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Dinosaur Tracks of Mesozoic Basins in Brazil

Impact of Paleoenvironmental and Paleoclimatic Changes

Springer

Chapter 1
Dinosaur Footprints Throughout Mesozoic Basins in Brazil

Ismar de Souza Carvalho

1.1 Introduction

The major paleogeographic configurations at the end of Paleozoic, related to global tectonics, induced environmental changes, including climate and distribution of landmasses and seas. The worldwide transformations resulted in mass extinctions and provided new possibilities to the organism's evolution. The influence of such changes on terrestrial ecosystems allowed the emergence of the dinosaurs during Triassic. This group is the result of ecological opportunities after the Permian-Triassic and a sustained long-term adaptive response to climatic shifts that lasted for ca. 57 Ma (Simões et al. 2022).

Dinosaurs were rare and geographically restricted during the first steps of their diversification in Late Triassic and the extinction of co-occurring groups such as aetosaurs, rauisuchians, and non-mammalian therapsids (Benton 1983; Brusatte et al. 2008; Langer and Godoy 2022; Langer et al. 2010; Dunne et al. 2023). Changes in the global climate played an important role in the dinosaur's distribution throughout the Mesozoic, especially during Triassic and the Triassic to Jurassic transition (Tucker and Benton 1982; Benton 1983; Whiteside et al. 2015; Brusatte et al. 2008; Olsen et al. 2022). After the end-Triassic mass extinction event they presented a wider distribution and greater abundance, an opportunistic expansion model (Dunne et al. 2023), in which a Triassic-Jurassic climatic crisis enabled their global abundance (Dunne et al. 2023). Part of this history is possible to observe from the fossils and ichnofossils found in the Brazilian sedimentary basins, that include large syneclises and rift basins throughout Mesozoic.

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During the end of Mesozoic, the tectonic events linked to the Gondwana break-up caused a new geographic position of the South American continent. Throughout an innovative cycle of great changes, occurred many extinction and diversification events of the flora and fauna as a response to the environmental transfigurations (Bittencourt and Langer 2011; Bronzati et al. 2015; Dunhill et al. 2016; Gorscak and O'Connor 2016). Concerning the Southern hemisphere, the South Atlantic origin has driven deep modifications in climate, geographic configuration, distribution of land and seas (Arai 2014a, b) with a direct influence in the biota, which were deeply modified by the South Atlantic tectonic scenarios. Nevertheless, in spite of the wide distribution in the Brazilian intracratonic and marginal sedimentary basins, the genesis of rocks originated in continental environments and the diversity of their fossils are poorly understood.

The dinosaur tracks are important elements to the reconstruction of terrestrial and coastal environments improving paleoenvironmental interpretation and the knowledge of the biota diversity. An overview of the spatial and temporal changes in the environments during the Mesozoic are important to understand the evolution and territorial distribution of the dinosaurs, improving the data obtained from fossils. Footprints are temporal markers of subaerial surfaces throughout the Mesozoic basins, recording cyclical changes in the environmental conditions during the deposition. They are produced in an exposed substrate or in a flooded area, resulting in distinct patterns of tracks. If there is a waterlogged substrate there will occur liquefaction of the sediments and local deformation, or in the case of more cohesive sediments, the morphological aspects of the footprint will be recorded, including features such as pads and claws, which enable the knowledge of the trackmaker. Besides behavioral insights into the trackmaker's biology, substrate properties, and environmental factors, footprints are also an important tool for the reconstruction of the terrestrial ecosystems during the Gondwanan Mesozoic throughout the Brazilian territory.

1.2 Geological Context

Preservation of animal footprints in the fossil record is strongly dependent on taphonomic processes, although it is the grain size and the sedimentation regime that determines if preservation will take place and if a footprint will be incorporated into the sedimentary record. The possibility of preservation is minimal during long-lasting periods of exposure without any sedimentation, and preservation is favored by rapid and significant sedimentation events. Thus, footprints are most commonly preserved in environments of cyclic sedimentation (Lockley 1991; Carvalho and Leonardi 2021; Carvalho et al. 2021a).

Dinosaur footprints and trackways are found in many sedimentary basins throughout the Brazilian Mesozoic. The basin's classification of sedimentary areas in Brazil is grouped in two wide groups of intracratonic (syneclises) and rift

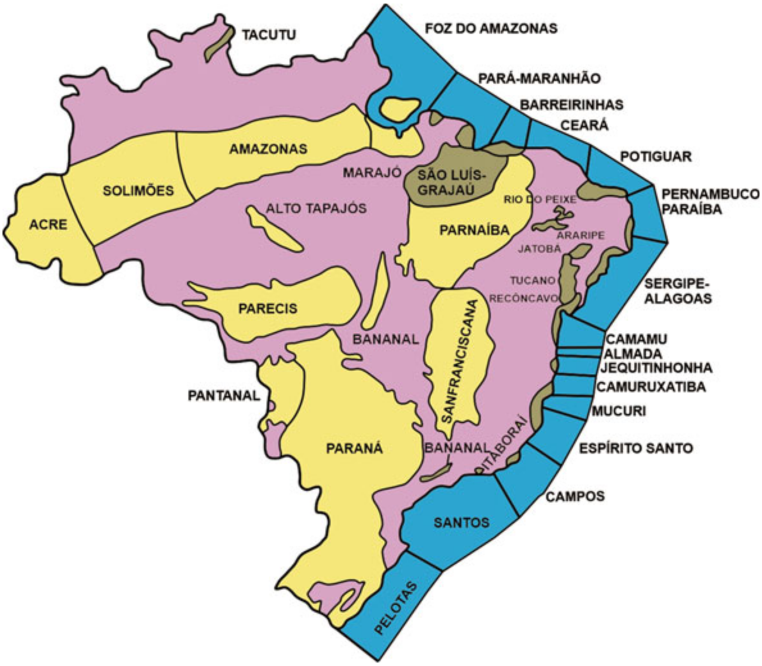

Fig. 1.1 Brazilian sedimentary basins with the large intracratonic (syneclises) and the rift basins (modified from Lucchesi 1998)

basins (Fig. 1.1). The main intracratonic basins are Paraná, Parecis, Sanfranciscana, Parnaíba and Amazonas basin whose geological history spans from Paleozoic to Cenozoic in a syneclise tectonic context, although initially developed on Cambro-Ordovician rift systems (Toczeck et al. 2019). During Mesozoic the South Atlantic opening created new basins in the present Atlantic margin and in the interior Proterozoic belts.

1.2.1 Paraná Basin

The Paraná Basin records a span time of sedimentation (Fig. 1.2) throughout most all of the Phanerozoic (Henrique-Pinto et al. 2021). It is a sag-type intracratonic depression developed on the South American platform covering an area of around 1.4 million km^2 (Milani 1992; Milani and Ramos 1998; Milani and Zalán 1999). Milani et al. (2007) divided the Paraná Basin into six supersequences: the Rio Ivaí (Sandbian-Aeronian, 455–438 Ma), Paraná (Pridoli-Famennian, 420–360 Ma), Gondwana I (Pennsylvanian–Lower Triassic, 323–247 Ma), Gondwana II (Anisian–Norian, 247–208 Ma), Gondwana III (Upper Jurassic–Berriasian, 149–139 Ma) and Bauru-Caiuá (Turonian–Maastrichtian, 93–66 Ma).

