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Dinosaur Tracks of Mesozoic Basins in Brazil

Impact of Paleoenvironmental and Paleoclimatic Changes

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Chapter 7
Walking in the Gondwanic Floodplains of Rio do Peixe Basins

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7.1 Introduction

The Rio do Peixe basins are a set of four associated basins in the Northeastern region of Brazil: Sousa, Uiraúna-Brejo das Freiras (also known as Triunfo Basin), Pombal and Vertentes (or Icozinho Basin) (Fig. 7.1). The Sousa Basin comprises an area of ~675 km^2 (~60 km E-W, ~17 km N-S, E-W-oriented) and is located in the western part of the Paraíba State, in the counties of Aparecida, São João do Rio do Peixe, and Sousa (Fig. 7.2). This basin, when compared with the others, contains the largest number of dinosaur tracks.

The Triunfo Basin, is nearby to the Sousa Basin. It is located in the northwest of Paraíba State, in the counties of Uiraúna, Poço, Brejo das Freiras, Triunfo, and Santa Helena. It has a roughly triangular shape, NE-SW oriented, with an area of ~450 km^2. The Pombal Basin, the easternmost basin (NW–SE oriented), is a small one, with an area of about 81 km^2 (~27 km long and ~3 km wide). There are few outcrops, and the rocks are generally excessively coarse-grained to preserve dinosaur footprints. The Vertentes Basin (or Icozinho) is a small, long and very narrow basin, NE-SW oriented, with an area of about 74 km^2 (~37 km long and ~1 to 3 km wide). The total area of these four basins is estimated at ~1,280 km^2 (Gonzaga et al. 2022).

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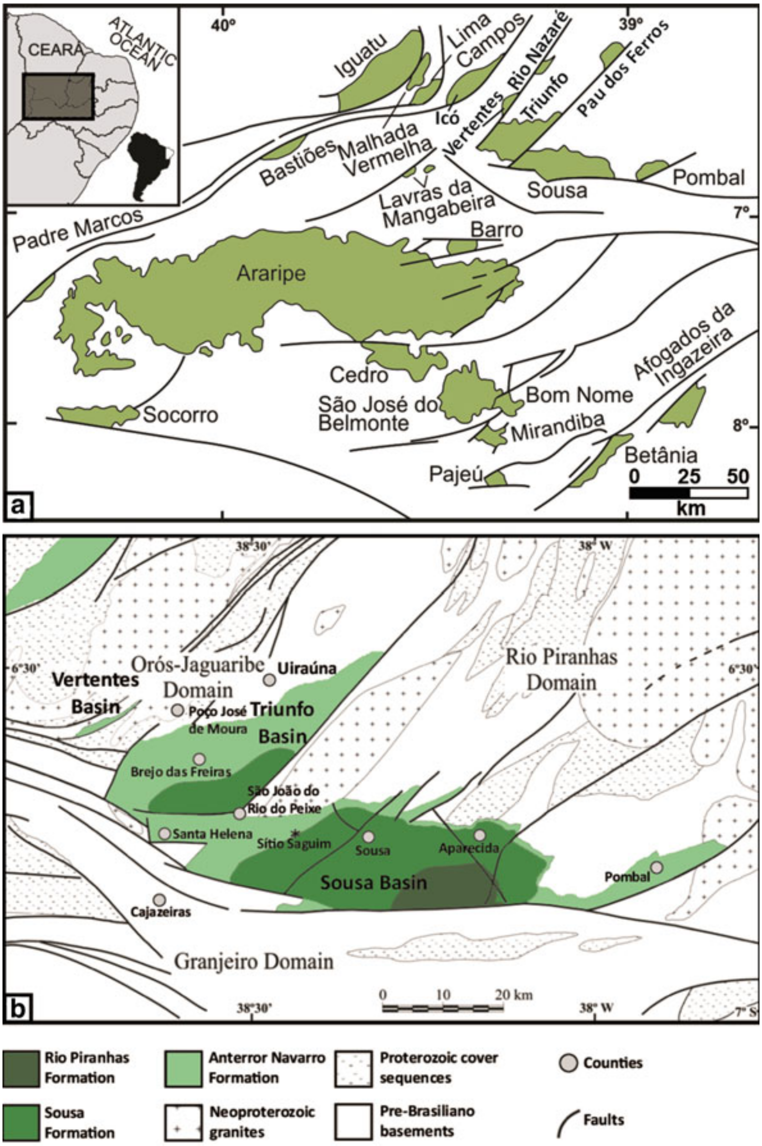

Fig. 7.1 Location map and geological framework of the Rio do Peixe basins area. **a** The intracratonic sedimentary basins of Northeastern Brazil. **b** Location and geological map of the four Rio do Peixe basins, western Paraíba, Brazil (modified from Carvalho 2000a and Castro et al. 2007)

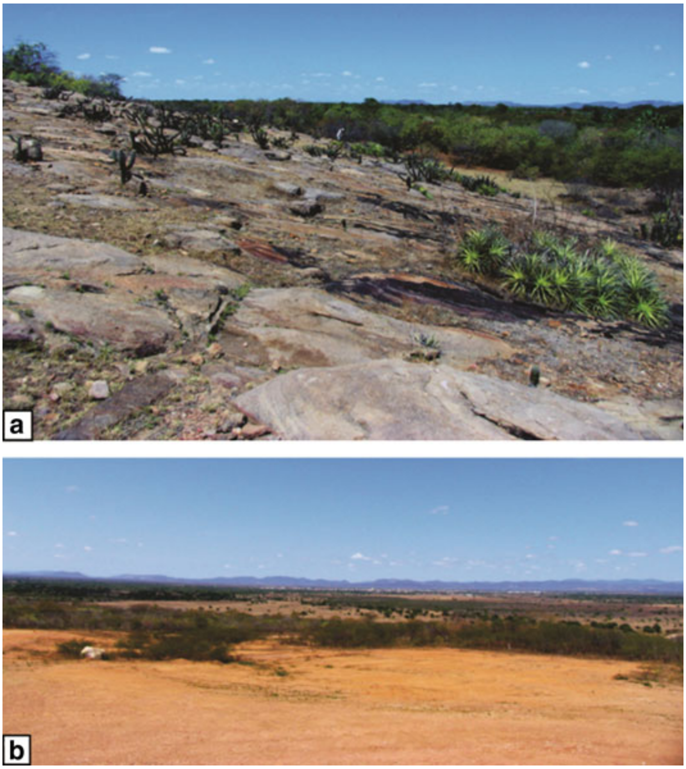

Fig. 7.2 The Sousa Basin half-graben, from its northern margin. Overview of the Sousa Basin from Riachão dos Oliveira hill (**a**) and from Benção de Deus hill (**b**)

The origin of these basins is related to fault movements along preexisting structural trends of the Proterozoic basement during South and equatorial Atlantic Ocean opening (Ramos 2023). The Rio do Peixe basins, like many others in the region, are aborted rifts. In the clastic continental sediments, dinosaur footprints are the most abundant fossils. The main tetrapod ichnofauna comprises isolated footprints and trackways of large and small theropods, besides ornithopods, sauropods and ankylosaurs. Fish trails are found in the Sousa Basin (Muniz 1985; Leonardi and Muniz 1985). There are also invertebrate ichnofossils such as trails and burrows produced by arthropods and annelids (Fernandes and Carvalho 2001). The fossils are palynomorphs, plant fragments and some logs, ostracods, conchostracans and fish scales. Rare dinosaur bones (Ghilardi et al. 2014, 2016; Carvalho et al. 2017) and Crocodylomorpha bones (Carvalho and Nobre 2001) were also found. Sousa, Triunfo and Pombal basins comprise 42 ichnofossiliferous sites. The dinosaur ichnofaunas present a same stratigraphic-time-paleogeographical context, and represent parts of a widespread megatracksite. In these basins was recorded a great number of individual dinosaur tracks. These represent the passage of at least 629 individuals of the various dinosaur clades; there are also a large number of small chelonian half-swimming tracks and some Crocodylomorpha traces.

The environmental setting at that time was influenced by the initial development of the Gondwana breakup, with an endemic biota living nearby ephemeral rivers and shallow lakes under hot climate conditions. These were preserved in alluvial fans, braided, meandering rivers and shallow lake deposits of Berriasian to lower Barremian age.

After the first description of dinosaur tracks in the Sousa Basin (Moraes 1924) there was an increase of new ichnosites (Leonardi 2021) and, consequently, a relevant literature on the subject was produced (Leonardi 1979a, b, 1980a, b, 1981, 1984a, b, 1985, 1987a, b, 1989, 1994, 2008, 2011, 2021; Leonardi et al. 1987a, b, c; Leonardi and Carvalho 2000c, 2002, 2021; Godoy and Leonardi 1985; Campos et al. 2015; Carvalho 1989, 1996, 2000a, 2000b, 2004a, 2004b; Carvalho et al. 1993a, b; Carvalho et al. 2013a, b, c, 2016, 2017; Carvalho and Fernandes 1992; Carvalho and Leonardi 1992, 2007, 2021, 2023; Santos and Santos 1987a, 1987b, 1989; Carvalho and Carvalho 1990; Fernandes and Carvalho 2001, 2007; Leonardi and Santos 2006; Santos et al. 2016; Siqueira et al. 2011; Viana et al. 1993).

7.2 Geological Context

The Rio do Peixe basins are four sedimentary basins (Fig. 7.1): Sousa, Triunfo, Pombal and Vertentes located at the western extremity of Paraíba State and in the southeastern Ceará State, in the Proterozoic Borborema Province, Northeastern Brazil. They largely correspond to the current catchment area of the Peixe River, a tributary of the Piranhas River (Fig. 7.3).

