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GIUSEPPE LEONARDI

MAIN RESULTS OF 45 YEARS OF ICHNOLOGICAL RESEARCH ON THE DINOSAUR TRACKS OF THE RIO DO PEIXE BASINS (PARAÍBA, BRAZIL, EARLY CRETACEOUS)

Abstract - Giuseppe Leonardi - Main results of 45 years of ichnological research on the dinosaur tracks of the Rio do Peixe basins (Paraíba, Brazil, Early Cretaceous).

The Rio do Peixe basins (Paraíba, Brazil) provided an impressive amount of dinosaur tracks of the Early Cretaceous. This is a summary exposure, with attention to the Geological setting, the methods used to study this fine heritage, beginning almost half a century ago. The value of fossil tracks to complete or replace the presence of skeletal remains is illustrated. Data are provided on the tracks of theropods, sauropods, ornithopods and ankylosaurs, as well as of other (rarer) contemporary animals; on their relationships and on the numerical value and percentage in the overall sample. Their behavior has been inferred: speeds, bearings, stance, gaits, social behavior. The importance of tracks for dating continental formations, difficult to date by other means, has been highlighted. Among other things, the discovery of new ichnosites in the Sousa basin is announced for the first time.

Keywords: Dinosaur tracks - Rio do Peixe basins - Early Cretaceous - Paraíba-Brazil - New ichnosites in the Sousa Basin.

Riassunto - Giuseppe Leonardi - Principali risultati di 45 anni di ricerche icnologiche sulle piste di dinosauri dei bacini del Rio do Peixe (Paraíba, Brasile, Cretaceo Inferiore).

I bacini del Rio do Peixe (Paraíba, Brasile) hanno fornito una quantità notevole di orme di dinosauri del Cretaceo Inferiore. Si tratta di una breve sintesi, con attenzione al contesto geologico, ai metodi utilizzati per studiare questo pregiato patrimonio, a partire da quasi mezzo secolo fa. È illustrato il valore delle piste fossili per completare o sostituire la presenza di ossa. Sono forniti dati sulle piste di teropodi, sauropodi, ornitopodi e anchilosauri, nonché di altri animali minori; e sulle loro relazioni e sul valore numerico e percentuale nel campione complessivo. Il loro comportamento è stato dedotto: velocità, direzioni, postura, andature, comportamento sociale. È stata evidenziata l'importanza delle orme fossili per la datazione di formazioni continentali difficili da datare con altri mezzi. Tra l'altro, è comunicata per la prima volta la scoperta di nuovi icnositi del bacino di Sousa.

Parole chiave: Piste di dinosauri - Bacini del Rio do Peixe - Cretaceo Inferiore - Paraíba-Brasile - Nuove località nel bacino di Sousa.

1. Introduction

After a convenient experience in the field, carried out mainly in Trentino and Alto Adige/Südtirol (Italy; Conti et al., 2020; Marchetti et al., 2020; Petti et al., 2020), the author found himself, from 1974, in Brazil as a missionary. He was there also a professor of Historical Geology, Geology of Brazil, Vertebrate Paleontology in the course of Geological Sciences and of Geology 1st for engineers at the Federal University of Paraná at Curitiba, capital of the state of Paraná, Southern Brazil. As such, with the support of the National Research Council of Brazil, he began systematic research in the field of Vertebrate Ichnology (Vertebrate tracks). He began mainly with an expedition (1975-76) to the state of Paraíba, based in the city of Sousa, in the western portion of that state, about 3,500 km NNE of Curitiba (Leonardi, 1979a).

The objective of this first expedition to Paraíba was to locate and rediscover two short dinosaur trackways discovered by Luciano Jacques de Moraes (Moraes, 1924), very rarely visited in the following half century, to the point that people had lost the memory of their location. During his expedition, the author rediscovered the two aforementioned tracks, excavated their continuation digging in the thick cover of sand and gravel, and then into the matrix rock, opening trenches (fig. 1).

In the same expedition, he found and studied other new tracks of dinosaurs. There followed in the subsequent 45 years and until today, 34 expeditions of the author in the region of Sousa (1975-2018). The field work was done sometimes alone, then more often with collaborators, mainly with Maria de Fátima C.F. dos Santos of the Museum Câmara Cascudo of Natal (Federal University of Rio Grande do Norte in Natal), and her team. The collaboration with Ismar de Souza Carvalho (Federal University of Rio de Janeiro) was very important for the ichnological study, and especially for the study of the geological setting of the region.

The discoveries of dinosaur tracks were more and more numerous and, consequently, a relevant literature on the subject was produced by this author and by his collaborators (Leonardi, 1979a, 1979b, 1980a, 1980b, 1984a, 1984b, 1984c, 1985, 1987a, 1987b, 1989, 1994, 2008, 2011; Leonardi et al., 1987a, 1987b, 1987c; Leonardi & Carvalho, 2000, 2002, 2021; Godoy & Leonardi, 1985; Carvalho, 1989, 1996, 2000a, 2000b, 2004a, 2004b; Carvalho et al., 2013, 2016, 2017, 2020; Carvalho & Fernandes, 1992, 2007; Carvalho & Leonardi, 1992, 2007, 2021; Santos & Santos, 1987a, 1987b, 1989; Carvalho & Carvalho, 1990; Fernandes & Carvalho, 2001; Leonardi & Santos, 2006; Santos et al., 2015; Viana et al., 1993). Several other geologists and paleontologists moved on to research in the area, which had become famous (fig. 2).