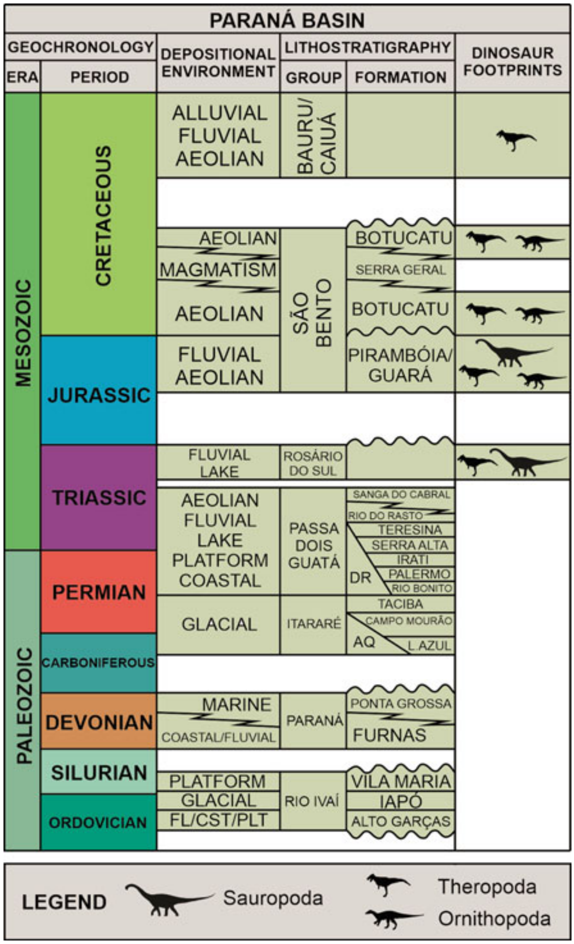

Fig. 1.2 Simplified stratigraphic chart of the Paraná Basin (modified from Milani et al. 2007; Teramoto et al. 2020) and occurrences of dinosaur footprints and trackways

The last three upper supersequences of Milani et al. (2007) are characterized by continental sedimentary rocks. The exclusive Triassic sedimentation is recorded with the Rosário do Sul Group (Gondwana II) followed by the Gondwana III-cycle (Henrique-Pinto et al. 2021). In the Carnian deposits of Santa Maria Formation (Rosário do Sul Group) there are dinosaur footprints (Fig. 1.3) interpreted as done by theropod and prosauropod trackmakers (Silva et al. 2007, 2008). Also in the Rio Grande do Sul State, during the Late Jurassic, there are footprints in sand bars of aeolian and fluvial deposits interpreted as ornithopod, theropod and sauropod trackmakers (Guará Formation, Francischini et al. 2015), accumulated in a semi-arid climate (Scherer and Lavina 2005, 2006). A correlated deposit is the Pirambóia Formation (São Paulo State), a Late Jurassic fluvial-aeolian unit, in which dinosaur footprints in cross section were recognized in wet interdune deposits (Christofoletti et al. 2021). A more arid climate during the last stages of Upper Jurassic and

Lower Cretaceous enable the establishment of extensive field dunes covering all the basin (Botucatu Formation, São Bento Group), where dinosaur tracks occur in aeolian dunes of the Botucatu paleodesert (Fernandes and Carvalho 2007; Leonardi et al. 2007). These deposits are coeval with the Early Cretaceous magmatic activity (Scherer 2000, 2002; Scherer et al. 2002; Brückmann et al. 2014) grouped as Serra Geral Formation (Mizusaki and Thomaz Filho 2004) or Serra Geral Group (Rossetti et al. 2018).

The upper continental sedimentation of the Bauru Supersequence (Bauru and Caiuá groups) is a post-volcanic section accumulated in the flexural depression loaded by the Serra Geral Group (Milani and De Wit 2008; Henrique-Pinto et al. 2021). There is a very distinct basin area and change of the depocenters when compared with the Paraná Basin. Then, this supersequence is considered to encompass other basin, the

Fig. 1.3 **a** Triassic footprints from Rosário do Sul Group (Caturrita Formation, Norian, Paraná Basin). **a** Dinoturbation in a sandstone bedding plane at Faxinal do Soturno, Rio Grande do Sul State; **b** a theropod footprint. Photograph **b** by Michel Godoy

Bauru Basin, covering an area of approximately 379,362 km^2 (Menegazzo et al. 2016). This basin includes a large area of Paraná, São Paulo, Mato Grosso, Mato Grosso do Sul, Goiás, and Minas Gerais states, as well as a part of Paraguay with sedimentation from the Turonian until the Maastrichtian, in semi-arid conditions (Batezelli 2010, 2017; Dias-Brito et al. 2001; Arai and Fernandes 2023). The Bauru Basin developed in the back-bulge province of a retroarc foreland system in response to Andean orogenic events with supracrustal load (Menegazzo et al. 2016). There is one reference of an isolated tridactyl footprint in the Maastrichtian deposits (Bauru Group, Marília Formation) of this basin (Riff et al. 2018) and few footprints and trackways in the Caiuá Group (Leonardi 1977; Fernandes et al. 2008).

1.2.2 Parecis Basin

It is located in the central-west region of Brazil, in the southwest sector of the Amazon Craton. During the Early Paleozoic, the Amazon region was affected by an extensional event, when a system of intracontinental rifts was established (Siqueira 1989). A syneclise was then developed over this Lower Paleozoic rift system (Pedreira and Bahia 2000). Part of the Silurian and Devonian history of the Parecis Basin is related to the Paraná Basin. The Mesozoic deposits are linked to an extensional event (Lower Jurassic), connected to the separation between South America and Africa. There are sandstones (Rio Ávila Formation), interpreted as deposition in aeolian environments, followed by basaltic flows with approximately 198 Ma (Marzolli et al. 1999). The Cretaceous Supersequence (Parecis Formation) is composed of conglomerates and sandstones, deposited in fluvial and aeolian environments (Pedreira da Silva et al. 2003). So far, no record of fossil footprints has been found in the Mesozoic deposits of this basin.

1.2.3 Sanfranciscana Basin

The Sanfranciscana Basin is a 220,000 km^2 syneclise basin (Fig. 1.4) established in the São Francisco Craton divided in two sub basins: Abaeté (south) and Urucuia (north). It is located in central-eastern Brazil (Minas Gerais, Goiás, Bahia, Tocantins, Piauí and Maranhão states), oriented in the N–S direction with approximately 1,100 km in length and 200 km in width (Cabral et al. 2021).

The sedimentary successions of Sanfranciscana Basin include the Santa Fé (Permian-Carboniferous), Areado (Lower Cretaceous), Mata da Corda (Upper Cretaceous) and Urucuia groups (Campos and Dardenne 1997a, b; Sgarbi 2000; Sgarbi et al. 2001, 2004).

The oldest sedimentary succession is the Santa Fé Group deposited during Late Carboniferous and Permian. The deposits are divided into Floresta (conglomerates and coarse sandstones) and Tabuleiro (mudstones, shales, siltstones and sandstones)

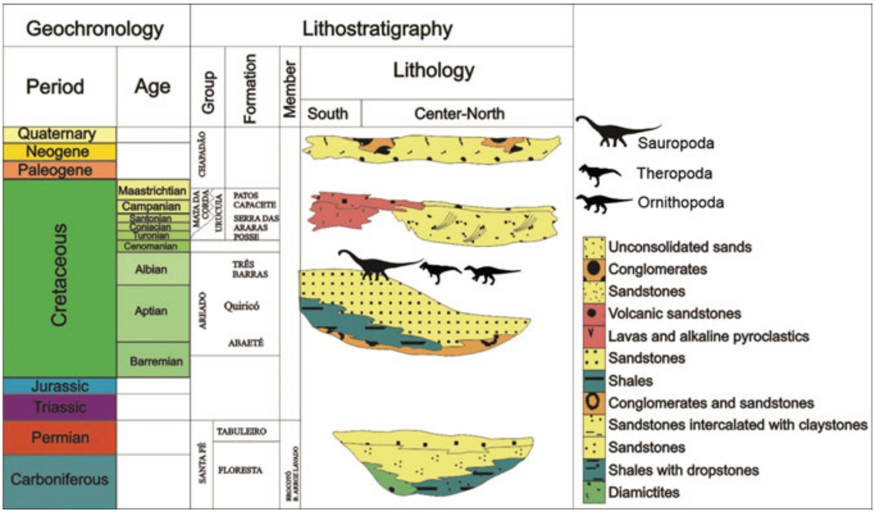

Fig. 1.4 Stratigraphic chart of Sanfranciscana Basin (modified from Carmo et al. 2004; Leite and Carmo 2021) and occurrence of dinosaur footprints and trackways

formations. It is a glaciogenic sequence that represents a gondwanan glaciation record (Campos and Dardenne 1997a).