These basins are located in the context of the Interior Rift System of Northeast Brazil. They are rift basins that evolved as a consequence of the Cretaceous Gondwana break-up, alongside earlier structural trends of the basement, during the South Atlantic Ocean opening (Matos 1992; Rapozo et al. 2021; Matos et al. 2021). As a result, there was the origin of several sedimentary basins throughout the normal and transcurrent fault movements within the Precambrian basement (Nogueira et al. 2015).

During the first rifting phase, the two major faults bordering the basins (Portalegre Fault and Malta Fault) caused normal displacement (Pichel et al. 2022) and left-lateral transtension on an E-W-striking major fault (Rapozo et al. 2019). The fault patterns controlled the E-W oriented Sousa half-graben and the SW oriented Triunfo, Vertentes and Pombal half-grabens. In the interior of these basins there are many minor faults, generally parallel to the major alignments, mainly to the Portalegre Fault (Araújo et al. 2019; Torabi et al. 2021; Nicchio et al. 2022; Oliveira et al. 2022; Pichel et al. 2022; Freitas et al. 2023). During the Lower Cretaceous (Berriasian to Hauterivian), under the same tectonic stress pattern, the basinal areas increased and during the last tectonic stage (early Barremian), there was a change in the tectonic

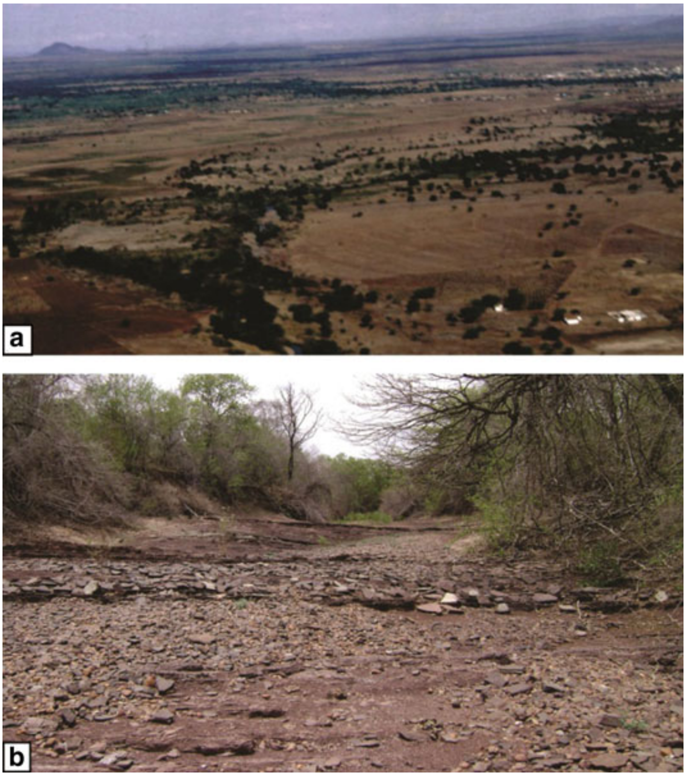

Fig. 7.3 The Sousa Basin and the Peixe River. **a** The Peixe River with its ciliary forest and its valley, corresponding in large part to the Sousa Basin, with the savannah and caatinga environments, partly cultivated with cotton; **b** The Peixe River during a long dry season, when the best outcrops of the Sousa Formation become visible

pattern, and sediment accumulation began to decline (Carvalho and Leonardi 2021). Later, in the post-rift phase, there would have been a reversal: the Rio do Peixe basins were subjected to a horizontal compression (ESE-WNW) from the Late Cretaceous onwards (Nogueira et al. 2015; Lima et al. 2017; Barbosa et al. 2021; Bezerra et al. 2017, 2023; Maciel et al. 2018).

The time interval of sedimentation, based on ostracods and palynomorphs, is characteristic of Berriasian to early Barremian stages (Early Cretaceous; Carvalho 2000a, 2004a; Lourenço et al. 2021). However, beneath the Lower Cretaceous succession (Fig. 7.4a, b), there are Lower Devonian (Eolochkovian–?Eopraguian) rocks identified through palynological analysis from drillings by Petrobras (Roesner et al. 2011). These sediments are the Santa Helena Group, divided in the Pilões Formation and Triunfo formations (Silva et al. 2014), indicating a multi-phase history of these basins (Silva et al. 2014; Carvalho and Leonardi 2021; Pichel et al. 2022). After the short Devonian deposition, during the Cretaceous, the Sousa Basin accumulated more than 2 km thick in the depocenter, and Triunfo Basin is a 2.5–3 km thick half-graben

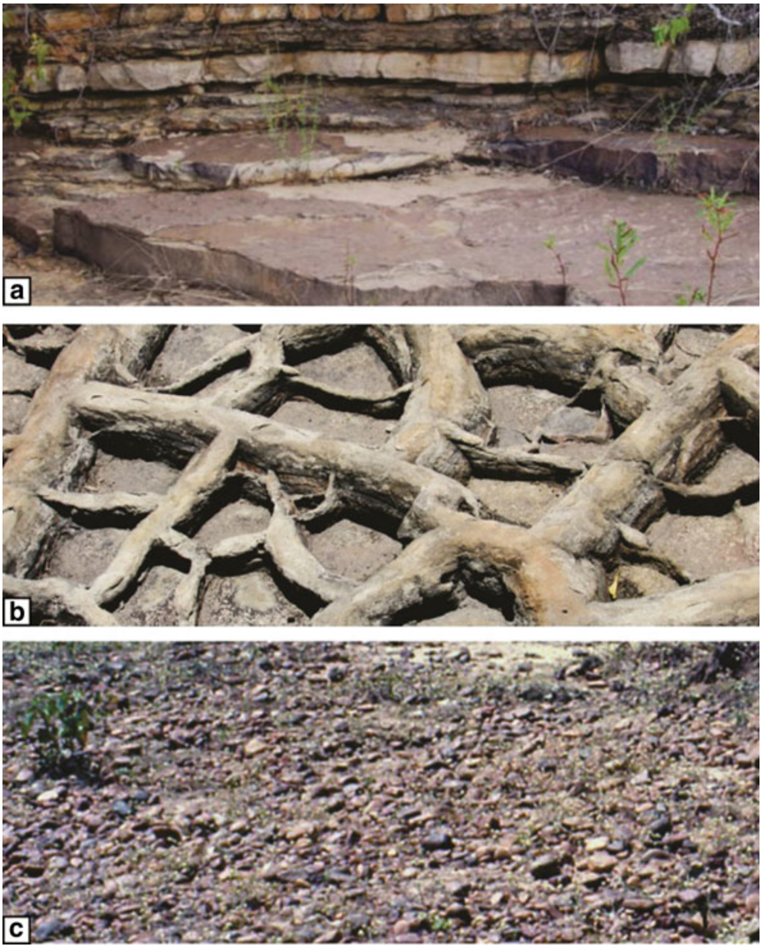

Fig. 7.4 **a** Antenor Navarro Formation succession at Serrote do Letreiro; **b** Molds of large mud craks from the Sousa Formation; **c** The Moura Formation, a Cenozoic and Recent deposits of loose sediments. All images from the Sousa Basin

(Córdoba et al. 2007; Carvalho and Leonardi 2021). On the contrary, during the later phases of Cenozoic reactivation of the marginal coastal basins of Pernambuco and Paraíba (Neogene-Quaternary; Lima et al. 2017), it seems that there was not expressive reactivation of the fault system in the Rio do Peixe basins, aspect that is also confirmed by a low sediment supply (Moura Formation; Fig. 7.4c).

So, after an initial Paleozoic phase, these basins were filled with Lower Cretaceous reddish and greenish shales, mudstones, siltstones and sandstones of the Rio do Peixe Group (Fig. 7.5). This unit comprises three formations. The Antenor Navarro Formation on the border of these basins is interpreted as coalescing alluvial fans and braided fluvial systems. The Sousa Formation, which is essentially microclastic (fine

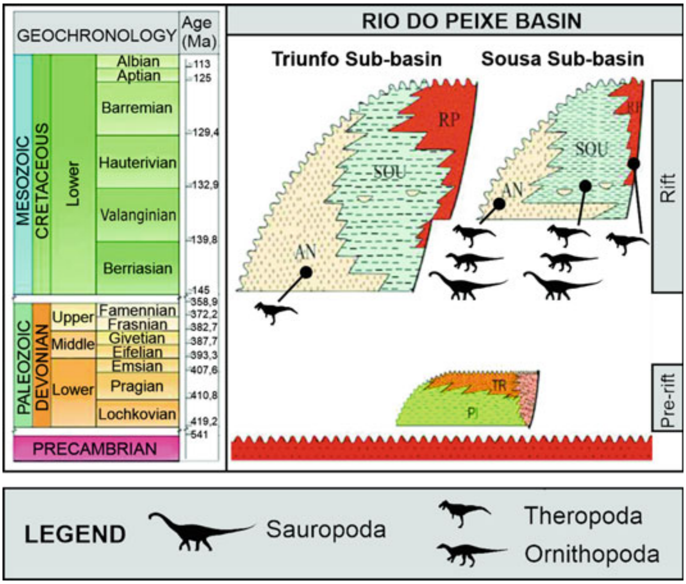

Fig. 7.5 Rio do Peixe Basins stratigraphical chart, and the lithostratigraphic units with dinosaur footprints. Abbreviations: PI: Pilões Formation; TR: Triunfo Formation (Devonian Group Santa Helena); AN: Antenor Navarro Formation; SOU: Sousa Formation; RP: Rio Piranhas Formation. Modified from Rapozo et al. (2021)

sandstones, siltstones, argillites, marls), indicates lacustrine, swampy, and meandering fluvial environments with microbial influence (Carvalho et al. 2013a). The Rio Piranhas Formation is interpreted as alluvial fans and temporary and braided rivers.