The research on tetrapod tracks was extended by Leonardi and by others, with success, from the Rio do Peixe basins to other Northeastern Brazil basins (Leonardi, 1980b, 1984c, 1994, 2008; Leonardi & Muniz, 1985; Leonardi & Spezzamonte, 1994; Leonardi & Carvalho, 2021). This research was later continued with great

Fig. 1 - The classic locality of the Passagem das Pedras, discovered by Luciano J. De Moraes, in the 1920s, in the Sousa county and in the Sousa Basin, with two tracks in the siltstones and shales of the Sousa Formation. Here, the trench dug in 1977 to uncover the trackway SOPP 5, paratype of *Moraesichnium barberenae* Leonardi, 1979. Note the primary and secondary mud-cracks in both main layers. In the background you can see one of the walkways and observation pitches that allow visitors to the natural park "Valley of the Dinosaurs" to see the trackways of the dinosaurs without trampling them.

success by Carvalho and others (Carvalho, 1989; Carvalho & Fernandes, 1992; Carvalho et al., 1993a, 1993b, 1994; Viana et al., 1993).

2. Geological setting

The Rio do Peixe basins are four sedimentary basins (fig. 3): the Sousa, Uiraúna-Brejo das Freiras (Triunfo), Pombal, and Vertentes basins. They are situated at the western extremity of Paraíba, in the counties of Sousa, São João do Rio do Peixe, Aparecida, Uiraúna, Poço, Brejo das Freiras, Triunfo, Santa Helena, and Pombal.

In the first two basins – Sousa and Uiraúna-Brejo das Freiras (Triunfo), especially

Fig. 2 - The holotype trackway *Sousaichnium pricei* Leonardi, 1979, at Passagem das Pedras (SOPP), Sousa county, Sousa Formation. It is famous, as its image, after its excavation in 1977 and published in 1979, has been reproduced in countless scientific publications. Some 52 hind-foot prints were excavated, along with about 25 forefoot prints, but only of the right manus. The trackway is attributed to a Gondwanan semibipedal ornithopod. The average width of the footprints is 35.7 cm. Picture by Ismar de Souza Carvalho.

the Sousa basin – a bountiful tetrapod ichnofauna have been found, consisting of tracks, mainly of large theropods, sauropods, and ornithopods. Fish trails have been also discovered and classified *Cochlichnus sousensis* Muniz, 1985 (Also see Leonardi & Muniz, 1985). Invertebrate ichnites, such as trails and burrows produced by arthropods and annelids, are also common (Fernandes & Carvalho, 2001). Along with the strong reddish color, typical of subaerial environments, there are some units of greenish shales, mudstones, siltstones and sandstones, where rare body fossils are present. These include ostracods, conchostracans, plant fragments, palynomorphs, fish scales, and bone fragments of crocodylomorphs, along with rare dinosaur bones.

An important novelty was to discover, in these basins, document and publish the important influence of microbialites (microbial mats) in the preservation of fossil tracks, not only in the limestones of carbonate platform but even in siliciclastic

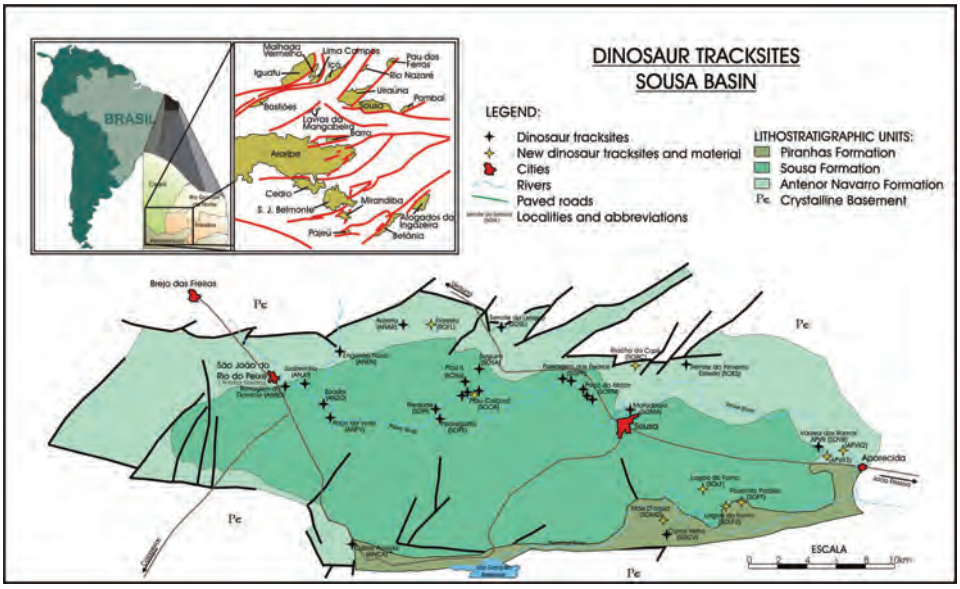

Fig. 3 - Location map of the Sousa basin, western Paraíba, northeast Brazil, and the distribution of its main local ichnofaunas (from Leonardi & Santos, 2006). The smaller maps are redrawn from Leonardi & Carvalho (2002).

sediments (Carvalho, Borghi & Leonardi, 2013).