The Lower Cretaceous Areado Group (Berriasian-Aptian) comprises the Abaeté, Quiricó, and Três Barras formations. The Abaeté Formation (up to 30 m thickness) is composed of matrix-supported and clast-supported conglomerates interpreted as deposited by braided rivers and alluvial fans (Campos and Dardenne 1997a). The Quiricó Formation (up to 100 m thickness) are constituted of fine-grained sediments, including shales, siltstones and fine grained siltstones with some levels of evaporates, that record a lacustrine sedimentation (Campos and Dardenne 1997a, b; Mescolotti et al. 2019). The ostracod data and palynologic content of the Quiricó Formation indicate a Barremian to Aptian age (Arai et al. 1995; Carmo et al. 2004). The Três Barras Formation (maximum thickness of 150 m) is mainly sandstones, with conglomerates and fine-grained siltstones and shales (Campos and Dardenne 1997a). Mescolotti et al. (2019) recognized within Três Barras Formation an unconformity (at least Cenomanian to Coniacian) separating the sedimentary succession into a lower (wet aeolian system) and an upper stratigraphic unit (dry eolian system). This is a record of the desertification events in the interior of southeast Brazil during the Cretaceous revealing prevailing winds from northeast, validating models of global paleo-circulation during the Cretaceous in Gondwana (Mescolotti et al. 2019). There was also the deposition in fluvial and deltaic environments.

The paleoclimate in the Sanfranciscana Basin during the Lower Cretaceous (Berriasian-Aptian) is interpreted as in the context of a tropical-equatorial hot arid belts (Skelton et al. 2003). Despite this basin is in the interior of Gondwana Supercontinent there are deposits of shallow lakes (Quiricó Formation) with the signs of a wide biota represented by palynomorphs, gymnosperms and angiosperms, annelids, insects, ostracods, spinicaudatans, elasmobranchs, actinopterygians, coelacanthiforms and dinosaurs (Barbosa 1965; Duarte 1968; Santos 1971; Lima 1979; Arai et al. 1995; Duarte 1997; Carvalho and Kattah 1998; 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 et al. 2015, 2018; Ribeiro et al. 2018; Coimbra 2020; Carvalho and Santucci 2021). The existence of shallow lake environments points to more humid conditions on the southern edge of the arid belt, between 20° and 30° latitude at south (Mescolotti et al. 2019; Nascimento et al. 2022). The dinosaur footprints and trackways of Sanfranciscana Basin occur into the lower portion of the Três Barras Formation. This lower succession is interpreted as moist aeolian systems. Then the dinosaur footprints are settled in an environment with more humid conditions probably related to the Quiricó lakes.

The Mata da Corda Group comprises volcanic alkaline rocks (80 Ma U–Pb average isotopic ages) that overlain the deposits of the Areado Group (Sgarbi et al. 2004). It includes the Patos (alkaline volcanic rocks) and Capacete (epiclastic sediments) formations. The Urucuia Group (Upper Cretaceous) is a 200-m-thick unit and covers an area of approximately 76,000 km^2 (Campos and Dardenne 1997a), composed of sandstones, divided into Posse and Serra das Araras formations. This unit is interpreted as dune field deposits of dry aeolian systems (Mescolotti et al. 2019) followed by an upper succession of fluvial sediments deposited by sheet flows (Spigolon and Alvarenga 2002). The last lithostratigraphic unit is the Chapadão Group, a Quaternary unit that represents the recent sandy, unconsolidated, covers of talus, residual or alluvium origin (Campos and Dardenne 1997a).

1.2.4 Parnaíba Basin

The Parnaíba Basin is a large Paleozoic syneclise in northeastern Brazil, located partially in Tocantins, Ceará, Piauí, Maranhão and Pará states (Fig. 1.5). It is a sag basin up to 3.5 km thick, 1,000 km long and 970 km wide, nearly circular-shaped area (Cordani et al. 1984). The Precambrian crystalline basement comprises a complex lithostructural and tectonic framework formed during the Neoproterozoic–Eopaleozoic Brasilian–Pan African orogenic collage (Almeida et al. 2000; Brito Neves and Fuck 2013; Castro et al. 2013; Porto et al. 2022). This area presents 600,000 km^2 and due the polycyclic tectonic evolution and distinctive sedimentation, Góes (1995) proposed the term Parnaíba Province, an area with four depositional centers (Góes and Feijó 1994): Parnaíba, Alpercatas, Grajaú and Espigão-Mestre basins. The Parnaíba Basin is filled with Ordovician to Early Triassic sediments, mostly of marine, but also fluvial, deltaic and desert environments. The Alpercatas Basin (Jurassic to Cretaceous age) encompasses fluvial-lacustrine and aeolian sedimentary rocks alternated between basaltic flows. The Grajaú and Espigão Mestre basins, both of Cretaceous age are filled with rocks deposited in closed marine environments (Grajaú Basin) and aeolian sandstones (Espigão Mestre Basin) of the northern

Fig. 1.5 Geotectonic units of the Parnaíba Province, which includes distinct depositional areas (Pedreira da Silva et al. 2003)

extension of the Urucuia domain of the Sanfranciscana Basin (Pedreira da Silva et al. 2003).

The chronostratigraphy and lithostratigraphy of the Parnaíba Basin (Fig. 1.6) present as the oldest Paleozoic deposits a pre-Silurian (Cambro-Ordovician) sequence filling up graben-like structures, attributed to the Jaibaras Group (Oliveira and Mohriak 2003; Cerri et al. 2020). After this first deposition there are three depositional supersequences (Pedreira da Silva et al. 2003): Silurian (Serra Grande Group), Devonian-Carboniferous (Canindé Group) and Carboniferous-Triassic (Balsas Group). The Serra Grande Group (Ipu, Tianguá and Jaicós formations) comprises conglomerates, sandstones and shales. The deposits of this unit are interpreted as fluvial and glacial, fluvial and marine deposits of Silurian age. The Canindé Group (Itaim, Pimenteiras, Cabeças, Longá and Poti formations) is composed of sandstones and shales of marine, glacial and fluvial environments. The Carboniferous-Triassic is the Balsas Group (Piauí, Pedra-de-Fogo, Motuca and Sambaíba formations), composed of sandstones, shales, carbonates and stromatolites interpreted as aeolian dunes and tidal flats (Santos and Carvalho 2009).