These deposits demonstrate the direct control of sedimentation by the tectonic activity (Souza et al. 2021; Oliveira et al. 2022). Deposition along the faulted borders of the basins are alluvial fans, changing to a braided fluvial system more distally. A meandering fluvial system with a wide floodplain was established in the central region of the basins, where perennial and/or temporary lakes were established (Carvalho 2000a; 2004a; Leonardi and Carvalho 1992, 2021; Lourenço 2021).

The mudstones, siltstones and black shales of the Sousa Formation (locality Sítio Saguim, Sousa Basin) are prospective for hydrocarbon generation (low liquid hydrocarbon generation potential but a moderate gas potential, ANP - Agência Nacional de Petróleo 2008; Iemini 2009). However, a validation to hydrocarbon exploration in the basin is so far expected (Carvalho et al. 2013c; Muniz et al. 2017; Gonzaga et al. 2022; Fig. 7.6).

Fig. 7.6 Oil exudation from Sousa formation at Sítio Saguim, interior of the Sousa Basin

7.3 Footprints: Diversity and Paleobiological Interpretation

The Sousa and Triunfo basins have a paleontological significance due to the abundance of dinosaur ichnofaunas that are part of an extensive Early Cretaceous megatracksite (Viana et al. 1993; Leonardi and Carvalho 2000, 2002) established during the break-up of Gondwana and the early stages of the South Atlantic opening. After 48 years of field work, 42 tracksites (26 in Sousa Formation; 11 in Antenor Navarro Formation; 5 in Rio Piranhas Formation) and about 96 tracks-bearing levels of the Rio do Peixe basins (74 in Sousa Formation; 17 in Antenor Navarro Formation; 5 in Rio Piranhas Formation) were recognized, mainly in the Sousa Basin (Leonardi 2021; Leonardi and Carvalho 2021).

These tracksites and the correspondent ichnofossiliferous levels contain trackways or isolated footprints assigned to different clades of dinosaurs: 395 large theropods (Fig. 7.7**a**); 31 smaller theropods with a third toe substantially longer than the other two toes; five additional, different kinds of small theropods; 16 medium-size theropods from Serrote do Letreiro (for a total of about 447 individual theropods); about 90 sauropods (Fig. 7.7**b**); 30 graviportal ornithopods (among them four quadrupedal and one sub-quadrupedal trackways, along with some isolated footprints, probably pertaining also to quadrupedal animals) (Fig. 7.7**c**); six small ornithopods; one ankylosaur (Fig. 7.7**d**); one small quadrupedal Thyreophora (altogether 36 ornithopods, 38 ornithischians); and at least 53 indeterminate dinosaur tracks. In total, the number of identifiable individual dinosaurs is 576, and the total number of individual dinosaurs, including the indeterminate tracks is at least 629; there are, in addition, some representatives of the mesofauna. There are also four possible dinosaur tail impressions (Leonardi and Carvalho 2000, 2021). These numerical data are updated with respect to those previously provided (Leonardi and Carvalho 2021) both for the increase of the discovered locations and for a revision of some classification cases.

The meso-ichnofauna, very rare in these basins, is represented by just one set of batrachopodid prints; some crocodilian traces (tracks and a body imprint in the mudstone) (Fig. 7.8a); one isolated lacertoid footprint (Fig. 7.8b); and a very large number of small chelonian swimming tracks (Leonardi and Carvalho 2000, 2021; Fig. 7.8c). The absence, for now, of pterosaur tracks is odd. The mammals seem to have left no traces, although an occurrence (of poor quality), cannot be excluded, with an eventual trackway at Riacho do Cazé (Sousa County), Antenor Navarro Formation, Sousa Basin (Fig. 7.8d). The detailed description and classification of the ichnofossiliferous sites of Sousa and Triunfo basins (and the few material found in the two smaller basins of Pombal and Vertentes) is presented by Leonardi and Carvalho (2021). Some new ichnosites (Serrote do Mocó Fig. 7.9a and Araçá-Rio Novo, Fig. 7.9b, Leonardi 2021; Pereiros, Carvalho and Leonardi 2023 (Fig. 7.9c); Engenho Novo 3rd, Leonardi 2021; (Fig. 7.9d) and the new site Buscapé, Fazenda Abóbora (unpublished) were recently discovered in the Sousa Basin, Sousa Formation. Table 7.1 summarizes the data from these ichnosites and Table 7.2 gives the geographical coordinates, to aid the tracksites location.

7.3.1 Fossil Tracks Complete or Replace Bones in Dinosaur Documentation

One of the advantages of fossil tracks is that in many paleoenvironments and continental stratigraphic units, where body fossils are poor or absent, good quality tracks complement or sometimes completely replace the documentation on the existence of dinosaurs and other animals. This is for example the case of the western Paraíba

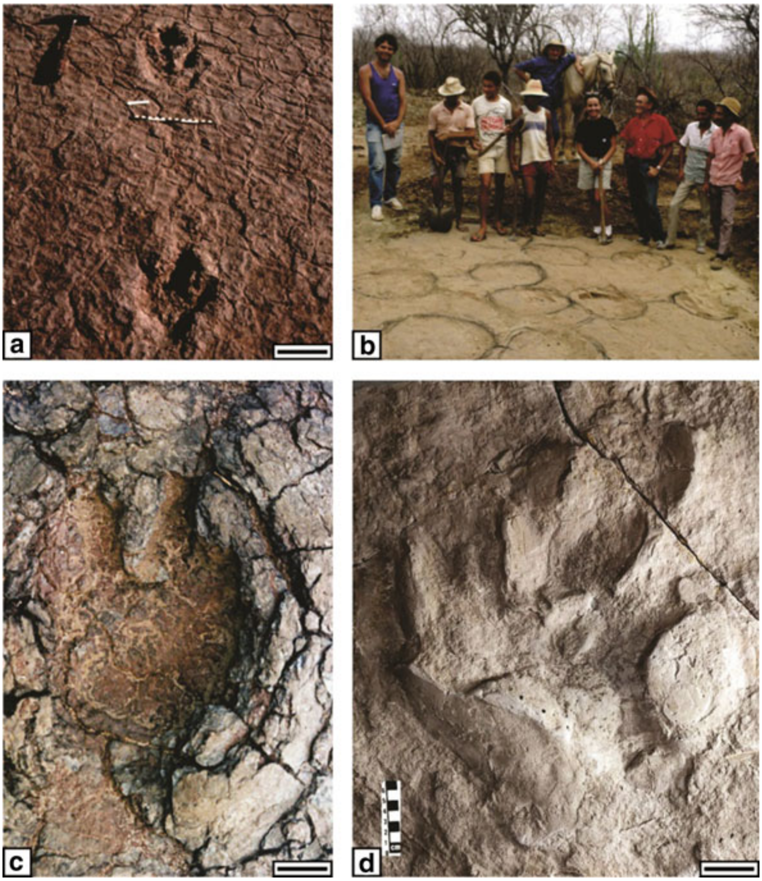

Fig. 7.7 The Rio do Peixe Basins contain trackways or isolated footprints assigned to different clades of dinosaurs: **a** Theropods; **b** Sauropods. Photo by Franco Capone; c Ornithopods; **d** Cast of an ankylosaurian hand-foot set (SOES 7), from Serrote do Pimenta, Antenor Navarro Formation. Photo by M. de Fátima C. F. dos Santos. Graphic scales: **a** = 10 cm; **b** = the diameter of the footprints of sauropods in excavation is 40 to 80 cm; **c** = 8 cm; **d** = 5 cm

State, but also other areas of the Brazilian northeast: the Mesozoic skeletons and bones are rare, with the exception of the Araripe Basin.

The fossil tracks present a true bonanza in the Rio do Peixe basins and especially in the Sousa Basin, with more than 600 dinosaurs recorded by their footprints in such a small area, and a very high diversity index. The body fossils, on the contrary, are reduced so far to a few bones corresponding to two individuals of titanosaurids (Ghilardi et al. 2014, 2016; Carvalho et al. 2017) and one or two notosuchian crocodyliformes (Carvalho and Nobre 2001). In the Sousa Basin, even if only a titanosaurid fibula had been found so far (Ghilardi et al. 2014, 2016), from

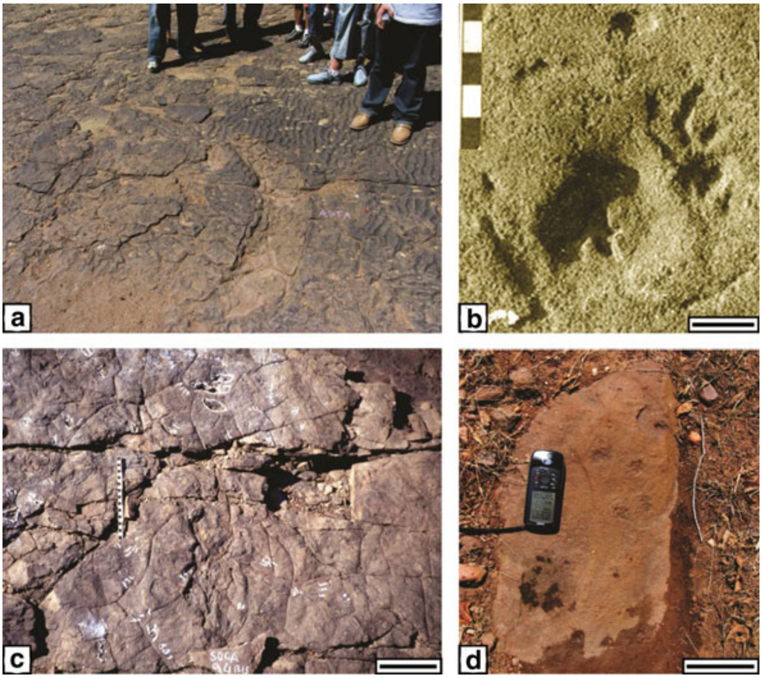

Fig. 7.8 Non-dinosaur tracks in the Sousa Basin. **a** Crocodilian body imprint at Tapera, Sousa Formation; **b** The single lacertoid footprint in the Rio do Peixe Basins, from Serrote do Pimenta ichnosite, Antenor Navarro Formation; **c** Footprints of swimming chelonians and a theropod, from the Piau locality, Sousa Formation; **d** A possible occurrence of mammal tracks, from Riacho do Cazé, Sousa County, Antenor Navarro Formation. Graphic scales: **a** = people as a graphic scale; **B** = 2 cm; **C** = 20 cm; **D** = 10 cm