Sousa (fig. 1), Uiraúna-Brejo das Freiras (Triunfo), Pombal and Vertentes Basins are intracratonic basins in Northeast Brazil that evolved along pre-existent structural trends of the basement during the opening of the southern Atlantic Ocean. Indeed, the region was now and again impacted, from the Late Jurassic onwards, by the onset and (aborted) make-up of intracontinental rifts (Matos, 1992; Rapozo et al., 2021; Matos et al., 2021).

As a result, several sedimentary basins resulted from reactivated fault movements within the Precambrian belt. In practice, this attempt at rifting and the onset and evolution of the intracontinental basins in NE Brazil, between them, also the basins of the Rio do Peixe, were engendered by the horizontal extension (approximately NW-SE in the Early Cretaceous) provoked by the breakup of Pangea in the Mesozoic (Nogueira et al., 2015).

Later, however, in the post-rift phase, there would have been a reversal: the basins that are the object of this paper were subjected to a horizontal compression (ESE-WNW) from the Late Cretaceous onwards (Nogueira et al., 2015).

The age of sediments in these basins, based on the study of ostracods and palynological material, is characteristic of the Berriasian to early Barremian stages (Early Cretaceous; Carvalho, 2000a, 2004a; Lourenço et al., 2021). However, under the Lower Cretaceous Group Rio do Peixe, Lower Devonian rocks were surprisingly

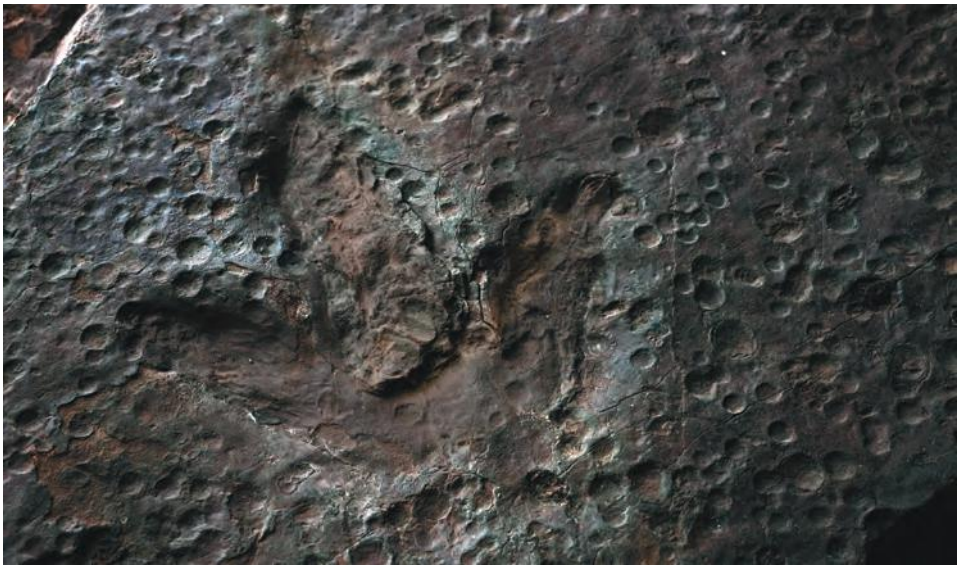

Fig. 4 - Medium-size theropod footprint at the level 13, subsite 2, of the Piau-Caiçara farm (SOCA 13217). This is a rocky pavement covered by the impressions of raindrops fallen (from north- and southward) after the crossing of 34 theropods.

identified through palynological analysis from boreholes drilled by Petrobras (Roesner et al., 2011).

These deep basins were filled with the Lower Cretaceous Group Rio do Peixe. It comprises three formations: the Antenor Navarro Formation, on the margin of the basins, points to a paleoenvironmental interpretation of coalescing alluvial fans and of anastomosing fluvial system; the Sousa Formation, an essentially microclastic sequence, points to lacustrine, swampy, and meandering braided fluvial paleoenvironments; and the Rio Piranhas Formation is represented by a paleoenvironment of alluvial fans and temporary and anastomosing creeks.

These deposits reflect direct control of sedimentation by tectonic activity. Deposition occurred along the faulted borders of the basins as alluvial fans, changing to an anastomosing fluvial system more downstream. In the central region of the basins, a meandering fluvial system with a wide floodplain was established, where perennial and temporary lakes developed (Carvalho, 2000a; 2004a; Leonardi & Carvalho, 1992, 2021; Lourenço et al., 2021).

The relationship between climate, sedimentation and regional situation was also studied; a rather arid climate was observed, tending, however, to become more humid with the progressive opening of the South Atlantic (fig. 4; Lima, 1983; Carvalho, 2000a).