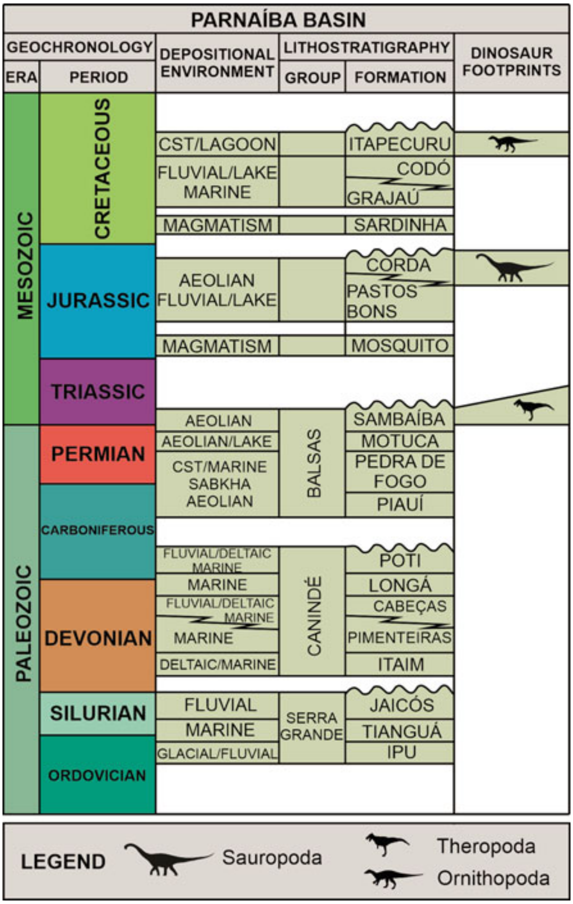

Fig. 1.6 Stratigraphic chart of Parnaíba Basin (adapted from Vaz et al. 2007; Araújo 2017; Pereira et al. 2021) and occurrences of dinosaur footprints and trackways

During the Mesozoic, the main regional tectonic elements were the Xambioá (E–W) Arch, located in the center of the basin, and the Ferrer–Urbano Santos Arch delimiting the small marginal basins associated with the opening of the Equatorial South Atlantic (Araújo 2017). Throughout the Jurassic and Cretaceous, magma flows and diabase dykes indicate the effects of the break-up of Pangea (Sardinha Formation) and Gondwana (Mosquito Formation).

The Alpercatas Basin is a rift system with the Jurassic supersequence of the Mearim Group (Pastos Bons and Corda formations) limited by the basalts (Góes and Feijó 1994) of Mosquito (Jurassic) and Sardinha (Lower Cretaceous) formations. The Pastos Bons Formation are a succession of shales and sandstones interpreted as fluvial and aeolian environments. The Corda Formation is bimodal sandstones, with some mudstone levels, is interpreted as a desert environment.

The Grajaú Basin (Góes and Rossetti 2001) is isolated from the São Luís Basin by the Ferrer-Urbano Santos structural arch. This basin is filled up by the Cretaceous supersequence (Aptian-Albian), including the Codó, Grajaú and Itapecuru formations (Rossetti and Truckenbrodt 1997; Rossetti 2001). The Grajaú Formation deposits are sandstones intercalated with the shales, carbonates and evaporites of the Codó Formation, interpreted as fluvial and lagoon environments. The Itapecuru Formation is a succession of sandstones, shales and mudstones interpreted as fluvial and deltaic deposits. The Espigão-Mestre Basin is located in the southern portion of the Parnaíba Province and it is the north area of the Urucuia sub-basin of the Sanfranciscana Basin (Pedreira da Silva et al. 2003). There are sandstones interpreted as aeolian deposits.

The footprints and dinosaur tracks found in the Parnaíba Province (or in a more common sense, Parnaíba Basin) are located in the Parnaíba, Espigão-Mestre and Grajaú basins. In the Parnaíba Basin - Sambaíba Formation, a dubious Triassic unit, there are many isolated theropod footprints (Fortaleza dos Nogueira locality, Maranhão State) identified by Assis et al. (2010). In the Espigão-Mestre Basin there are seven sauropod trackways (Leonardi 1980, 1994; De Valais et al. 2015; Lopes et al. 2021) in the Corda Formation (Barremian), São Domingos county, Itaguatins locality, Tocantins State (Fig. 1.7). In the Grajaú Basin is found an isolated footprint in the Itapecuru Formation (Aptian), identified as a *Caririchnium* footprint (Menezes et al. 2019), Itapecuru River, Maranhão State.

1.2.5 Amazonas Basin

The Amazon region comprises many sedimentary basins grouped as the Amazonas Province, in which the larger basins are Acre, Solimões, Alto Tapajós, Amazonas and Marajó. These basins are isolated by structural arches and throughout their geological history they present some episodes of environmental connections, especially during the Devonian marine transgressions and later through the Cenozoic fluvial systems.

The most complete stratigraphic succession occurs in the Amazonas Basin. It presents an area of 515,000 km^2 with 5,000 m thickness (Cunha et al. 1994) overlapping Precambrian magmatic and metamorphic rocks (Fig. 1.8). The oldest Paleozoic deposits are conglomerates and sandstones, probably Cambrian-Ordovician—the Prosperança Formation. Subsequently, the Ordovician-Devonian Supersequence (Trombetas Group) presents clastic rocks deposited in marine environments (Cunha et al. 1994). Follow the deposition of the Devonian-Carboniferous Supersequence, comprising the Urupadi and Curuá groups, which represent fluvial and deltaic environments and also include a glacial interval. The Carboniferous-Permian Supersequence (Tapajós Group) includes both continental and restricted marine environments. At the beginning of the Jurassic occurred extensive basaltic magmatism as part of the CAMP Province—Central Atlantic Magmatic Province (Marzolli et al. 1999). The final sedimentation cycle in the Amazonas Basin are two continental sequences: Upper Cretaceous (Alter do Chão Formation) and Cenozoic (Solimões

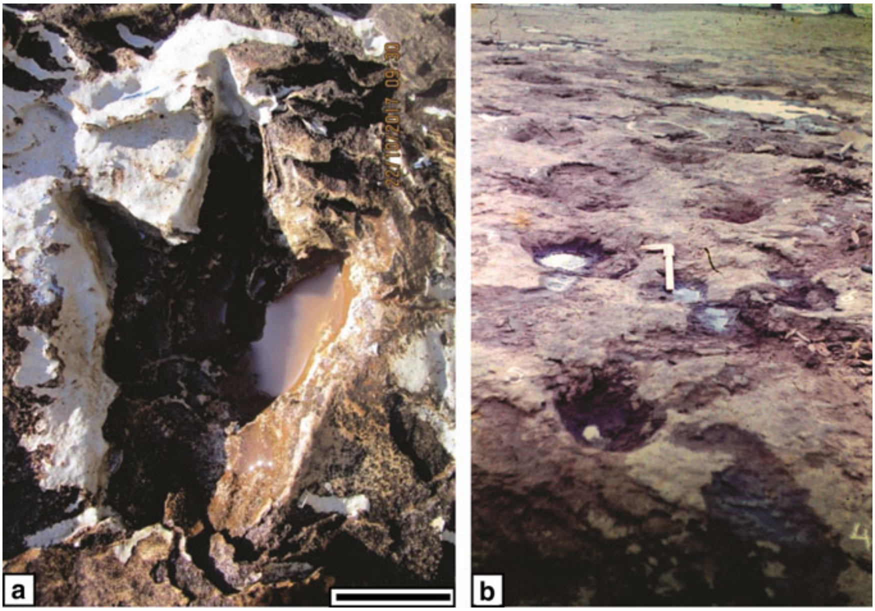

Fig. 1.7 **a** Theropod footprint from the Sambaíba Formation (Parnaíba Basin), a probable Late Triassic-Jurassic lithostratigraphic unit. Fortaleza dos Nogueiras locality, Maranhão State. Photograph by Rafael Matos Lindoso; scale bar: 3 cm. **b** Three sauropod trackways from the Corda Formation (Parnaíba Basin), Lower Cretaceous. Itaguatins locality, Tocantins State. Photograph by Giuseppe Leonardi

and Içá formations) sequences, deposited in the context of fluvial and lacustrine environments (Mendes et al. 2012).

