meridional da bacia Sanfranciscana, oeste de Minas Gerais. An Acad Bras Ciênc 65(2):217–218
Kattah SS, Koutsoukos EAM (1992) Ocorrências de radiolários em fácies de origem marinha no Mesozóico da Bacia Sanfranciscana. Revista da Escola de Minas 45:214
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
Kuban GJ (1991) Elongate dinosaur tracks. In: Gillette DD, Lockley MG (eds) Dinosaur tracks and traces. Cambridge University Press, Cambridge, pp 57–72
Langer MC, Martins NO, Manzig PC, Ferreira GS, Marsola JCA, Fortes E, Lima R, Sant'ana LCF, Vidal LS, Lorencato RHS, Ezcurra MD (2019) A new desert-dwelling dinosaur (Theropoda, Noasaurinae) from the Cretaceous of south Brazil. Sci Rep 9:9379. https://doi.org/10.1038/s41598-019-45306-9
Leite AM, Carmo DA (2021) Description of the stratotype section and proposal of hypostratotype section of the Lower Cretaceous Quiricó formation, São Francisco Basin, Brazil. Anais da Academia Brasileira de Ciências 93(Suppl. 2):e20201296. https://doi.org/10.1590/0001-3765202120201296
Leite AM, Carmo DA, Ress CB, Pessoa M, Caixeta GM, Denezine M, Adorno RR, Antonietto LS (2018) Taxonomy of limnic Ostracoda (Crustacea) from the Quiricó Formation, Lower Cretaceous, São Francisco basin, Minas Gerais State, Southeast Brazil. J Paleontol 1–20. https://doi.org/10.1017/jpa.2018.1
Leonardi G (1977) Two new ichnofaunas (vertebrates and invertebrates) in the eolian Cretaceous sandstones of the Caiuá Formation in northwest Paraná. In: 1º Simpósio Regional de Geologia, São Paulo, 1977, Sociedade Brasileira de Geologia, Actas, pp 112–128
Leonardi G (1980) On the discovery of an abundant ichnofauna (vertebrates and invertebrates) in the Botucatu Formation s.s. in Araraquara, São Paulo, Brazil. Anais da Academia Brasileira de Ciências 52(3):559–567
Leonardi G (1981a) As localidades com rastros fósseis de tetrápodes na América Latina. In: 2º Congresso Latinoamericano de Paleontologia, Porto Alegre, 1981, Porto Alegre, Anais 2:929–940
Leonardi G (1981b) Novo icnogênero de tetrápode mesozoico da Formação Botucatu, Araraquara, SP. An Acad Bras Ciênc 53(4):793–805
Leonardi G (1991) Inventory and statistics of the South American dinosaurian ichnofauna and its paleobiological interpretation. In: Gillette DD, Lockley MG (eds) Dinosaur tracks and traces. Cambridge University Press, Cambridge, pp 165–178
Leonardi G (1994) Annotated Atlas of South American Tetrapod Footprints (Devonian to Holocene). Ministério das Minas e Energia, Rio de Janeiro, Companhia de Pesquisa e Recursos Minerais, p 247

Leonardi G, Godoy LC (1980) Novas pistas de tetrápodes da Formação Botucatu no estado de São Paulo. In: 31º Congresso Brasileiro de Geologia, Camboriú, 1980, Camboriú, Santa Catarina, Sociedade Brasileira de Geologia, Anais 5:3080–3089

Leonardi G, Lima FHO (1990) A revision of the Triassic and Jurassic tetrapod footprints of Argentina and a new approach on the age and meaning of the Botucatu Formation fooptrints (Brazil). Revista Brasileira de Geociências 20(1–4):216–229

Leonardi G, Sarjeant WAS (1986) Footprints representing a new Mesozoic vertebrate fauna from Brazil. Mod Geol 10:73–84

Lima MR (1979) Palinologia dos calcários laminados da Formação Areado, Cretáceo de Minas Gerais. In: 2º Simpósio Regional de Geologia, Rio Claro, Sociedade Brasileira de Geologia, Atas pp 203–216