3. Material

The paleontological relevance of the Sousa and Uiraúna-Brejo das Freiras basins is the profusion of dinosaurian ichnofaunas that represent parts of an extensive Early Cretaceous megatracksite (Viana et al., 1993; Leonardi & Carvalho, 2000, 2002) established during the early stages of the South Atlantic opening. In the field work of the aforementioned 45 years and 34 expeditions, 37 tracksites and about 96 tracks-bearing levels of the Rio do Peixe basins were discovered, chiefly in the Sousa Basin (see fig. 3).

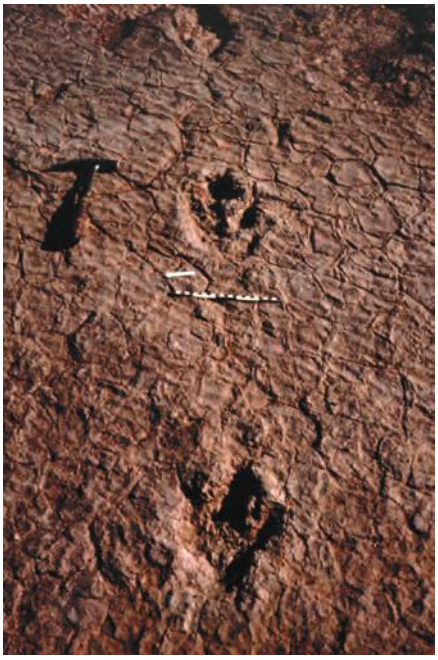

Fig. 5 - Ichnosite of Matadouro (SOMA), municipality of Sousa, Sousa Formation, in the bed of the Peixe River. A fine theropod trackway (SOMA 1). Graphic scale in centimeters.

These tracksites and the correspondent ichnofossiliferous levels contain the following numbers of trackways or isolated footprints assigned to different categories of dinosaurs: 329 large theropods (figures 1 and 5); 31 smaller theropods having 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 381 individual theropods); 59 sauropods (fig. 6); 38 graviportal ornithopods (among them four quadrupedal and one sub-quadrupedal trackways, along with some isolated footprints, probably pertaining also to quadrupedal animals) (fig. 2); one ankylosaur; one small quadrupedal thyreophoran; two small ornithopods, probable dryosaurids (altogether 42 ornithischians); and at least 53 indeterminate dinosaurian tracks. In total, the number of identifiable individual dinosaurs is 482, and the number of individual dinosaurs including the indeterminate tracks is at least 535. There are also four possible dinosaurian tail impressions (Leonardi & Carvalho, 2000, 2021).

The meso-ichnofauna, very rare in these basins, is represented by just one set of batrachopodid prints; some crocodilian traces (tracks and body imprints in the mudstone); one lacertoid footprint; and a very large number of small chelonian swimming tracks (Leonardi and Carvalho, 2000).

Two new ichnosites were recently discovered by this author (2018) in the Sousa Basin, in addition to the 37 tracksites mentioned above. They are unpublished so far. Some summary data are reported here, pending the possibility of performing new campaign work.

Fig. 6 - Ichnosite Engenho Novo (ANEN), county of São João do Rio do Peixe, Sousa Formation. An important and rare (in the whole Sousa basin ichnofaunas) and unfortunately incomplete hand-foot set of a large sauropod (ANEN 10). Note the wide and thick displacement rims of the prints. The horse-shoe-shaped forefoot prints are almost obliterated by the high anterior displacement rim of the hind-foot print. The hammer as a scale (32 cm).

The first tracksite, on the Serrote do Mocó (ANSM; S 06 42.752, W 38 24.752), is rather close to the Engenho Novo tracksite (ANEN) near a bridge over the Rancho creek; the new locality presents a series of interdigitations between the Sousa Formation and the Antenor Navarro Formation. The first formation shows, on this site, beautiful theropod footprints, probably attributable to abelisaurids, imprinted in fine ripple marked surfaces (fig. 7); the second formation shows deep footprints of medium-sized sauropods.

The second location, which we will call Araçá-Rio Novo (ANAN; S 06 45.025, W 038 25.472), has good surfaces of reddish layers of the Sousa Formation, with fine theropod tracks as above, and abundant ripple-marks.

4. Methods

Many methods of fieldwork and lab work employed during the time of the more important field expeditions (1975-1989) are today regarded as rather traditional. For example, trackways or even whole rocky pavements were drawn on graph paper. Sketches of the small or great rocky floors (up to 2,000 m²) were created with a

Fig. 7 - The new ichnosite Serrote do Mocó (ANSM) near a bridge over the Rancho creek, county of São João do Rio do Peixe. The site is located near the limit between the Sousa Formation and the Antenor Navarro Formation. It shows beautiful theropod footprints, probably attributable to abelisaurids, imprinted in fine ripple marked surfaces. Graphic scale in centimeters.

compass, metric tape, and strings stretched taut in the main directions, above all along the midlines of the trackways, and then with the gridded quadrant system (Leonardi, 1977) using a rectangular wooden frame with nylon threads stretched at right angles forming squares with sides 5 cm long. The drawing of each 5 × 5-cm square was then reproduced on a convenient smaller scale on graph paper. The angles among the strings were measured directly with a contact goniometer (Leonardi, 1977). It would have been easier to employ a drone to get a bird's-eye view (and to take photos) of our trackways, but there were no drones when we developed this field research.