the fossil footprints, we can estimate the existence of about 608 dinosaur individuals of distinct clades. In the Triunfo Basin, the unique formally described dinosaur species is the sauropod *Triunfosaurus leonardii* Carvalho et al. 2017 (Fig. 7.10), despite the presence of theropod footprints. Among the tracks from these basins it is possible to estimate at least 447 individual theropods divided into large predators, mostly abelisaurids, but without excluding spinosaurs (340 individuals, represented by at least five different forms; Fig. 7.11); 31 small theropods, probably noasaurids or velocisaurids (Fig. 7.12), with long and slender feet, producing tracks similar to those of the *Grallator-Eubrontes* plexus of the Laurasian continents; 16 medium-sized theropod individuals, different, but attributable to the same plexus and forming a single population (Fig. 7.13); not to mention the about 60 swimming theropods, that one cannot classify correctly. The sauropods are less frequent in these formations. In the Sousa Basin their fossil footprints indicate 67 individuals divided into five great groups that marched in herds, with evident gregariousness; and 23 isolated individual tracks (about 90 sauropods, all together). Sauropod tracks are often of

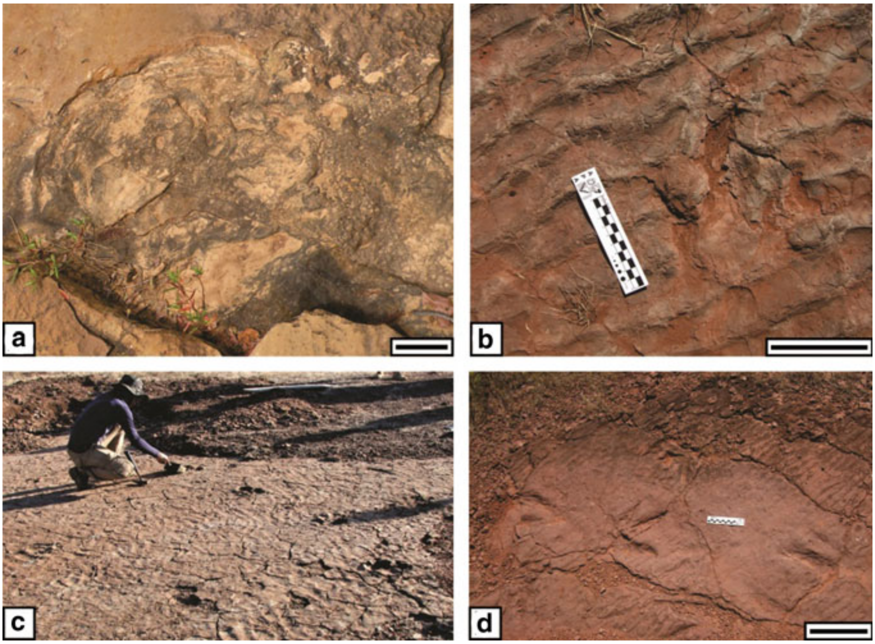

Fig. 7.9 Tracksites from the Sousa Basin. **a** Serrote do Mocó, with sauropod tracks; Photo by Luiz Carlos Gomes da Silva; **b** Theropod tracks and ripple marks at Araçá Rio Novo; **c** The Pereiros ichnosite, with three theropod trackways; **d** Engenho Novo 3rd, with several theropod and sauropod tracks. Graphic scales: **a** = 15 cm; **b** = 10 cm; **c** = Ismar Carvalho as reference scale; **d** = 20 cm

poor quality, and typically very large (Fig. 7.14**a**). The largest, with a diameter of 120 cm, is located in the locality Piau-Caiçara.

The ornithopods were rarer, and their trackways are partially bipedal (Fig. 7.14**b**), partly quadruped (Fig. 7.14**c–d**) and partly semi-quadruped. Most are isolated and therefore not gregarious individuals, usually graviportal animals of large dimensions (about 30 individuals). The main ones have been assigned to three ichnogenera (Leonardi 1979a, 1984a), attributed to iguanodontids, probably of African affinity, without excluding other types. There are also some specimens of small ornithopod tracks (about 6 specimens). One of the most important discoveries in the Sousa Basin was that of a hand-foot pair of an ankylosaurian, probably a nodosaurid (SOES 7; Leonardi 1984a, 1994). The discovery of it in 1979 was the first indication of the presence of ankylosaurs in South America (Fig. 7.15**a–b**). Another particularly interesting specimen is a rather enigmatic short trackway, of difficult interpretation because it is an underprint. It is the track SOPP 15 (Leonardi 1994, 58; Leonardi and Carvalho 2021), of four hand-foot sets, found in the locality Passagem das Pedras, level 1, perhaps a Thyreophoroidea trackmaker. Together they are 38 Ornithischia (6.60% of the total individual tracks classifiable); and 537 Saurischia (93.23% of the total individual tracks classifiable).

Table 7.1 Ichnosites and ichnofaunas of the Rio do Peixe Basins. Ank = Ankylosauria; Chel = Chelonians; Croc = Crocodylomorph; IS = Dinosauria, uncertain classification; Juv = juvenile dinosaur; Liz = Lizard-like track; Mam = ?Mammal tracks; Ornith = quadruped ornithischian; Triunfo = Triunfo Basin

Code	Ichnosite	Basin	Formation	Theropods	Sauropods	Ornithopods	Others dinos	IS	Total dinos	Levels
Sousa Formation										
SOAB	Abreu	Sousa	Sousa	1					1	1
ANAC	Araçá de Cima	Sousa	Sousa	1					1	1
ANAN	Araçá Rio Novo	Sousa	Sousa	>5					>5	?
ANBD	Barragem do Domício	Sousa	Sousa	3					3	3
SOBP	Baixio do Padre	Sousa	Sousa	1		1			2	2
SOBU	Buscapé, ex Abobora	Sousa	Sousa	1					1	1
ANEN1	Engenho Novo1	Sousa	Sousa	24	1	1		2	28	?
ANEN2	Engenho Novo2	Sousa	Sousa	2					2	1
ANEN3	Engenho Novo3	Sousa	Sousa	>9	>10				19	2
ANJU	Juazeirinho	Sousa	Sousa	4					4	4
SOMA	Matadouro	Sousa	Sousa	4					4	2
SOPP	Passagem das Pedras	Sousa	Sousa	14		4	1 Juv 1ornith	~20	~40	8
SOPE	Pedregulho	Sousa	Sousa	2					2	2
SJPE	Pereiros	Sousa	Sousa	3					3	2
SOCA	Piau-Caiçara	Sousa	Sousa	~170	9	7	(1 croc Chel)	~23	~209	25
SOPU	Piau 2	Sousa	Sousa	2					2	2
SOPI	Piedade	Sousa	Sousa	4		2		1	7	3
SOPM	Poço do Motor	Sousa	Sousa	8					8	3

(continued)

Table 7.1 (continued)

Code	Ichnosite	Basin	Formation	Theropods	Sauropods	Ornithopods	Others dinos	IS	Total dinos	Levels
SOPV	Poço da Volta	Sousa	Sousa	1					1	1
ANSM	Serrote do Mocó	Sousa	Sousa		~1				1	1
SOSA	Sítio Saguim	Sousa	Sousa	4		1			5	1
APTA	Tapera	Sousa	Sousa	>5	2	1	(1croc)		>8	3
APVR1	Varzea dos Ramos 1	Sousa	Sousa	>60	1	?1			~62	2
APVR2	Varzea dos Ramos 2	Sousa	Sousa	1					1	1
APVR3	Varzea dos Ramos 3	Sousa	Sousa	10					10	2
ANZO	Zoador	Sousa	Sousa	1					1	1
Antenor Navarro Formation										
UIAR	Arapuã	Triunfo	Ant.Nav		1				1	1
ANAR	Aroeira	Sousa	Ant.Nav		1				1	1
UIBA	Baleia	Triunfo	Ant.Nav	2					2	1
ANCA	Cabra Assada	Sousa	Ant.Nav	7		2		4	13	?
POGR	Grotão	Pombal	Ant.Nav					1	1	1
UIPO	Pocinho	Triunfo	Ant.Nav	4					4	2
SORC	Riacho do Cazé	Sousa	Ant.Nav	~5	~ 5		(mam?)		~10	2
SORP	Riacho dos Oliveira	Sousa	Ant.Nav			1			1	?
SOSL	Serrote do Letreiro	Sousa	Ant.Nav	>24	~20	1		2	~47	3
SOES	Serrote do Pimenta	Sousa	Ant.Nav	~32	8	3	ank, (liz)		~44	3
SOFB	Floresta dos Borba	Sousa	Ant.Nav	>4	~20	>2			~26	3

(continued)

Table 7.1 (continued)

Code	Ichnosite	Basin	Formation	Theropods	Sauropods	Ornithopods	Others dinos	IS	Total dinos	Levels
Rio Piranhas Formation										
SOCV	Curral Velho	Sousa	Rio Pir	7		5			12	1?
SOLF 1	Lagoa do Forno 1	Sousa	Rio Pir	6	8				14	1
SOLF 2	Lagoa do Forno 2	Sousa	Rio Pir	1					1	1
SOMD	Mãe d'Água	Sousa	Rio Pir	>2	>2	4			>8	>1
SOFP	Fazenda Paraíso	Sousa	Rio Pir	13	1				14	>1
Total ichnofaunas of Sousa Formation										
26	26	–	26	>340	>24	>18	2	46	>430	>74
Total ichnofaunas of Antenor Navarro Formation										
11	11	–	11	>78	55	>9	1	7	>150	>17
Total ichnofaunas of Rio Piranhas Formation										
5	5	–	5	>29	>11	9	0	0	>49	>5
Total ichnofaunas of Rio do Peixe Basins										
42	42	–	42	>447	>90	>36	3	53	>629	>96