The Acre Basin is in the same geological context of Amazonas Basin and they share a common Paleozoic history. It is a retroarch basin of the Andes mountain range (Milani and Thomaz Filho 2000). The Jurassic Supersequence (Juruá-Mirim Formation) is constituted by sandstones, evaporites and basalt flows in the context of terrestrial environments. The Cretaceous Supersequence (Moa, Rio Azul, Divisor and Ramón formations) presents sandstones and shales deposited in fluvial and lakes environments.

It was not found until now any dinosaur footprint in the Mesozoic deposits of the Amazon Province (Acre, Solimões, Alto Tapajós, Amazonas and Marajó basins). Despite there are Jurassic and Cretaceous outcrops in the Amazonas and Acre basins, there are few geological studies in this region and no data concerning dinosaur footprints.

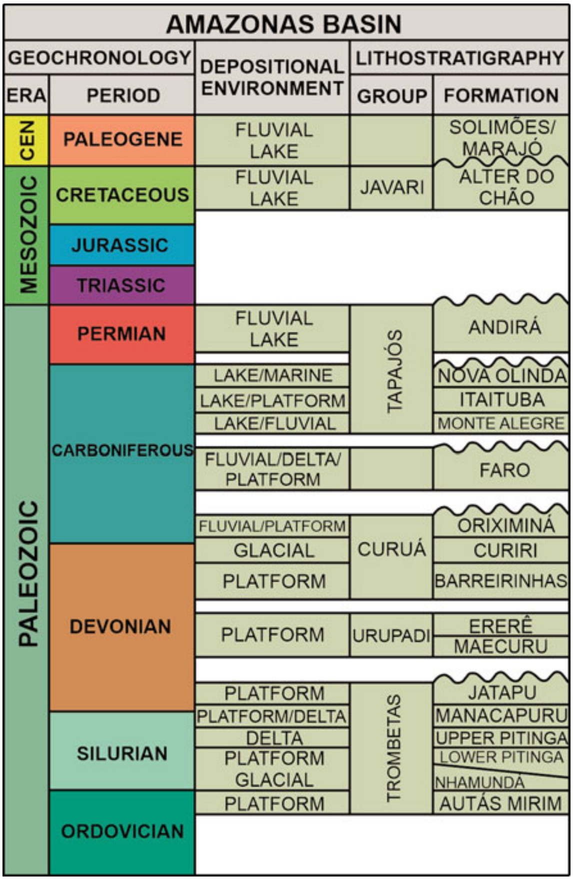

Fig. 1.8 Stratigraphic chart of the Amazonas Basin (adapted from Cunha et al. 1994, 2007). Although the wide area of this basin there is no occurrences of dinosaur footprints and trackways

1.2.6 *Rift Basins*

The Brazilian rift basins are related to the tectonic events during the breakup of Gondwana. During the Late Jurassic, intense tectonic activity fragmented the crust and created small half grabens with a great accumulation of sediments. Small lakes that captured the drainage network (Machado et al. 1990) were the main continental environments, with an eventual physical linkage, where the dinosaur footprints are found. These occurrences are not synchronous and did not coincide temporally throughout the Cretaceous, as the beginning of the South Atlantic occurred during three diachronous tectono-sedimentary domains (Popoff 1988): Austral (southern), tropical (midlatitude), and equatorial (northern). Then, there are many small interior basins in Northeastern Brazil (tropical tectonic domain), bordering the Atlantic margin (tropical and equatorial tectonic domain), and also in the Amazon region (equatorial tectonic domain). The outcrops indicate deposition in a wide variety of geological settings, including fluvial, lacustrine and seashore environments.

The majority of ichnosites are found in the Early Cretaceous intracontinental basins of Sousa, Triunfo (both included in the Rio do Peixe basins), Lima Campos, Malhada Vermelha and Araripe. In the marginal Atlantic basins there are few occurrences, generally cross-section and isolated footprints. The exception is the São Luís Basin in the equatorial margin, where a large number of theropod, sauropod and ornithopod footprints are distributed in six ichnosites located in the São Luís and Alcântara counties, Maranhão State.

1.2.6.1 Intracontinental Basins of Northeast Brazil

These basins are intracratonic areas (grabens and half-grabens) in which the sedimentation was controlled by the reactivation of Precambrian tectonic structures during the first steps of the South America and Africa drifting (Ponte 1992; Mabesoone 1994; Valença et al. 2003). The region of the Precambrian basement (Meso- and Neo-Proterozoic), where they are found, is known as Borborema Province (Santos and Brito Neves 1984).

The Borborema Province shows diverse tectonic, metamorphic, and magmatic events that are interpreted to belong to a larger Precambrian paleocontinent expanding into Africa (Trompette et al. 1993). This area was periodically affected by the formation of intracontinental rifts (Matos 1992; Córdoba et al. 2008) and the reactivated fault movements within the ancient Precambrian fault lines (E-W and SW–NE oriented) created several sedimentary basins (Fig. 1.9).

These basins lie in the western of Paraíba, Rio Grande do Norte, Piauí, Pernambuco, and in the southern Ceará states, Northeast Brazil. There is a diversity of

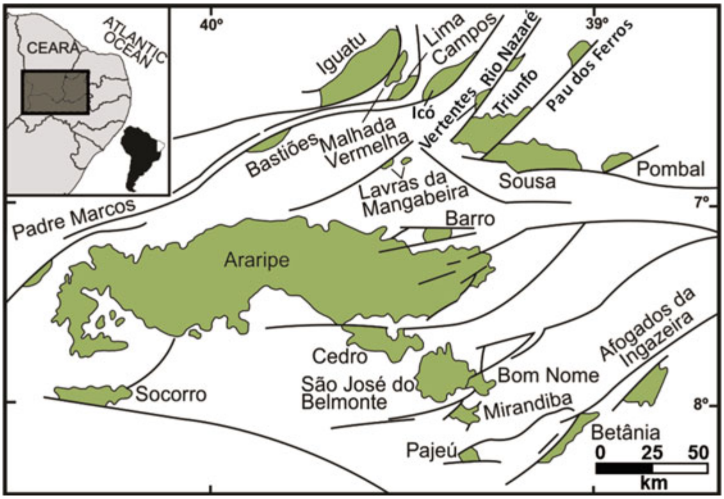

Fig. 1.9 Location map of the interior rift basins in the Northeast Brazil (modified from Carvalho et al. 2013a, b)