The main campaign work was carried out in decades when theropods were simply divided into coelurosaurs and carnosaurs, a division founded largely on size. Since then, not only for theropods but for all of the dinosaurs, things have changed drastically over and over again.

In the past, the rocky pavements in the Rio do Peixe basins were photographed in detail from above while the photographer - this author - stood on a stool or on a folding ladder. All of these photographs were taken under the same lighting conditions, then the photographs were printed and then stuck in a photo mosaic. At that time, there were no digital cameras or programs for merging photographs.

Similarly, there were no GPS devices, and it was particularly difficult to calculate the locations of the sites in a mostly flat valley, without significant landmarks, and with small-scale topographical maps.

5. Main Results

5.1. *Fossil Tracks Complete or Replace Bones in Dinosaur Documentation*

One of the advantages of fossil tracks, is that in many paleoenvironments and in the continental stratigraphic units, poor in body fossils, good quality tracks complement well or sometimes completely (or almost completely) replace the documentation on the existence of dinosaurs and other animals in a certain region; this is for example the case of the western Paraíba, but also of the whole Brazilian northeast: the skeletons and the Mesozoic bones are very rare. This author was the first to publish a dinosaur bone (Leonardi & Borgomanero, 1981) and one of the first to establish a new genus for a pterosaur skull (Leonardi & Borgomanero, 1985), both from the Araripe basin; skeletal remains of these orders and of other animals exist in the intracratonic basins of the Brazilian Northeast; but they are very rare indeed.

Thanks to the finding of so abundant classifiable fossil tracks, you can describe dinosaurian faunas accompanied at times by mesofauna, and have a real registry of these faunas, divided into several and different associations, corresponding to the ichnofossiliferous levels, and even into populations; as well as corresponding to the animal groups present in the area.

In the specific case of the Rio do Peixe basins and particularly of the Sousa basin, there is, by means of the fossil tracks, a true bonanza, with more than 500 dinosaurs recorded by their footprints in such a small area, and a very high diversity index. The body fossils, on the contrary, are reduced for now to a few bones corresponding to two individuals of titanosaurids (Ghilardi et al., 2014, 2016; Carvalho et al., 2017) and of one or two notosuchian crocodiles (Carvalho & Nobre, 2001).

The consideration of the importance of fossil tracks to complete or often to replace the rare presence of dinosaur body fossils, is all the more valid for the Early Cretaceous, especially the Neocomian. More generally, they are poorly known not only in Brazil or in the whole South America but the world over, in comparison with the rich dinosaurian faunas of the middle and Late Jurassic and the Late Cretaceous.

5.2. *A Dinosaurian "Registry Office"*

In the case of the Sousa Basin, even if only a titanosaurid fibula has been found so far (Ghilardi et al., 2014, 2016), from the fossil footprints discovered and studied, we can affirm the existence of about 530 dinosaur individuals. In the Uiraúna-Brejo Basin, also called Triunfo Basin, the unique formally described dinosaur species

Fig. 8 - Serrote do Letreiro (SOSL) tracksite, Antenor Navarro Formation, Sousa county. This coarse-grained rocky surface shows, along with Indian petroglyphs, 34 theropod tracks, often filled in by coarser sand and so in apparent reverse relief. The hammer as a scale (32 cm).

Fig. 9 - Serrote do Pimenta ichnosite, Estreito Farm, Antenor Navarro Formation, Sousa county. Holotype of *Caririchnium magnificum* Leonardi, 1984b during the second phase of excavations in 1988. It is a long trackway (25 excavated meters) of a quadruped iguanodontid, with 7 manus-pes sets and, after a long gap, several additional sets of poor quality. The clipboard, length 32 cm, as a scale.

from Rio do Peixe Basins is the sauropod *Triunfosaurus leonardii* Carvalho, Salgado, Lindoso, Araújo Jr., Nogueira & Agnelo, 2017; but, because of the tracks discovered, it is known that there were also theropods. Both of these bone specimens of titanosaurid sauropods come from the sandstones of the Rio Piranhas Formation,

Among these tracks representing the presence of dinosaurian individuals, in detail, appear first 379 individual theropods. These can be divided into large predators, mostly belonging to abelisaurids (329 individuals, represented by at least five different forms, but probably even more; figures 1, 4-5, 7-8); 31 small theropods, probably noasaurids or velocisaurids, with proportionately long and slender feet, producing tracks similar to those of the *Grallator-Eubrontes* plexus of the Laurasian continents; and 16 medium-sized theropod individuals, different, but attributable to the same plexus, and forming a single population (fig. 8).

Fig. 10 - A cast of an ankylosaur, probably nodosaurid, rare hand-foot set from Serrote do Pimenta (SOES), kept in the collections of the Câmara Cascudo Museum of Natal. Courtesy of the Câmara Cascudo Museum. Graphic scale in cm.