Table 7.2 The ichnosites of the Rio do Peixe Basins and geographic coordinates, datum WGS 84 (Siqueira et al. 2011; Leonardi and Carvalho 2021). The coordinates were collected at different times, over 48 years, using different methods and devices (or maps)

Code	Ichnosite	Basin	Formation	Coordinates
SOAB	Abreu	Sousa	Sousa	06°44′25″S/ 38°19′00″W
ANAC	Araçá de Cima	Sousa	Sousa	06°44.995S/ 38°24.673W
ANAN	Araçás Rio Novo	Sousa	Sousa	06º44′41.2″S/ 38º25′08.6″W
ANBD	Barragem do Domício	Sousa	Sousa	06°44.165 S/ 38°26.288W
SOBP	Baixio do Padre	Sousa	Sousa	06°45.113 S/ 38°19.993W
SOBU	Buscapé, ex Abobora	Sousa	Sousa	–
ANEN1	Engenho Novo1	Sousa	Sousa	06º42′51.7″S/ 38º24′43.0″W
ANEN2	Engenho Novo2	Sousa	Sousa	06º42′51.7″S/ 38º24′43.0″W
ANEN3	Engenho Novo3	Sousa	Sousa	06º42.896S/ 38º24.752″W
ANJU	Juazeirinho	Sousa	Sousa	06°44.685 S/ 38°25.144W
SOMA	Matadouro	Sousa	Sousa	06°45′06.93″S/ 38°13′41.72″W
SOPP	Passagem das Pedras	Sousa	Sousa	06°44′00.51″S/ 38°15′41.57″W
SOPE	Pedregulho	Sousa	Sousa	06º45′22.6″S/ 38º20′56.7″W
SOCA	Piau-Caiçara	Sousa	Sousa	06º44′24.9″S/ 38º19′54.9″W
SOPU	Piau 2	Sousa	Sousa	06°43′52″S/ 38°19′37″W
SOPI	Piedade	Sousa	Sousa	06º44′55.4″S/ 38º20′56.5″W
SOPM	Poço do Motor	Sousa	Sousa	06°44′18.139″S/ 38º15′28.947″W
SOPV	Poço da Volta	Sousa	Sousa	06º45′20.10″S/ 38º24′43.9″W
ANSM	Serrote do Mocó	Sousa	Sousa	06º41.7965/ 38º24.974″W
SJSP	Sítio Pereiros	Sousa	Sousa	06°47′18.71″S/ 38°29′11.81″W
SOSA	Sítio Saguim	Sousa	Sousa	06º43′24.3″S/38º 20′15.5″W

(continued)

Table 7.2 (continued)

Code	Ichnosite	Basin	Formation	Coordinates
APTA	Tapera	Sousa	Sousa	06°46.188 S/38° 06.695W
APVR1	Varzea dos Ramos 1	Sousa	Sousa	06º46′09.0″S/38º 06′40.5″W
APVR2	Varzea dos Ramos 2	Sousa	Sousa	06°46′38″S/ 38°05′42″W
APVR3	Varzea dos Ramos 3	Sousa	Sousa	06°46′38″S/ 38°06′15″W
ANZO	Zoador	Sousa	Sousa	06°45.301S/38 24.595W
UIAR	Arapuã	Triunfo	Ant.Navarro	06°34′45″S/ 38°25′40″W
ANAR	Aroeira	Sousa	Ant.Navarro	06°41′44″S/ 38°22′06″W
UIBA	Baleia	Triunfo	Ant.Navarro	06°12′10″S/ 38°25′13″W
POGR	Grotão	Pombal	Ant.Navarro	06°45′32″S/ 37°54′40″W
UIPO	Pocinho	Triunfo	Ant.Navarro	06°35′13″S/ 38°25′15″W
SORC	Riacho do Cazé	Sousa	Ant.Navarro	06º43.153″S/ 38º13.14.548W
SORP	Riacho dos Oliveira	Sousa	Ant.Navarro	06°43.347″S/ 38°14.636W
SOSL	Serrote do Letreiro	Sousa	Ant.Navarro	06°41′36.89″S/ 38°18′29.72″W
SOES	Serrote do Pimenta	Sousa	Ant.Navarro	06º43′18.8″S/ 38º11′44.1″W
SOFB	Floresta dos Borba	Sousa	Ant.Navarro	06°41′055″S/ 38°20′733″W
ANCA	Cabra Assada	Sousa	Ant.Navarro	06º49′53.8″S/38º 23′50.3″W
SOCV	Curral Velho	Sousa	Rio Piranhas	06º49′47.474″S/ 38º12′9.812″W
SOLF 1	Lagoa do Forno	Sousa	Rio Piranhas	06°48.066 S/ 38°10.039W
SOLF 2	Lagoa do Forno	Sousa	Rio Piranhas	06°48.563 S/ 38°10.492W

(continued)

Table 7.2 (continued)

Code	Ichnosite	Basin	Formation	Coordinates
SOMD	Mãe d'Água	Sousa	Rio Piranhas	06°48′58.5″S/ 38°12′41.5″W
SOFP	Fazenda Paraíso	Sousa	Rio Piranhas	06°48.793S/ 38°09.857W

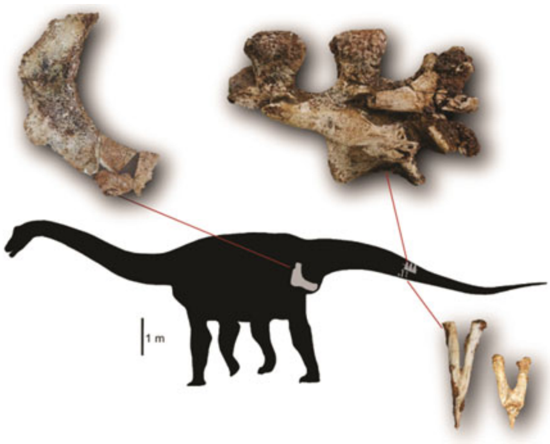

Fig. 7.10 The sauropod *Triunfosaurus leonardii* Carvalho, Salgado, Lindoso, Araújo Jr., Nogueira & Agnelo, 2017 from the Triunfo Basin. In these basins the fossil bone are very rare. Graphic scale = 1 m. Art by Deverson Silva

Based on the numerical data, according to their characteristics (Leonardi 2021) there are 128 trackways assigned to herbivorous dinosaurs (22.26% of individual trackways and isolated footprints) and 447 trackways attributed to theropods (77.74% of the identifiable individual trackways and isolated footprints). The ratio of herbivorous to theropod individual trackways in this ichnofauna is 1: 3.47. However, probably not all theropods were carnivorous and predatory; some were necrophagous; other forms of that clade could be herbivorous or omnivorous rather than strictly carnivorous. There were also piscivorous and insectivorous animals. This is particularly likely for small to midsize theropods.

There are at least 99 quadrupedal trackways (about 90 sauropods, and nine ornithischians, correspondent to about seven quadrupedal ornithopods and two quadrupedal thyreophorans; 17.22% of the identifiable individual trackways and isolated footprints) and 476 bipedal trackways (82.78% of the identifiable individual tracks). The ratio of quadrupedal to bipedal tracks is 1: 4.81.

The relationship between youth and adult tracks is also interesting. In the Rio do Peixe basins, the former tracks are very rare, consequently, little can be said about the age-class structure of the trackmakers. The only footprint in Sousa Basin that is, almost certainly, that of a juvenile is an isolated tridactyl track on Passagem das Pedras site, which is the smallest dinosaur track discovered so far in these basins (footprint length = 5.6 cm). There are no other very small dinosaur individuals (hind-foot prints shorter than 12 cm). This phenomenon might indicate very heavy

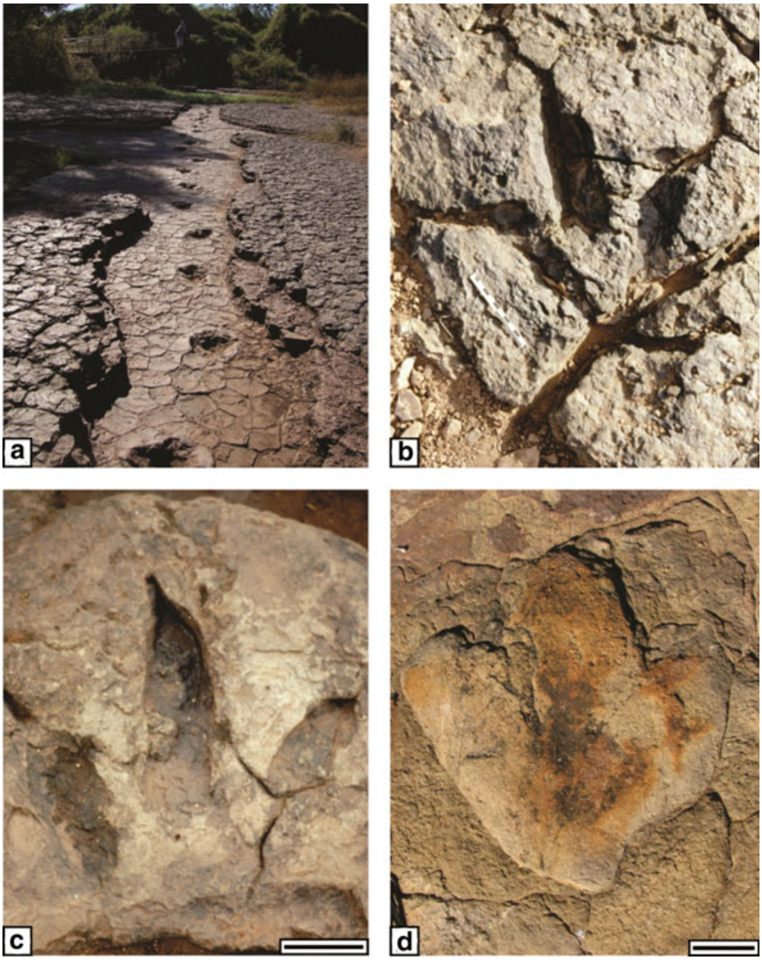

Fig. 7.11 Diversity of tracks among the 447 individual theropods found in the Sousa Basin, Sousa Formation. **a** A trackway of *Moraesichnium barberenae* Leonardi 1979a, b **b** A theropod track from Caiçara-Piau locality; **c** Theropod footprint from Sítio Saguim; **d** An anomalous theropod footprint, pertaining to a normal theropod trackway, but that seems to belong to an ornithopod. It is a footprint with infilling material more coarse from the adjacent top layer. Graphic scale: **a** = the average stride is 197.2 cm; **b** = the length of the footprint is 20 cm; **c** and d = 5 cm