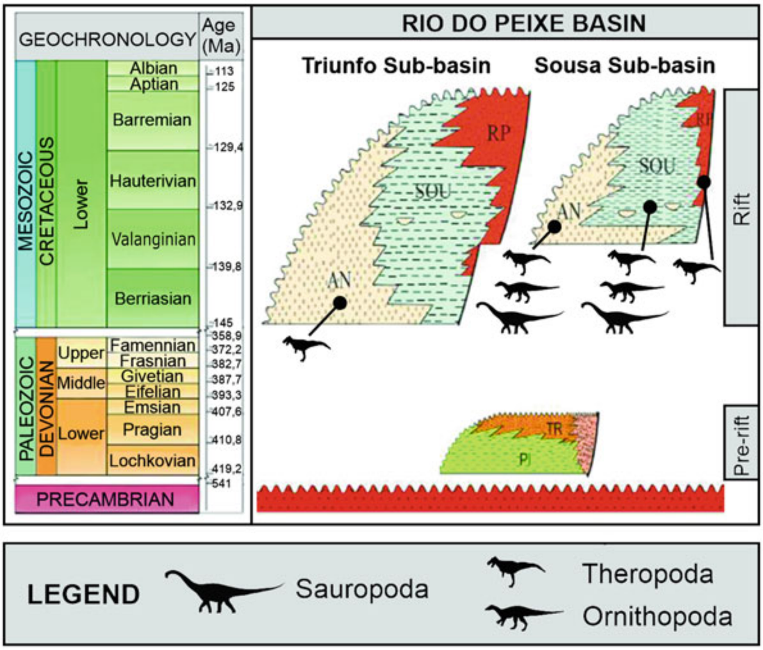

Fig. 1.10 Stratigraphic chart of Rio do Peixe basins. Santa Helena Group (PI—Pilões Formation; TR—Triunfo Formation) and Rio do Peixe Group (AN—Antenor Navarro Formation; SO—Sousa Formation; RP—Rio Piranhas Formation). 2021 Modified from Rapozo et al. (2021)

vertebrate and invertebrate ichnofossils, especially Early Cretaceous dinosaur footprints in the Rio do Peixe (Leonardi 1979a, b, 1989; Carvalho 1996a; Carvalho et al. 1993, 1995, Carvalho and Leonardi 2021, 2022; Leonardi and Carvalho 2021) and Araripe basin's (Carvalho 2004; Carvalho et al. 1994a, b, 2021a, b). During the Barremian-Berriasian in the Rio do Peixe basins (Fig. 1.10), the dinosaur footprints (Figs. 1.11 and 1.12) occur in the Rio do Peixe Group, that includes the Antenor Navarro (alluvial fans/braided channels), Sousa (shallow lacustrine/floodplain), and Rio Piranhas (alluvial fans/braided channels) formations (Srivastava and Carvalho 2004). In the ?Barremian, Aptian and Cenomanian of Araripe Basin they are found in the Mauriti (fluvial), Rio da Batateira (deltaic/floodplain), Crato (alkaline lake) and Exu formations (Viana et al. 1993; Carvalho 2000a, b, 2004; Carvalho et al. 2021a, b).

1.2.6.2 Marginal Atlantic Basins

The south to north breakup of Western Gondwana started in the southern region of South America during the Late Jurassic reaching the equatorial margin by late Aptian-early Albian. In general there are four megasequences of sedimentation (Fig. 1.13)

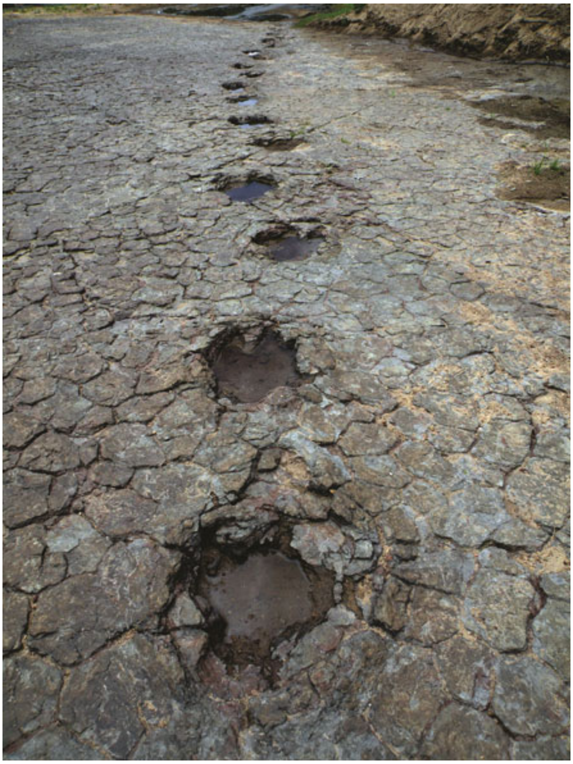

Fig. 1.11 *Sousaichnium pricei*, an ornithopod trackway from the Sousa Basin (Sousa Formation, Sousa Basin) preserved in a floodplain succession.

controlled by the evolution of the rifting events (Cainelli and Mohriak 1999). The southern basins, such as Pelotas, Santos, Campos and Espírito Santo are offshore regions and there are no outcrops of the Mesozoic successions. The Recôncavo-Tucano-Jatobá is an aborted rift system filled by the pre-rift and continental megasequences, in which there are some dinosaur footprints in the continental deposits of the pre-rift (Late Jurassic) and continental megasequences (Aptian). They are found as cross section footprints in the Aliança and Sergi formations (Recôncavo Basin, Carvalho and Borghi 2008) and as isolated tridactyl footprints in the Tucano Basin (São Sebastião Formation, Dantas et al. 2019).

The South Atlantic marginal basins of Sergipe-Alagoas and Potiguar present outcrops of the rifting evolution events. This allows the observation of bedding planes with dinosaur footprints in the Aptian succession of Sergipe-Alagoas Basin (Maceió Formation, Carvalho and Souza-Lima 2008) and the Aptian?–Cenomanian of the Potiguar Basin (Açu Formation, Leonardi et al. 2021).

In the Equatorial Atlantic margin, the dinosaur footprints of São Luís Basin occur in Cenomanian fine-grained quartz's sandstones of the Alcântara Formation (Fig. 1.14). The tracksites are located in the early equatorial seashore of the Atlantic Ocean, in the environmental setting of an estuary that occupied a low gradient coastal

Fig. 1.12 A theropod footprint from Sousa Basin (Antenor Navarro Formation) preserved in reddish sandstones of alluvial fan deposits from Serrote do Letreiro, Sousa County (Paraíba State). Scale bar: 4 cm

plain, under a dry and hot climate. Distinctive dinosaur communities are found in these environments (Carvalho 1995, 2001; Carvalho and Pedrão 1998).

1.2.6.3 Tacutu Basin

The Tacutu Basin is a NE-SW asymmetric graben system (4,500 km^2), with an extension of 300 km and up to 50 km wide, located in the borders of Brazil and Guyana Republic in the Amazon region. The sedimentary succession (Pedreira da Silva et al. 2003; Castro et al. 2021) comprises an initial pre-rift Jurassic Supersequence (Apoteri and Manari formations) with volcanic rocks and reddish siltstones of lacustrine environments (Eiras et al. 1994; Marzolli et al. 1999). Later, during a rift phase, there are fluvial, playa lake and deltaic deposition of evaporites, shales, sandstones and conglomerates (Rupununi and Pirara formations) followed by Cretaceous siltstones and sandstones (Tacutu and Serra do Tucano formations). Barros et al. (2023) reported dinosaur footprints in the Serra do Tucano Formation (Barremian-Albian), probably in floodplain deposits. The brief description indicates that there are a large number of footprints interpreted as sauropod, ornithopod, theropod and thyreophoran trackmakers.