The sauropods are less frequent in these formations. Their fossil footprints indicate in the basin of Sousa 59 individuals divided into three great groups that marched in herds, with evident gregariousness; and some isolated individual tracks. Sauropod tracks are often of poor quality, and typically very large (fig. 6). We can speak of at least three different kinds. The ornithopods were rarer, and their trackways are partially bipedal, partly quadruped (fig. 9) and partly semi-quadruped (cf. fig. 2). Most are isolated and therefore not gregarious individuals, usually of large dimensions (38 individuals). The main ones have been assigned locally by this author to three ichnogenera (Leonardi, 1979a, 1984b), attributed to iguanodontids, without excluding other forms. There are also some specimens of small ornithopod tracks, possibly dryosaurids.

One of the most important discoveries in the Sousa basin was that of a hand-foot pair of an ankylosaurid, probably a nodosaurid (SOES 7; Leonardi, 1984b; fig. 10): discovered in 1979, it was the first indication of the presence of ankylosaurs in South America.

Another particularly interesting specimen, which we would like to remember here, is a rather enigmatic trackway because of its bad quality (it was undoubtedly an underprint). It is the trackway SOPP 15 (Leonardi, 1994, 58; Leonardi & Carvalho, 2021), of four hand-foot sets, found in the locality Passagem das Pedras, level 1, perhaps attributable to Thyreophoroidea; in its enigmatical aspect and other characteristics it recalls the trackway MDK1 of the Marocche di Dro (Trento, Italy), despite the latter coming from sediments of the Lower Jurassic (Avanzini et al., 2001).

After this quick report on the dinosaur groups to which we attributed the tracks of Rio do Peixe Basins, it is good to remember that the South American dinosaurs are mostly very different from those of the northern continents. This diversity corresponds to the very probable 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, India, Antarctica, and Australia.

It is exciting to be able to compare the assorted groups, from the numerical point of view. So, for example, there are 101 trackways assigned to herbivorous dinosaurs (21% of the identifiable individual trackways and isolated footprints) and 381 trackways attributed to theropods (79% of the identifiable individual trackways and isolated footprints); the ratio of herbivorous to theropod individual trackways in this dinosaurian fauna, represented by tracks, is 1 : 3.77. It is good to remember, in passing, that probably not all theropods were carnivorous and predatory; some were probably necrophagous; other members of that clade, could be herbivorous or omnivorous rather than strictly carnivorous forms. This is particularly likely for small to midsize theropods.

There are at least 66 quadrupedal trackways (13.66% of the identifiable individual trackways and isolated footprints) and 417 bipedal trackways (86.34% of the identifiable individual tracks). The ratio of quadrupedal to bipedal tracks is 1 : 6.22.

The relationship between youth and adult tracks is also interesting. In the basins of the Rio do Peixe, the former tracks are very rare, which is a phenomenon difficult to interpret. Consequently, little can be said about the age-class structure of the makers of our ichnofaunas. 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 in this study (footprint length = 5.6 cm). There are no other very small dinosaurian individuals (hind-foot prints shorter than 12 cm). This phenomenon might indicate very heavy mortality on the part of very young individuals (Leonardi, 1984a). It is possible, of course, that this is an artifact of preservation: it is possible that dinosaurs of very small size were simply not heavy enough to leave footprints because of the relative compactness of the soil.

5.3 *Behavior of the Rio do Peixe Dinosaurs*

The study of the fossil tracks also is the primary and "unrivaled" (Gatesy & Ellis, 2016) method for making inferences about the behavior of the trackmakers.

5.3.1 *Speeds*

As for their speeds, in these basins seventy-five trackways permitted estimation of trackmaker speeds. The result was clear: the estimated speed of fifty-eight of these trackways (78.67% of the sample) is between 3 and 7 km/h. The makers were therefore traveling with a walking gait and speed. Seven trackways show a slower estimated speed (≤ 2 km/h; 9.33%); four of these are sauropods. Nine (12%) trackways point to a speed between 8 and 23 km/h. Of these, five (6.67%) have calculated speeds of 8-10 km/h; another four (5.33%) are distributed over a range

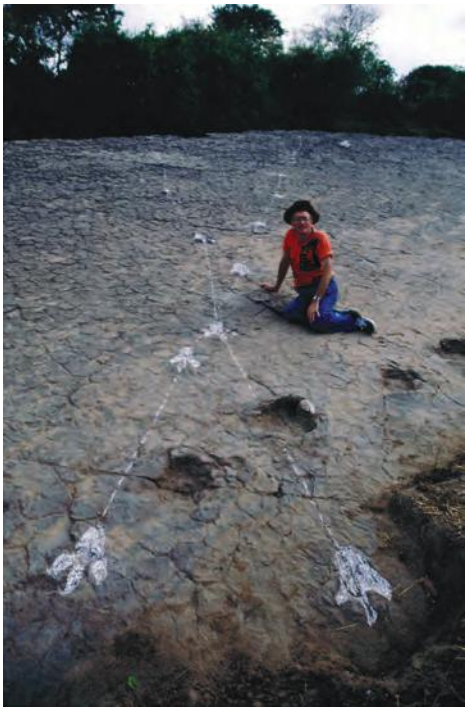

Fig. 11 - Passagem das Pedras (SOPP), Sousa county, Sousa Formation. The author is observing the intersection of two trackways imprinted by running predatory dinosaurs of the same kind, paratypes of *Moraesichnium barberenae* (SOPP 3 and 4; respectively running or trotting at about 20,7 and 12,8 km/h), with the trackway of a quietly walking ornithopod, the holotype of *Sousaichnium pricei* (here footprints 20 to 23 of the trackway. The iguanodontid was pacing at about 4.2 km/h). Courtesy of Franco Capone.

between 12.8 and 23 km/h. These last four trackways, all belonging to medium to large theropods (fig. 11), correspond to the fastest runners of the Rio do Peixe ichnofauna (Leonardi et al., 1987a, b, c).