mortality on the part of very young individuals (Leonardi 1981). It is also possible to be an artifact of preservation, where small sized dinosaurs were not heavy enough to leave footprints because of the substrate firmness.

In a total of 42 ichnosites in the Rio do Peixe basins, against what one would expect in theory, those in which meat eaters outnumber plant eaters (31 sites out of 42; that is 73.81% of all sites) are more abundant than those in which the opposite occurs, (7 sites, 16.67%). There are three sites where the parity between carnivores

Fig. 7.12 A noasaurid track, 9 cm long, from the Caiçara-Piau locality, Sousa Formation, SOCA 1321. Photo by M. de Fátima C.F. dos Santos. Graphic scale = 1.3 cm

and herbivores is reached (7.14%) and a site with a track not classifiable (2.38%). Besides, ichnosites in which there are only theropod tracks, are rather numerous in the Rio do Peixe basins. They are 19, out of 42 ichnosites, and it corresponds to the 45.24% out of all 42 ichnosites. This high number of sites with apparent exclusive presence of theropods is well explained by Pérez-Lorente (2015, p. 325): "Because theropod footprints are the most abundant, so are outcrops with theropod footprints".

In addition to these 19 ichnosites where the theropods are represented only by tracks (45.24% out of 42 sites), there are: 1 ichnosite with tracks of theropods, sauropods, ornithopods and one quadrupedal Thyreophora (four clades, 2.38%); 1 ichnosite with tracks of theropods, ornithopods and one quadrupedal Thyreophora (three clades, 2.38%); 7 ichnosites with tracks of theropods, sauropods, ornithopods (three clades, 16.67%); 4 ichnosites with tracks of theropods and sauropods (two clades, 9.52%); 5 ichnosites with tracks of theropods and ornithopods (two clades, 11.90%); 3 sites with only sauropod tracks (7.14%); 1 site with only ornithopod tracks (2.38%); 1 site with only large unclassifiable herbivore tracks (2.38%). There are also few sites where rare tracks of animals of the mesofauna are also recorded, they are 4 (9.52% of all the 42 sites). These last localities are Caiçara-Piau, Riacho do Cazé, Serrote do Pimenta, and Tapera.

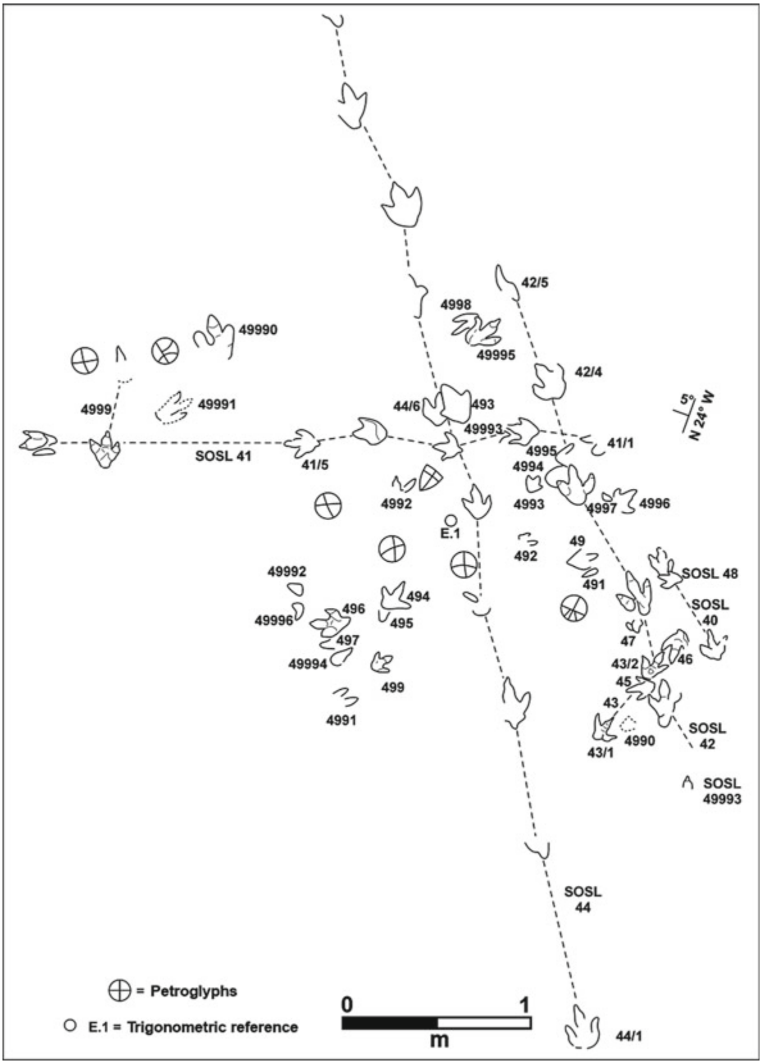

Fig. 7.13 An original drawing, by G. Leonardi, of the bedding surface of the Antenor Navarro Formation, at the Serrote do Letreiro tracksite, Sousa Basin. All individuals probably belonged to the same population. Fossil footprints are associated with later prehistoric petroglyphs

7.3.2 Behavior of the Rio do Peixe Dinosaurs

The study of the fossil tracks also is the most important and unparalleled (Gatesy and Ellis 2016) method for making inferences about the behavior of the track-makers. Seventy-eight trackways were sufficiently long and conveniently measurable, permitted estimation of trackmaker speeds. The result was clear: the speed of

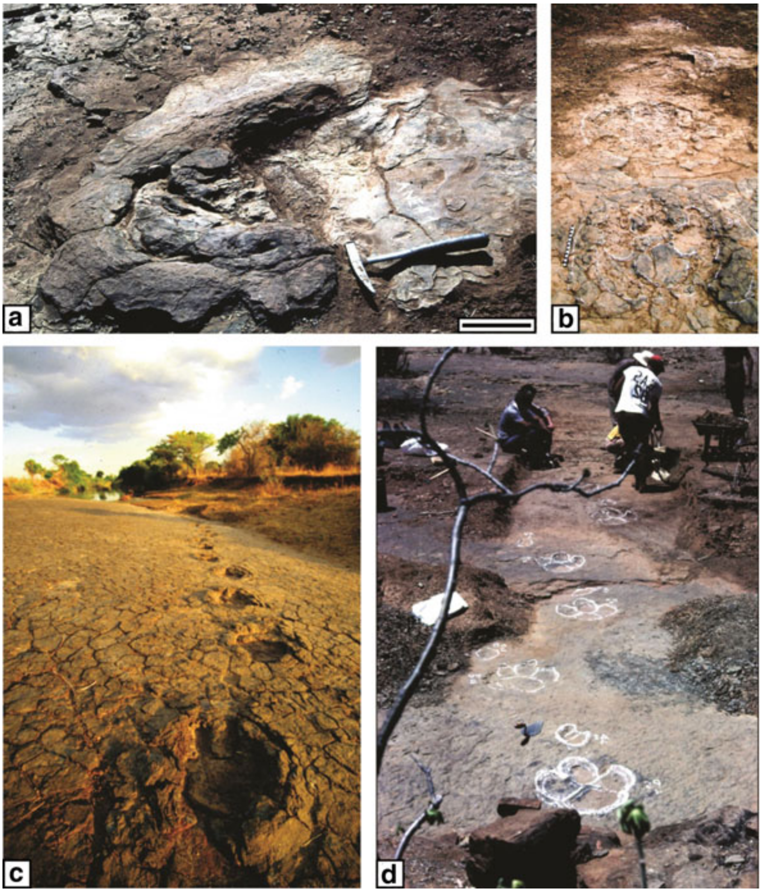

Fig. 7.14 Tracks of plant eating dinosaurs. **a** Manus-pes pair of a sauropod from Engenho Novo ichnosite; São João do Rio do Peixe County, Sousa Formation, Sousa Basin; **b** A trackway of a bipedal graviportal ornithopod from Baixio do Padre, Sousa County, Sousa Formation, Sousa Basin. It pertain to the ichnogenus *Caririchnium*, but the gait is herein bipedal; **c** The main trackway of the Passagem das Pedras ichnosite, *Sousaichnium pricei*, a semi-bipedal iguanodontid. Sousa County, Sousa Formation, Sousa Basin; **d** Holotype of *Caririchnium magnificum*, pertaining to a graviportal quadrupedal ornithopod. Serrote do Letreiro, Sousa County, Antenor Navarro Formation, Sousa Basin. Graphic scales: **a**= 15 cm; **b**, **c** and **d**: the average widths of the hind-footprints are respectively: 51.2; 35.7: 47.8 cm

fifty-nine of these trackways (75.64% of the sample) was estimated between 3 and 7 km/h. The trackmakers were, therefore, traveling with a walking gait. Seven trackways show a slower estimated speed ($\leq$2 km/h; 8.98%); four of these are sauropods, three are ornithopods. Twelve trackways (15.38% of the sample) point to a speed between 8 and 23 km/h. Of these, eight (10.25%) have calculated speeds of 8–13 km/h; another four (5.12%) are distributed over a range between 13 and 23 km/h. These