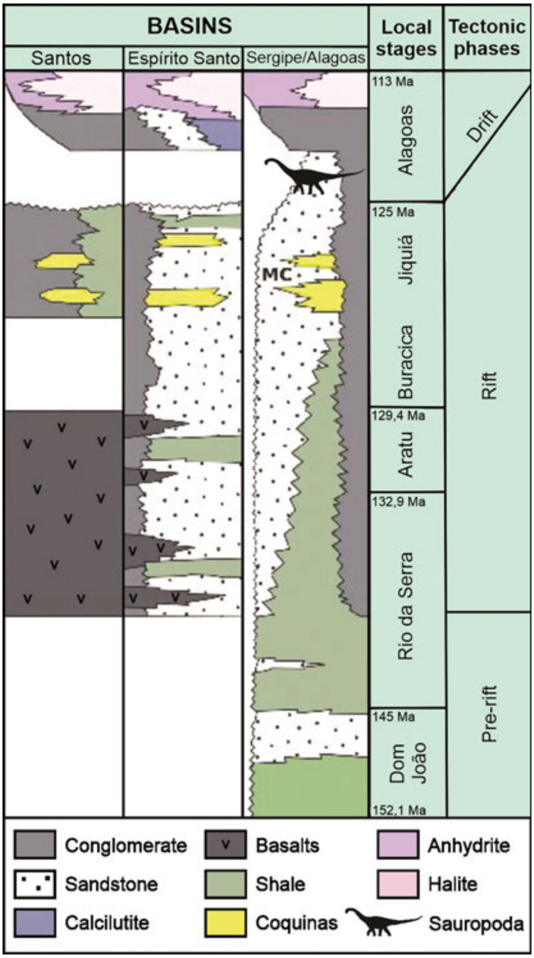

Fig. 1.13 Stratigraphic columns of Mesozoic Brazilian marginal basins (Santos, Espírito Santo and Sergipe-Alagoas basins). The chart presents the local stages Dom João (Tithonian), Rio da Serra (Berriasian-lower Hauterivian), Aratu (Hauterivian-lower Barremian), Buracica (upper Barremian), Jiquiá (upper Barremian-lower Aptian) and Alagoas (upper Aptian). Modified from Cainelli and Mohriak (1999) and Menezes et al. (2016)

1.3 Paleogeographic and Paleoenvironmental Distribution of the Footprints

In the Paraná Basin (South Brazil), the Triassic records (Rosário do Sul Group, Anisian–Norian, ~247–208 Ma) are reddish sandstones and shales from fluvial and lake deposits. There are many fossils of permineralized logs and a wide diversity of bone remains (Langer 2003; Ferigolo and Langer 2006; Bittencourt and Langer 2011; Langer and Ferigolo 2013; Langer et al. 1999; Mestriner et al. 2023; Pacheco et al. 2019; Müller and Garcia 2023) and footprints (Silva et al. 2007, 2008) of the oldest dinosaurs. The prevailing climatic condition was hot and dry, with intermittent wet periods. Petrified logs indicate a subtropical to tropical climate, with irregular seasonality and short-term droughts, suggesting semi-arid conditions (Scaramuzza

Fig. 1.14 Footprints from de Cenomanian (Alcântara Formation, São Luís Basin) preserved in a tidal flat environment at Ponta da Guia, São Luís County (Maranhão State)

dos Santos et al. 2023). A similar climate is also found during the Late Jurassic deposition of the Guará and Pirambóia formations (Francischini et al. 2015; Christofoletti et al. 2021). Sand bars, fluvial and interdune deposits accumulated in a semiarid climate (Scherer and Lavina 2005, 2006). From then on, a broad process of aridization occurred in the interior of the Gondwana. At the beginning of the Cretaceous, there was hyperarid conditions, resulting in a 1,300,000 km^2 desert (Botucatu Paleodesert) covering the center-south of Brazil, as well as the west of Uruguay, east of Paraguay and northeast of Argentina (Almeida 1953; Bertolini et al. 2021). The origin of the Botucatu Paleodesert and even other large aeolian deposits, such as those in the Sanfranciscana Basin, resulted from the Pangea geographic configuration of the Late Permian. The distribution of continents, low sea level and atmospheric currents, resulted in vast aridity during almost all of the Mesozoic (Almeida and Carneiro 1998). This climate model was changed after the West Gondwana break up, during the Early Cretaceous. There were changes in the atmospheric circulation, humidity and temperature and, therefore, to the disappearance of this great desert.

The deposits of this paleodesert are the sandstones of the Botucatu Formation, which overlap and are sometimes interspersed with the basalt flows of the Serra Geral Formation and the Caiuá Group (Leonardi 1977). They are interpreted as extensive dune fields and humid interdune areas, where the footprints of mammals, dinosaurs (Figs. 1.15 and 1.16) and small invertebrates were preserved (Leonardi 1977; Leonardi and Carvalho 2002; Francischini et al. 2015). In the Rio Paraná Formation (Caiuá Group) there is an association of footprints of dinosaurs and small mammals preserved in aeolian sandstones, indicating animals adapted to aridity (Fernandes et al. 2008).

At the end of the Jurassic and Early Cretaceous, an important event is the extrusion of basalts (ages between 127 and 137 million years, Brückmann et al. 2014) indicative of intense fissure eruptions (Serra Geral volcanism) associated with the South America and Africa drifting (Assine et al. 2004). The basalt flows (Serra Geral Formation) are interspersed with sandstones from the Botucatu Paleodesert (Scherer

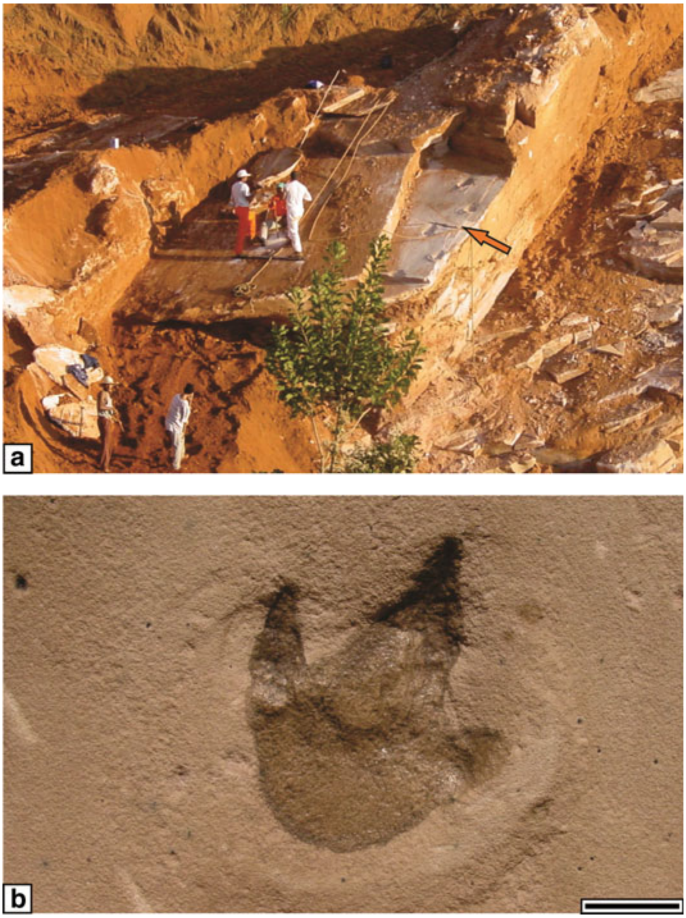

Fig. 1.15 The geographic configuration of Gondwana resulted in hyperarid conditions originating a 1,300,000 km^2 desert (Botucatu Paleodesert, Paraná Basin) where dinosaur footprints are found in dunes and interdune areas. **a** The arrow indicates a surface in a dune deposit of the Botucatu Formation with an ornithopod trackway; **b** an isolated theropod footprint in a flagstone of the Botucatu Formation. Scale bar: 3 cm. Both images from the São Bento Quarry, Araraquara County (São Paulo State). Photographs by Marcelo Adorna Fernandes