Lockley M (1991) Tracking dinosaurs. Cambridge University Press, Cambridge, p 238

Lockley M, Conrad K (1991) 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

Lockley MG, Gillette DD (1991) Dinosaur tracks and traces: an overview. In: Gillette DD, Lockley MG (eds) Dinosaur tracks and traces. Cambridge University Press, Cambridge, pp 3–10

Mescolotti PC, Varejão FG, Warren LV, Ladeira FSB, Giannini PCF, Assine ML (2019) The sedimentary record of wet and dry eolian systems in the Cretaceous of Southeast Brazil. Braz J Geol 49(3) https://doi.org/10.1590/2317-4889201920190057.

Milàn J, Bromley RG (2006) True tracks, undertracks and eroded tracks, experimental work with tetrapod tracks in laboratory and field. Palaeogeogr Palaeoclimatol Palaeoecol 231:253–264

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

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. N M Mus Nat Hist Sci Bull 37:352–364

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

Nascimento DL, Martinez P, Batezelli A, Ladeira F (2022) Corrêa L (2022) From the micromorphology of paleoweathering fronts to paleoenvironmental analysis: a case study of the Cretaceous dune fields of Sanfranciscana Basin, Brazil. Catena 211:106008

Pessagno Jr. EA, Dias-Brito D (1996) O silexito a radiolários do sul da Bacia Sanfranciscana, Brasil: idade, origem e significado. In: 4º Simpósio sobre o Cretáceo do Brasil, Águas de São Pedro, Sociedade Brasileira de Geologia, Boletim pp 213–221

Pessagno Jr. EA, Dias-Brito D, Castro JC (1997) Tectonostratigraphic significance of radiolarian chert in Lower Cretaceous continental sequence, Minas Gerais, Brazil. In: 29th GSA Annual Meeting, Utah, p 374

Pires-Domingues RA (2009) Paleogeografia do Alto de Paracatu: o registro geológico dos *bone-beds* de dinossauros da Bacia Sanfranciscana. Universidade de São Paulo, Tese de Mestrado, p 110

Reynolds RE (1991) Dinosaur trackways in the Lower Jurassic Aztec Sandstone of California. In: Gillette DD, Lockley MG (eds) Dinosaur tracks and traces. Cambridge University Press, Cambridge, pp 285–292

Ribeiro AC, Poyato-Ariza FJ, Bockmann FA, Carvalho MR (2018) Phylogenetic relationships of Chanidae (Teleostei: Gonorynchiformes) as impacted by *Dastilbe moraesi*, from the Sanfranciscana basin Early Cretaceous of Brazil. Neotrop Ichthyol 16(3):e180059. https://doi.org/10.1590/1982-0224-20180059

Romano M, Whyte MA (2003) Jurassic dinosaur tracks and trackways of the Cleveland Basin, Yorkshire: preservation, diversity and distribution. Proc Yorks Geol Soc 54:185–215

Santos MECM (1971) Um nôvo artrópodo da Formação Areado, Estado de Minas Gerais. An Acad Bras Ciênc 43:415–420

Santos RS (1985) *Laeliichthys ancestralis*, novo gênero e espécies de Osteoglossiformes do Aptiano da Formação Areado, estado de Minas Gerais, Brasil, In: Campos DA, Ferreira CS, Brito IM, Viana CF (eds) Paleontologia e Estratigrafia, Coletânea de Trabalhos Paleontológicos. DNPM, Brasília, pp 161–167

Santucci RM, Pinto RL, Almeida MF, Souza LM, Mineiro AS, Santos DM (2014) Um dente de terópode da Formação Quiricó, Bacia Sanfranciscana (Aptiano) do norte de Minas Gerais. In: 9º Simpósio Brasileiro de Paleontologia de Vertebrados, Vitória, pp 124

Sanz E, Arcos A, Pascual C, Pidal IM (2016) Three-dimensional elasto-plastic soil modelling and analysis of sauropod tracks. Acta Palaeontol Pol 61(2):387–402