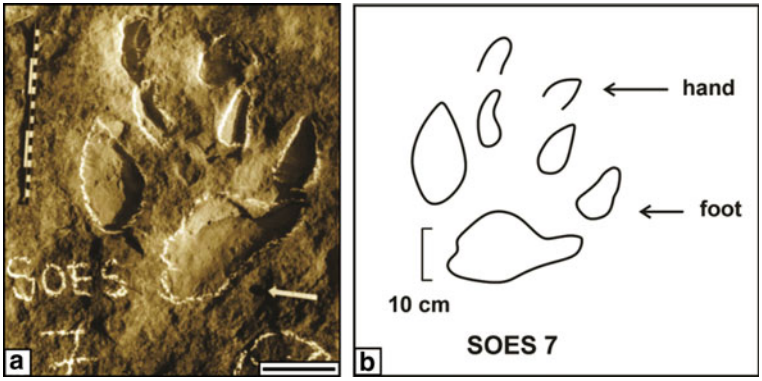

Fig. 7.15 a–b The discovery (1979) of this hand-foot set attributed to an ankylosaurian, probably a nodosaurid, at the Serrote do Pimenta tracksite (SOES 7; Leonardi 1984a; 1994), was the first evidence of ankylosaurs in South America. Sousa Basin, Antenor Navarro Formation. Graphic scale = 10 cm

last four trackways, all belonging to medium to large theropods (Fig. 7.16a), corresponds to the fastest runners of the Rio do Peixe ichnofauna (Leonardi et al. 1987a, b, c). It is important to be cautious when estimating or calculating speed from fossil track records (Lockley and Meyer 1999), despite the fact that we can calculate that dinosaurs in the Rio do Peixe basins in general kept a walking pace, and only rarely took a running gait. The quadrupeds always moved slowly or very slowly. The bipeds, including theropods, did not run very often or very quickly; the calculated maximum speed that was found in the Rio do Peixe Basins is about 23 km/h (Leonardi et al. 1987a, b, c; Fig. 7.16b). This situation is common for non-avian dinosaurs (Leonardi and Mietto 2000). A similar, more recent statement on low dinosaur speeds can be found, for example, in Xing et al. (2014).

The general evidence that dinosaurs have a high degree of metabolism is not doubted here. However, it is not so evidently reinforced by the known ichnological record, and it ought to be better examined on the basis of many detailed, extensive and statistic studies on their trackways (Leonardi et al. 1987a, b, c; Molnar and Farlow 1990), rather than on the basis of some isolated, biased, and/or unchecked information. When the latter occurs, it guides the huge racing dinosaurs of Bakker (1986a, b) and Paul (1987a, b).

The bearings or directions of the footprints from the Rio do Peixe Group of the Sousa Basin (Leonardi and Carvalho 2021), based on 386 individual trackways, point to a rather tetramodal model, with two main modes in the NE and SW quadrants, and two secondary modes in the other two quadrants. There seem, then, to be four associations of dinosaurs, moving along preferential paths, on different levels, and in diverse times and occasions. As earlier described for the locality Piau-Caiçara' tracks (Godoy and Leonardi 1985), and at least for the Sousa Basin tracks in general, most of these tracks are parallel or nearly parallel to the ridges of the ripple marks. These crests, in turn, indicate the dominant orientation of the water's edge, which

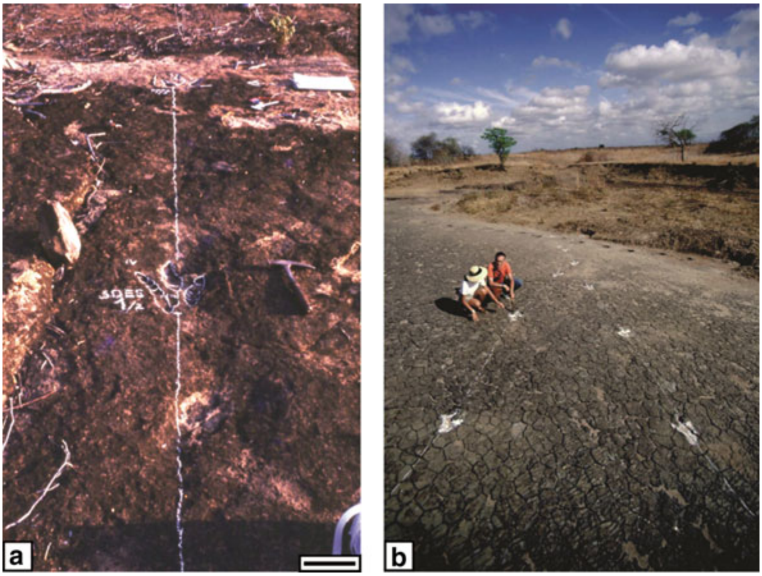

Fig. 7.16 On the behavior of dinosaur. **a** This very straight and narrow trackway corresponds to one of the fastest runners of the Rio do Peixe ichnofauna: a large theropod track (SOES 1) at Serrote do Pimenta (Antenor Navarro Formation), with about 22 km/h. Graphic scale = 20 cm; **b** Another theropod track (SOPP 3) at Passagem das Pedras (Sousa Formation), with an estimated speed of 23 km/h. **b** Photograph by Franco Capone

is often parallel to the regional faults that gave rise to the Rio do Peixe basins. It is clear, therefore, that the directions of movements were strongly conditioned by the local and regional morphology of the territory, in particular by the bodies of water and, indirectly, by the regional tectonic patterns (Godoy and Leonardi 1985; Leonardi 1989; Leonardi and Carvalho 2021). It would be possible that they could easily reach Africa afoot (nearly 450 km from Sousa), by following one of these paths, specifically along the Patos-Garoua fault system, possibly reaching the current territory of Cameroon.

All tracks in the Rio do Peixe basins, including those of sauropods, are rather narrow, attesting to an entirely erect position of the trackmaker. All sauropods were clearly quadrupeds. Theropods, both large and small, were all bipedal (Molnar and Farlow 1990), with very narrow trackways, in contrast to the old model of large theropods giving a Cossack dance show (Molnar and Farlow 1990; Wade 1989). Ornithopods, in the Sousa Basin, were bipeds, quadrupeds or, in one case, semi-quadrupeds. In some cases, the tail mark is perhaps preserved in the Sousa Basin. The rarity of tail drags or marks is habitual for dinosaurs. It is evident that most of the dinosaurs in the Rio do Peixe basins, including both bipedal and quadruped ones, kept their tail away from touching the ground.

Dinosaur tracks of the Rio do Peixe basins produced by bipeds (probably 476 individual tracks, or ~82.78% of the 575 classified dinosaur tracks) heavily surpass those of quadrupeds (about 99 individuals, or ~17.22% of the serviceable sample). The ratio of biped tracks to quadruped tracks is thus 4.81: 1. We stated earlier that walking gaits surpass almost entirely running gaits. There are cases of semi-bipedal or semi-quadruped animals; especially ornithopods. No hopping, galloping or sprawling (except for a single lizard-like footprint) gaits are represented at these basins. A particular case is that of the trackway SOPP 1, of an iguanodontid, quadruped or semi quadruped in a different way, because in its very long trackway it leaned slightly on the ground with the right hand only, and not with the left. It can be interpreted as a taphonomic aspect or even an abnormal behavior. A rather usual manner of gait in the Sousa Basin (~10.43%) is that of dinosaurs, mainly theropods, which, swimming (Fig. 7.17a) and perhaps searching for fish or other food in shallow water, pushed with their feet on the bottom of a shallow lake bed, and produced what are called swimming-tracks or more correctly, half-swimming-tracks (Leonardi 1987). Altogether, there are about 59 individual theropod half-swimming tracks and a single probable ornithopod half-swimming track in these basins (~60 cases vs. 1).

Except for sauropods, which almost always lived in herds, most dinosaurs in the Rio do Peixe basins were lonely animals. The gregarious behavior is attested by clusters of sauropod tracks of at least 7–20 individuals (Fig. 7.17**b**; Leonardi 1989, 1994; Carvalho 2000b; Leonardi and Santos 2006); the number of animals in these herds could have been higher, because some tracks were probably destroyed by erosion, and some have yet to be found out and/or excavated. Theropods and ornithopods, instead, ordinarily traveled as individual animals. There are, however, three exceptions among the theropods: the population of small and medium-sized theropods (~16 individuals at Serrote do Letreiro; Fig. 7.17c); the assemblage of some long-heeled theropods of the ichnogenus *Moraesichnium* Leonardi 1979a, b at Passagem das Pedras (Fig. 7.17d); and perhaps the nearly 30 theropods of Piau-Caiçara farm on the “rainy” level 13/2.

7.4 Paleogeographic Distribution of the Footprints

The South American (and, in general, Gondwanan) dinosaurs are very different from those of the northern continents. Some integration and coexistence between the dinosaur species of the two supercontinents, Gondwana and Laurasia, occurred much later with the phenomenon that we could name: Dinosaur American Biotic Interchange (DABI), which occurred towards the end of the Cretaceous, due to the junction between the two American continents, a phenomenon analogous with the GABI, the Great American Biotic Interchange (Cione et al. 2015).