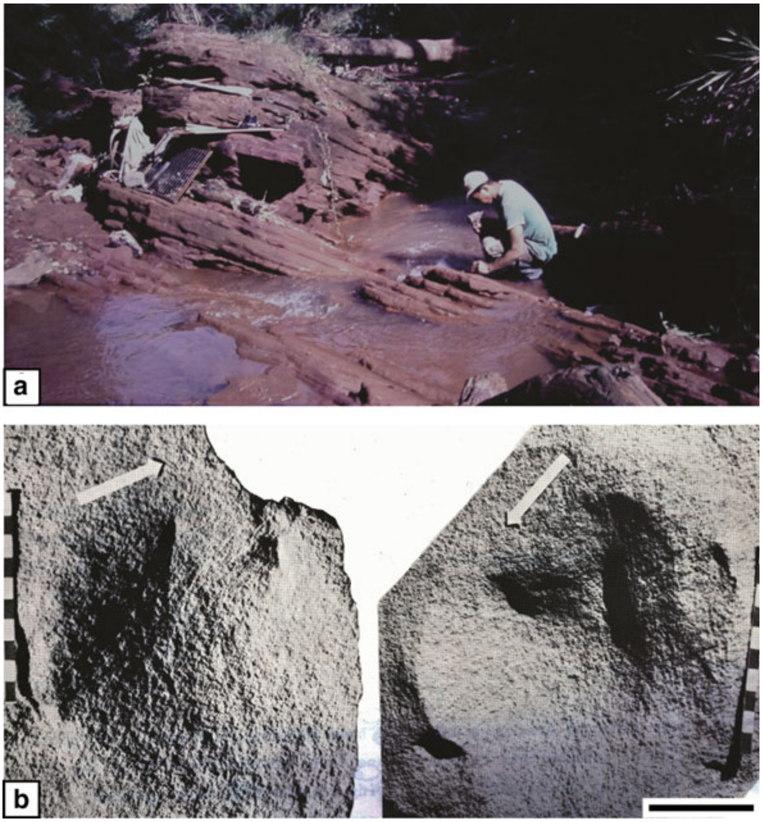

Fig. 1.16 **a** Outcrop in the Catingueiro creek of the Lower Cretaceous aeolian sandstones of Caiuá Group (Bauru Basin); **b** theropod footprints in the Catingueiro creek, Cianorte County (Paraná State). Scale bar 5 cm. Photographs by Giuseppe Leonardi

2000, 2002; Scherer et al. 2002). Due to changes in the depocenters, after the Serra Geral volcanism, a new depositional setting was established named as Bauru Basin.

In the Parnaíba Basin, the aridity was striking since the early Mesozoic. During the Triassic, deposition occurred mainly in lacustrine and aeolian environments. A wide area of reddish sandstones, with large cross stratifications (Sambaíba Formation), is interpreted as the deposition of aeolian dunes. At the end of the Triassic and Early Jurassic (approximately 202–200 Ma) there is a record of intense volcanism that reflects the breakup of Pangea and the birth of the Central Atlantic Ocean (Nogueira et al. 2021). Throughout the Cretaceous, continental environments dominated, although at the end of the Early Cretaceous, there were marine ingressions related to the Brazilian equatorial margin opening.

A major landmark of the Mesozoic is the opening of the Atlantic Ocean, with the definitive rupture of West Gondwana. This is the South Atlantic Event, which comprises a set of tectonic, sedimentary and magmatic events, from the Permian-Triassic onwards. The spreading of the ocean floor occurred in three different moments (approximately 130 Ma, 113 Ma, and 110 Ma) starting from south to north, and reaching the Brazilian equatorial margin at the end of the Early Cretaceous (Chang et al. 1992; Matos 1992). Only after 110 million years ago there was a continuous and stable oceanic crust (Matos et al. 2021a, b).

The structural lineaments of the Brazilian and Pan-African provinces were intensely reactivated, with expressive vertical movements. In the interior of the Borborema Province and along the current Brazilian continental margin there were crustal ruptures and the origin of new sedimentary basins (Pedreira da Silva et al. 2003), such as the Rio do Peixe basins, in Northeast Brazil. On the continental margin, the tectonics controlled the phases of subsidence, sea level changes and sedimentation, with diverse environments in the course of the opening of the Atlantic Ocean (Chang and Kowsmann 1987; Petri 1987).

Throughout the pre-rift events (syn-rift I, Upper Jurassic), a great depression known as the Afro-Brazilian Depression, allowed the accumulation of continental sediments from rivers and temporary lakes (Ponte 1972) and consequently a higher humidity in the continental interior. Along the borders of this depression, topographic barriers played an important role in reducing wind velocity from the southeast, establishing climatic zones that probably controlled the flora and fauna distribution (Golonka et al. 1994). Despite the fact that it dominated a semi-arid climate, the locally higher precipitation led to the growth of abundant vegetation, mainly along the northern margin of the Afro-Brazilian Depression (García and Wilbert 1994; Da Rosa and Garcia 2000).

Later, there was a divergent movement between the South American and African plates, inducing a 3,500 km rift system on the present Brazilian continental margin. Thus, during the Early Cretaceous, alluvial fans, rivers and lakes were the main environments in the rift basins (Guardado et al. 1989; Lima Filho et al. 1999; Mabesoone et al. 1979, 2000; Córdoba et al. 2008). Transitional environments occurred between the rift and the drift phases, ranging from continental to marine environments (upper Aptian-lower Albian).

The current paleogeographical models demonstrate that despite the south to north tectonic opening, the first marine ingressions originated from the northern region, linked to the Tethys Sea (Azevedo 2004; Dias-Brito 1987, 2000; Arai 2009, 2014a, b, 2016; Tucker and Dias-Brito 2017; Araripe et al. 2022; Fauth et al. 2023; Lemos et al. 2023). Some sauropod dinosaurs from South America and Africa revealed that terrestrial connections persisted until about 100 million years ago (Calvo and Salgado 1996), but at the end of the Turonian (89.8 Ma, Late Cretaceous) dominated settled the open sea, approaching the conditions that still exist today. Hot weather were widespread, although there was probably a wide range of humidity (Petri 1983, 1998; Lima 1983; Lima and Coelho 1987; Carvalho 1996b; Carvalho and Carvalho 1990; Skelton 2003; Souza-Lima and Silva 2018; Degani-Schmidt et al. 2023) and marked climatic cycles in some regions (Gomes et al. 2021; Guerra-Sommer et al. 2021a, b). A humidification process, changing from arid to a tropical climate, with the onset of the equatorial humid belt, took place due the origin of the Atlantic Ocean during the Gondwana breakup (Carvalho et al. 2022; Salgado-Campos et al. 2021, 2022; Luft-Souza et al. 2022; Scaramuzza dos Santos et al. 2020, 2021, 2022, 2023; Dummann et al. 2023).

The tectonic evolution of the Mesozoic rift basins appears to be a strong constraint on the distribution of sedimentary environments and, consequently, on the possibility of preservation of fossil footprints. In addition, the distribution of outcrops in the marginal basins represents a limitation for the number of dinosaur footprints in a time interval favorable to their frequency.

1.4 Conclusions

The distribution of dinosaur footprints through time and space in the Brazilian territory covers all the Mesozoic era in the intracratonic and marginal rift basins with distinct geological history.

Since the Triassic (Carnian) of the Paraná Basin the first dinosaurs are recognized by their footprints, including theropods and prosauropods. The continental environments, including fluvial floodplains and lakes in an arid climate, were populated by a great number of the first dinosaur lineages. During almost all the Mesozoic, the land masses distribution, low stand eustatic level and atmospheric currents were responsible for an arid climate with episodes of hyperaridity. In the Early Cretaceous, the paleogeographic setting allowed an extreme arid climate and the origin of the Botucatu Paleodesert. The trackmakers that lived in this environment showed specific adaptations to this environment.

During the Gondwana breakup, the atmospheric circulation, humidity and temperature changed following the ending of the Botucatu Paleodesert. Furthermore, new ecological spaces were available with the origin of the South Atlantic Ocean throughout the late Early Cretaceous. From this moment new groups of dinosaurs left their footprints in coastal environments during the early tectonic stages of the rift basins.

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