Sarjeant WAS, Leonardi G (1987) Substrate and Footprints. In: Leonardi G (ed) Glossary and Manual of Tetrapod Footprint Palaeoichnology. Brasília, DNPM (Geological Survey of Brazil, Brasília)

Scherer CMS (2000) Eolian dunes of the Botucatu formation (Cretaceous) in Southernmost Brazil: morphology and origin. Sed Geol 137:63–84

Scherer CMS (2002) Preservation of aeolian genetic units by lava flows in the Lower Cretaceous of the Paraná Basin Southern Brazil. Sedimentology 49(1):97–116

Scherer CMS, Lavina EL (2005) Sedimentary cycles and facies architecture of aeolian-fluvial strata of the Upper Jurassic Guará Formation, Southern Brazil. Sedimentology 52:1323–1341

Scherer CMS, Lavina EL (2006) Stratigraphic evolution of a fluvial-eolian succession: the example of the Upper Jurassic-Lower Cretaceous Guará and Botucatu formations, Paraná Basin, Southernmost Brazil. Gondwana Res 9:475–484

Scherer CMS, Faccini UF, Lavina EL (2002) Arcabouço estratigráfico do Mesozóico da Bacia do Paraná. In: Holz M, De Ros LF (eds) Geologia do Rio Grande do Sul. Instituto de Geociências/CIGO, pp 335–354

Scorza FP, Santos RS (1955) Ocorrência de folhelho fossilífero no município de Presidente Olegário, Minas Gerais. Boletim do Departamento Nacional de Produção Mineral—Divisão De Geologia e Mineralogia 155:1–27

Sgarbi GNC, Sgarbi PBA, Campos JEG, Dardenne MA, Penha UC (2001) Bacia Sanfranciscana: o registro Fanerozóico da Bacia do São Francisco In: Pinto CP, Martins-Neto MA (eds) Bacia do São Francisco: Geologia e Recursos Naturais. SBG, Belo Horizonte, pp 93–138

Sgarbi PCB, Heaman LM, Gaspar JC (2004) U-Pb perovskite ages for Brazilian kamafugitic rocks: further support for a temporal link to a mantle plume hotspot track. J S Am Earth Sci 16(8):715–724. https://doi.org/10.1016/j.jsames.2003.12.005

Silva RR (2013) Descrição osteológica e posicionamento filogenético de um terópode (Dinosauria, Saurischia) do Cretáceo Inferior da Bacia Sanfranciscana, município de Coração de Jesus, Minas Gerais. Tese de Mestrado, Universidade de São Paulo, Brasil, p 121

Suguio K, Barcelos JH (1983) Paleoclimatic evidence from the Areado Formation, Cretaceous of the Sanfranciscana Basin, State of Minas Gerais, Brazil. Revista Brasileira de Geociências 13:229–231

Thulborn T (1990) Dinosaur tracks. London, Chapman and Hall, 1st edn. 410

Winkler DA, Jacobs LL, Congleton JD, Downs WR (1991) Life in a sand sea: biota from Jurassic interdunes. Geology 19:889–892

Zaher H, Pol D, Carvalho AB, Nascimento PM, Riccomini C, Larson P, Juarez-Valieri R, Pires-Domingues R, Silva Jr. NJd, Campos DA (2011) A complete skull of an Early Cretaceous sauropod and the evolution of advanced titanosaurians. PlosOne 6:1–10

Zaher H, Pol D, Navarro BA, Delcourt R, Carvalho AB (2020) An Early Cretaceous theropod dinosaur from Brazil sheds light on the cranial evolution of the Abelisauridae. CR Palevol 19(6):101–115. https://doi.org/10.5852/cr-palevol2020v19a6

Zeng X (1982) Fossil handbook of hunan province (Geology Bureau of Hunan Province)

Zhen S, Zhen B, Rao C (1986) Dinosaur footprints of Jinning. Yunnan Mem Beijing Nat His Museum 33:1–18

Zhen S, Jianjun L, Chenggang R, Mateer NJ, Lockley MG (1991) A review of dinosaur footprints in China. In: Gillette DD, Lockley MG (eds) Dinosaur tracks and traces. Cambridge University Press, Cambridge, pp 187–197