Speed estimated or calculated from fossil records should be considered with due caution (Lockley & Meyer, 1999), but, despite this warning, dinosaurs in the Rio do Peixe basins generally walked and only very rarely ran. 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). We are sure that this is not just the case of the Rio do Peixe: it is in fact a very common situation, almost general to the whole world and throughout the time of non-avian dinosaurs (Leonardi & Mietto, 2000). A similar, more recent statement on low dinosaur speeds can be found, for example, in Xing et al. (2014).

The general statement of dinosaurs' high rate of metabolism is not questionable; however, it is not so evidently buttressed by the known paleoichnological record, and it ought to be better examined on the basis of many thorough, extensive and statistic studies on their trackways (Leonardi et al., 1987a, b, c); also see Molnar and Farlow, 1990, 218, fig. 7.5), rather than on the basis of some isolated, biased, and/or unchecked information. When the latter happens, it guides to the huge racing dinosaurs of Bob Bakker (1986a, 1986b) and of Paul (1987a, 1987b).

5.3.2 *Bearings*

I measured in the field the bearings or directions of all the classifiable and calculable tetrapod ichnological material from the Rio do Peixe Group of the Sousa basin and its three constituent formations, but excluded data from the innumerable

small half-swimming footprints attributed mainly to chelonians. This is a large sample, based on 386 individual dinosaur tracks. The bearings of these tracks 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 aggregations of dinosaurs, moving along privileged corridors or paths.

As earlier described for the locality Piau-Caiçara' tracks (Godoy & Leonardi, 1985), and also true for the Sousa Basin tracks in general, most of these tracks are parallel or nearly parallel to the ridges of the ripple marks. In turn, the dominant orientation of the beaches, as indicated by these crests, is often parallel to the regional tectonic lines that gave rise to the basins of the Rio do Peixe. It is clear, therefore, that the directions of the dinosaurs in their movements were strongly conditioned by the local and regional landscape, in particular by the shores of the lakes and, indirectly, by the regional tectonic texture (Leonardi, 1989).

Out of curiosity, one might suggest that, following one of these corridors, let's say the northeast direction, they could, without too much difficulty, reach Africa, which, then, was not so far away (nearly 450 km from Sousa).

5.3.3 *Stance*

All trackways in the Rio do Peixe basins, including those of sauropods, are rather narrow, attesting to an entirely erect position of the maker. All sauropods were clearly quadrupeds; the theropods, large and small, were of course all bipedal (Molnar & Farlow, 1990, 213), with very narrow trackways, in contrast to the old model of large theropods giving a Cossack dance show (Molnar & 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 footprints is customary for dinosaurs. It is therefore clear that virtually all the dinosaurs of the Rio do Peixe basins, both bipedal and quadruped (like almost all dinosaurs all around the world), kept their tail away from the ground.

5.3.4 *Manners of Gaits*

Dinosaur tracks of the Rio do Peixe basins made by bipeds (at least 417 individual tracks, or ~86.34% of the classified tracks) heavily surpass those of quadrupeds (about 66 individuals, or ~13.66% of the serviceable sample). The ratio of biped tracks to quadruped tracks is thus 6.32:1. We said above that walking gaits exceed almost totally running gaits. There are cases of semi-bipedal or semi-quadruped animals; especially ornithopods. No hopping, galloping or sprawling gaits are represented at these basins.

A rather usual manner of gait in the Sousa basin (11,21 %) is that of dinosaurs, mainly theropods, which, swimming and perhaps fishing in shallow water, pushed with their feet on the bottom of the bodies of lake bed, and produced what are

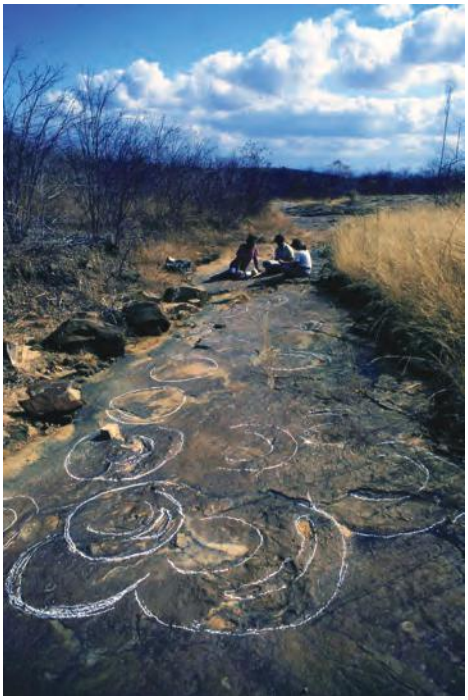

Fig. 12 - Serrote do Letreiro (SOSL), Antenor Navarro Formation, Sousa. The dry bed of the Riacho do Pique rivulet. The stream bed is crossed (from left to right) by the shallow trackways of a herd of at least 15 sauropods as well as trackways of some small to medium theropods. Courtesy of Franco Capone.

called swimming-tracks or more correctly, half-swimming-tracks. Altogether, there are about 60 individual theropod half-swimming tracks and a single probable ornithopod half-swimming track in these basins.

