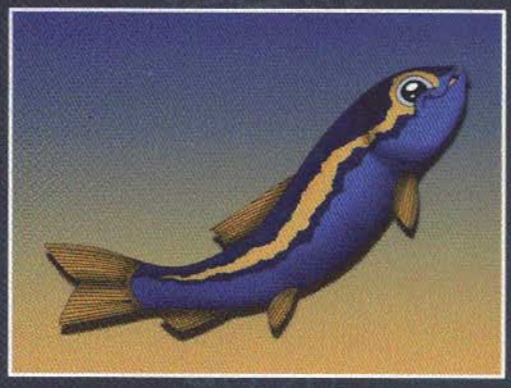

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THE DESERT ICHNOFAUNA FROM BOTUCATU FORMATION (UPPER JURASSIC – LOWER CRETACEOUS), BRAZIL

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ABSTRACT

The Botucatu Formation (Paraná Basin, Brasil) comprises one of the richest tetrapod ichnologic deposits of late Jurassic in South America. The ichnofossils are found in eolian sandstones, reddish colored in lithofacies considered to be dune and interdune deposits. The sandstones of Botucatu Formation originally covered a surface estimated in at least 1,300,000 km^2, constituting the largest known fossil desert in the world. His distribution area is surely one of the world's largest megatracksites. The tetrapod tracks from the Botucatu Formation comprise bipedal dinosauroids of relatively large and smaller types, both theropodian and ornithopodian; along with theromorphoid and mammaloid forms. The mammaloid forms are attributed to unknown early mammals; the theromorphoids forms, which were attributed to Tritylodontoidea when the Botucatu sandstones were though to be Lower Jurassic, are now attributed also to large early mammals. This ichnofauna seems to be completely endemic and, therefore, it was not sufficient studied. Invertebrate trace fossils also occur, produced by insects, arachnids and earthworms. Eighteen ichnosites have been discovered along the strip of nearly 2,500 km where the Botucatu Formation sandstones outcrops at the eastern side of the Paraná Basin, of which the most important is Ouro ichnosite; two sites, in Mato Grosso do Sul and Paraguay, along the western side. A complete and detailed study of this ichnofauna is in its initial phase.

Key-words: ichnofossil, Botucatu Formation, Paraná Basin

RESUMO

A icnofauna desértica da Formação Botucatu (Jurássico Superior – Cretáceo Inferior), Brasil. A Formação Botucatu (Bacia do Paraná, Brasil) compreende um dos mais ricos depósitos icnológicos de tetrápodes do Jurássico Superior da América do Sul. Os icnofósseis são encontrados em arenitos eólicos avermelhados, em litofácies consideradas como depósitos de dunas e interdunas. Os arenitos da Formação Botucatu originalmente recobriam uma superfície estimada de pelo menos 1.300.000 km^2, constituindo o maior deserto de areia já existente na superfície da Terra. Certamente, em sua área de distribuição ocorre um dos maiores *megatracksites* do mundo. As pegadas de tetrápodes da Formação Botucatu compreendem formas dinossauróides bípedes

com tipos relativamente grandes e pequenos, theropodomorpha e ornithopodomorpha; além disso, formas Teromorfóides e mamiferóides também estão presentes. As formas mamiferóides são atribuídas a pequenos mamíferos primitivos desconhecidos; as formas teromorfóides, as quais foram atribuídas a Tritylodontoidea enquanto os arenitos da Formação Botucatu eram considerados como pertencentes ao Jurássico Inferior, são agora atribuídos também aos mamíferos primitivos, contudo, de porte maior. Esta icnofauna parece ser completamente endêmica, portanto não suficientemente estudada. Também ocorrem traços fossilizados de invertebrados, produzidos por insetos, aracnídeos e anelídeos. Dezoito sítios icnológicos foram descobertos ao longo da faixa de aproximadamente 2.500 km, onde os arenitos da Formação Botucatu afloram do lado leste da Bacia do Paraná, dentre os quais o mais importante é o sítio icnofossilífero do Ouro; dois sítios foram registrados em Mato Grosso e Paraguay, ao longo do lado oeste. Um estudo mais completo e detalhado desta icnofauna está em sua fase inicial.