The diversity of the dinosaur faunas between Northern and Southern America depends on the probable total biogeographic isolation of South American and, more generally, Gondwanan faunas, from those of boreal continents (Laurasia) during Middle and Late Jurassic and almost all of the Cretaceous, a typical case of endemism (Bonaparte 1986, 2007). There is, instead, a notable affinity between South American dinosaur faunas and those of the other Gondwanan plates: Africa, Madagascar,

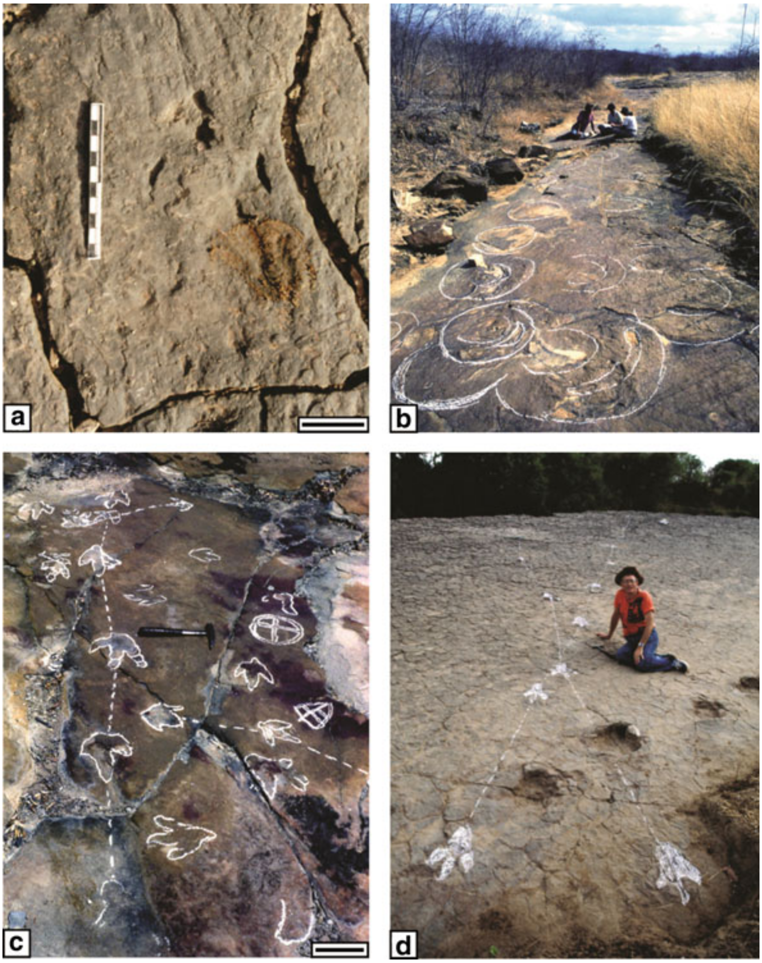

Fig. 7.17 **a** Typical imprint of a swimming theropod, pushing on the bottom with the toetips. Piau-Caiçara locality, Sousa County, Sousa Basin, Sousa Formation; **b** The gregarious behavior is attested by clusters of sauropod tracks of at least 7–20 individuals, which proceed in parallel herd, here preserved on the bottom of the rivulet Riacho do Pique, at Serrote do Letreiro, Sousa County. Antenor Navarro Formation, Sousa Basin. Photo by Franco Capone; **c** Gregarious (rare) behavior of a theropod population in Serrote do Letreiro tracksite, Sousa County. Antenor Navarro Formation, Sousa Basin; **d** An assemblage of several long-heeled theropods of the ichnogenus *Moraesichnium* at Passagem das Pedras, Sousa County. Sousa Formation, Sousa Basin. Photograph by Franco Capone. Graphic scale: a = 4 cm; **c** = 20 cm

India, Antarctica, and Australia. This applies even more to the present territory of Northeastern Brazil, which in the Early Cretaceous was probably still attached, at least partially, to Africa, but detached from the rest of what would later have been South America.

Indeed, the dinosaur fauna of the oldest portion of the Early Cretaceous (Berriasian to lower Barremian, Rio da Serra-Aratu stages) represented by their tracks in the Rio do Peixe basins, as well as the few other representatives of the meso-ichnofauna, had to be a very special fauna. As a matter, it ought to be more similar to that of West and Central Africa, rather than that of other regions of present-day Brazil and South America, since the easternmost area of the Brazilian territory (Rio Grande do Norte, Paraíba, at least part of the Ceará and Pernambuco states) was isolated by an epicontinental sea during the Early Cretaceous.

The landscape of the mentioned basins, during Early Cretaceous, were mainly flat surfaces, elongated narrow valleys, between chains of low mountains of mostly Proterozoic rocks, with a possible Paleozoic or Early Mesozoic cover, now disappeared. Low mountain or hill ranges, flanked the sinking basin. One side of the valley, controlled by a fault, usually a strike-slip fault, was steeper, rockier, and consequently less covered by vegetation. The other side could be less inclined and with a less inclined slope. The mountains on the sides of the basins could be covered on the top by woods or coniferous groves, mostly Araucariaceae and with all an undergrowth of tree ferns, Cycadoidea, like *Podozamites* and Conipherophyta, like *Otozamites*. Along the borders of the valleys ran ephemeral streams, generally of low flow, at the base on alluvial fans of Precambrian polymictic material, partially reworked, consisting of gravel and coarse immature sands. These torrential streams often originated anastomosed ephemeral channels in the largest basins.

The fauna could pass from the upland areas in the lowland prairies and vice-versa, both to graze, if they were plant-eaters, both to reach water points, easier to gush than in the highlands. If they were meat-eaters, just in those points that somehow served as a necessary gathering point of the fauna, especially in the seasons and other periods of dryness and aridity.

The sediments, transported by water, became gradually finer: coarse sand, fine-grained sand, silt, and finally mud. The interior of these basins, especially in those of greater area, were often abundant in water and low vegetation. At the depocenter there were lakes, shallow and ephemeral, with rather warm and alkaline waters.

7.5 Paleoenvironmental and Paleoclimatic Contexts

At the beginning of the Mesozoic, the southern hemisphere had a warm and arid climate. This is clearly observed by the generalized presence of wind deposits along the Brazilian and African intracratonic basins (Lima 1983). The connection of South America and Africa as a single continental block did not allow for greater humidity in what was then the continental hinterland. A greater degree of humidity was allowed due the fragmentation of the Gondwana supercontinent and the creation of a lake and river systems along the rift valleys. This suggests a link between climate change and the tectonic events that led to the separation of South-American and African continents. Although low, this humidity contributed to increased local rainfall and led to the growth of abundant vegetation in the region (Lima 1983; Carvalho 2000a).

During the Early Cretaceous, warm climate was widespread. According to Petri (1983, 1998) and Lima (1983), in the beginning of Cretaceous the climate was more humid in regions located to the south of the tropical domain (the Recôncavo-Tucano-Jatobá basins). Despite the tropical domain's hotter and drier climate, the existence of fresh-water lakes is suggested by invertebrate fossils, as the large conchostracans *Palaeolimnadiopsis reali* in some lacustrine facies of the Sousa Basin that locally provided more humid conditions (Carvalho 1989; Carvalho and Carvalho 1990).

At that time, the southern continents were still amalgamated in the Gondwana supercontinent, and the Atlantic Ocean was in its initial developing phase. In north-eastern Brazil, across an area of hundreds of square kilometers, ephemeral rivers and shallow lakes constituted important environments for an abundant endemic biota in many basins (Lima Filho et al. 1999; Mabesoone et al. 1979, 2000). The rarity of levels with rain-drop marks (only one recognized in the Sousa Basin, none in the others; Fig. 7.18), the scarcity of plant remains, logs and fossils suggest a relatively arid to semi-arid climate.

Another aspect is that dinosaur footprints are so strongly distributed in the Sousa Basin, compared to other basins (Fig. 7.19). Although sedimentological and taphonomic aspects may well control this disparity, it also could depend on different microclimates, at least due the presence or not of lakes and the pH of their waters. One might think that the valley of the Sousa Basin was similar to, in the present time,

Fig. 7.18 The stratigraphic level 13/2 at the Piau-Caiçara tracksite, Sousa Formation, Sousa Basin. The upper surface of the mudstone layer was covered by footprints of about thirty theropods of the same population, and the small craters produced by the rain, fall after the passage of that pack of meat-eater dinosaurs. Here, in this representative specimen, a footprint and some other theropod digits. Photo by Ragnhild Borgomanero. The width of the track is 14 cm

Fig. 7.19 Environmental reconstruction of the Sousa Basin (Antenor Navarro Formation) in the Early Cretaceous (Berriasian-Berramian). One ankylosaurian and titanosaurians crossing a fluvial fan deposit on the North margin of the basin. In the background to the left (South), behind the two titanosaurids, one notices the straight line of Proterozoic hills that depend on the Malta fault (E-W). Art by Guilherme Gehr

the great oasis of Faiyum in the Libyan-Nubian desert, located in Egypt, southwest of Cairo, so fertile and luxuriant, compared to the situation of aridity surrounding, and also so rich in crocodiles.

7.6 Conclusions

The four Rio do Peixe basins, and notably the Sousa Basin, present an impressive amount of Early Cretaceous dinosaur tracks in sediments dated from the Berriasian to the lower Barremian. Data on the presence of different groups of dinosaurs and other coeval animals, their correlations, the numerical value and percentage of their presence in the overall sample were herein provided. Several aspects of their behavior have been deduced: speeds, manners of gaits, directions, posture, individual and social behavior. The importance of quantifying the ichnological material, by means of a large number of data, and to its statistical study, has also been underlined.

The presence of dinosaur tracks in the Rio do Peixe basins induced the scientific tourism, which enabled job positions allowing the economic flourishment of the region. It would however be important and urgent to carry out a new vulnerability diagnosis of these ichnosites and the establishment of proposals for geoheritage protection.

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