5.3.5 *Individual or Social Behavior*

Most dinosaurs in the Rio do Peixe basins were lonely animals, except for sauropods, which almost always lived in herds. This behavior is attested by clusters of sauropod tracks of at least 7-15 individuals (fig. 12; Leonardi, 1989, 1994; Carvalho, 2000b; Leonardi & Santos, 2006); the number of animals in these herds could have been higher, much 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 at Serrote do Letreiro (fig. 8); the assemblage of five long-heeled theropods of the ichnogenus *Moraesichnium* Leonardi, 1979 at Passagem das Pedras (figures 1 and 11); and perhaps the nearly 30 theropods of Piau-Caiçara farm on level 13/2 (cf. Fig. 4).

6. Dating stratigraphic units by fossil tracks

One of the benefits of the study of tetrapod fossil tracks is that they can from time to time, date the stratigraphic units that are not datable or dated by other methods. This was the case with the dating of the Rio do Peixe Basins formations and particularly the Antenor Navarro Formation.

Previous authors had often dated that formation as Paleozoic (Devonian to Permian) due to a lack of body fossils and its general aspect, and also because they had not yet found out the dinosaur tracks. Reallocation of this psammitic formation

to the Mesozoic and then, with some initial uncertainty, to the Early Cretaceous, was made only after this author detected in it the first tracks of sauropods and theropods in the locality Serrote do Letreiro, in July-August 1977 (Leonardi, 1979b).

This was also the case of other mainly psammitic formations of northeastern basins, situated at the base of their stratigraphic sections. They were considered Silurian or Devonian by the most part of the authors, until at the beginning of the 1990s appeared an article with a rather noteworthy title: "Silurian dinosaurs: a chronogeological anachronism in the interior Basins of the Northeast?" (Carvalho, Viana & Lima, 1994; see also Carvalho, Viana & Lima, 1993a, b; Viana et al., 1993).

7. Conclusions

The basins of the Rio do Peixe, and notably the Sousa Basin, have furnished an impressive amount of tetrapod tracks of the Early Cretaceous, most notably in sediments dated from the Berriasian to the lower Barremian. A concise presentation has been given here, with special attention to their Geological setting, the methods employed in the study of this invaluable paleontological heritage, whose study was begun almost half a century ago; these were therefore methods that today are considered vintage, especially with regard to the first decades of this research. The helpfulness of fossil tracks to complete and often totally substitute the presence of body fossil and consequently of skeletal remains was illustrated. Data on the presence of different groups of dinosaurs and other (scarcer) 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 e social behavior. The importance of fossil tracks for dating continental formations, which are difficult to date by other means, has also been underlined.

Imminent (August, 2021) is the publication of a large volume, the result of 45 years of work in the field, laboratory and brain work, entitled: "Dinosaur Tracks from Brazil: A Lost World of Gondwana" (Leonardi & Carvalho, 2021, xv + 456 pp.), that will exhibit and illustrate this theme in a much more abundant and complete way. Among other things, this book gives great importance to quantifying the ichnological material, by means of a very large number of tables of data, and to its statistical study.

With the release of this book, however, the research on the ichnofaunas of the Rio do Peixe basins and other similar Cretaceous basins of the Northeast of Brazil is not, however, concluded; there remains a great deal of field, lab, and brain work to be done. There are important local ichnofaunas that were discovered and surveyed only in a hurried manner, without meticulous study, such as the new tracksites presented for the first time in this article. There are also some minor ichnofaunas that

were seen and quickly surveyed many years ago that deserve a new inspection and reviewing. The Triunfo and Patos basins are also worth another look.

Every year, during the "winter", as the inhabitants call the rainy season, the Rio do Peixe and its tributaries destroy tracks but concurrently bring to light new layer surfaces and new footprints. In all these basins the work ought to be continued, improving and revising previous ichnological studies with modern techniques like laser scanning, geometric photogrammetry, three-dimensional modeling and use of drones.

For many years the presence of dinosaur tracks has done a notable service to the local population, having produced a flow of intelligent, cultural tourism, which enables jobs to be created and improves the living standards of people, in a town and county that was previously known for being a modest center of agriculture, specialized in the cultivation of cotton. Sousa is now known as the capital of the "Dinosaur Valley". In 1992 the Dinosaur Valley Natural Monument was established, with its protected and valued paleontological areas, and its museum and visitor center.

Among other things, the image of dinosaurs captured the popular imagination, and very often supermarkets, shops, hotels take their name, logo and features from one or the other of the famous inhabitants of that "Gondwanan valley" during the Cretaceous. The whole city could almost be called a "Cretaceous Park".

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