Palavras-chave: Icnofóssil, Formação Botucatu, Bacia do Paraná

1. INTRODUCTION

The tetrapod ichnological site of Ouro is situated in the State of São Paulo, in the Municipality of Araraquara, 4 kilometers E of the Ouro railway station on the railway line from São Carlos to Araraquara, approximately 8 km ESE from the center of the town of Araraquara. There were there several quarries: São Bento - Corpedras (code: ARSB); Califórnia (ARCA); Cerrito Velho (ARCE); Cerrito Novo (ARCN); Santa Águeda (ARSA); Chibarro (ARCH). Presently only the São Bento - Corpedras quarry is open. The sandstones are quarried and used as a source of building material, particularly as flagstones for paving of sidewalks and for facing walls and pillars. The coordinates of the site (mean) are 21°49'S; 48°05'W.

The sandstones that present the tetrapod footprints are named Botucatu Formation. This lithostratigraphic unit embodies Mesozoic eolian sandstones that extends along a stretch of Brazilian territory comprised between the states of Minas Gerais and Rio Grande do Sul, appearing also in the states of Mato Grosso and Goiás (Figure 1). In Paraguay, Uruguay and Argentina these sandstones receive different Formation names.

The Botucatu Formation lithofacies are considered to be the dune (foreset and topset) and interdune facies deposits. These are interpreted as great dunes climbing, in an inland desert with high sand supply. In this way there was the construction of an erg, that overpass the freatic level changes, allowing that the interdunes areas keep always dry (Caetano-Chang, 1997). Despite this environmental condition of the Botucatu desert, some small lakes should have existed, especially in areas where the tetrapod ichnofauna is abundant.

2. GEOLOGY

The Botucatu Formation comprises Mesozoic aeolian sandstones, reddish colored, that originally covered a surface estimated in at least 1,300,000 km^2, constituting the largest known fossil desert in the world. From the paleontological point of view, the sandstones in the Botucatu Formation are void of body fossils, which have been interpreted as a consequence of the desert environment.

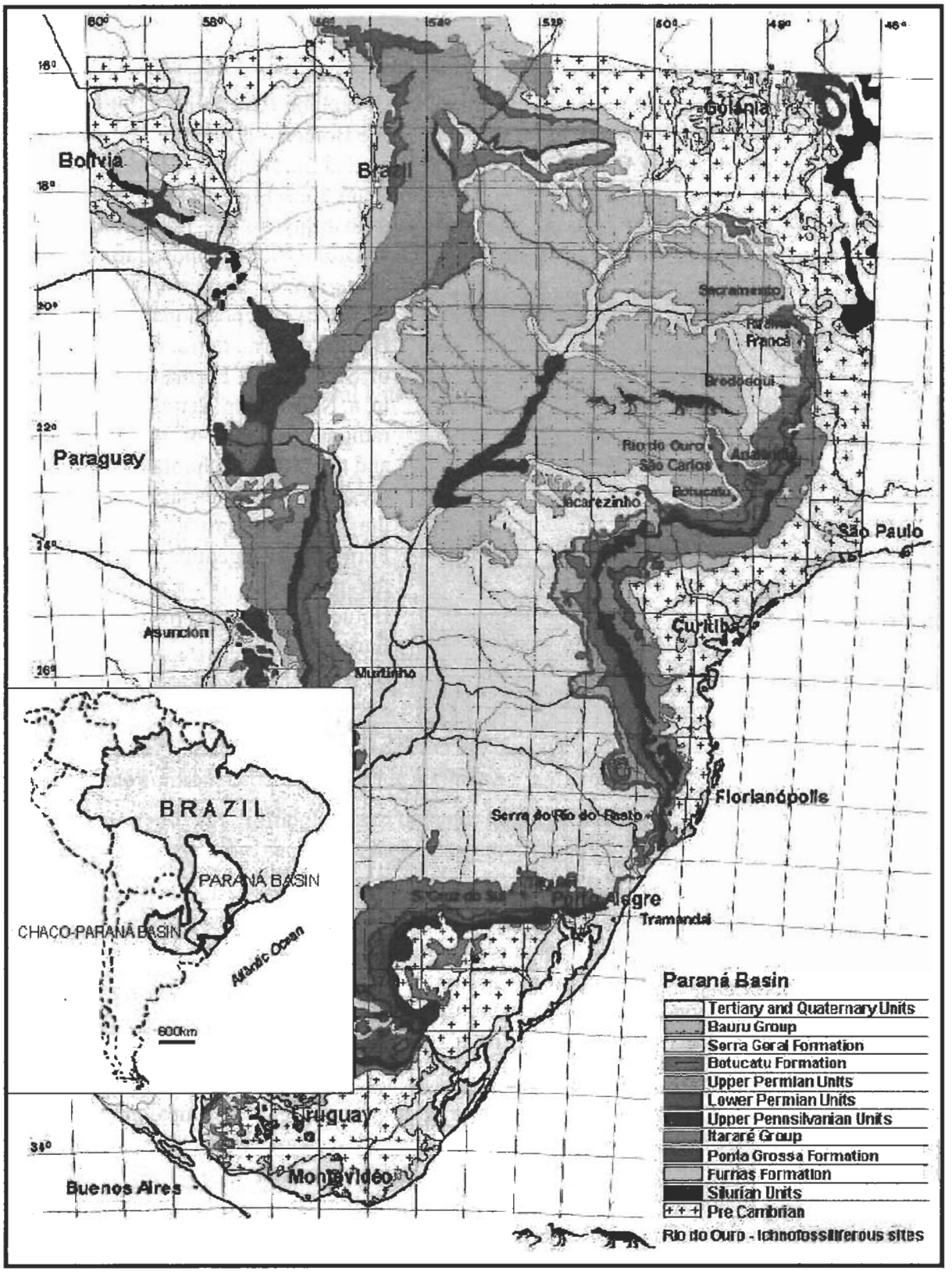


Fig. 1: Geological map of Paraná Basin and distribution area of Botucatu Formation (modified from Mapa Geológico da Bacia do Paraná, 1981).

The age of these deposits have been traditionally considered as belonging to the Triassic. Therefore, Leonardi & Oliveira (1990) recognized that the date is not known with any precision. The reason for this is the environment: it represents a hot, dry, continental interior desert, where body fossils of animals and plants do not occur, nor pollens. There is only radiometric dating (120 - 140 Ma) on the flood basalts of the Serra Geral Formation that capped the Botucatu Formation. The ichnological analysis presented by Leonardi & Oliveira (1990) postulated that the Botucatu Formation, at least in outcrops of São Paulo State, and particularly in the Araraquara area (Figure 2) could be considered between the Rhaetian and Middle Jurassic, with greater probability for the Lower Jurassic or the lower most section of Middle Jurassic. Despite this, Scherer *et al.* (2002) proposed to the Mesozoic stratigraphic framework of the Paraná Basin five depositional sequences. The Botucatu Formation and the volcanic flows of Serra Geral Formation were included in a Neocomian Sequence based on the radiometric ages of the volcanic rocks and through the ichnofaunistic correlation presented by Bonaparte (1996) between the Botucatu Formation and La Matilde Formation (Argentina). They considered the possibility of a temporal range to Botucatu Formation from Late Jurassic to Early Cretaceous.

Fig. 2: São Bento Quarry, ichnosite of Ouro (Araraquara County, São Paulo State); large ornithopod trackway at right side of the workers.

3. HISTORY OF THE SITE

In 1911, the Brazilian mining engineer Joviano Pacheco discovered the first slab from the Botucatu Formation with a tetrapod trackway, as a flagstone in a sidewalk in the town of São Carlos, 39 km SW of Araraquara, where very probably it originated. The original flagstone was deposited by Pacheco, in the Geographic and Geological Commission Museum of São Paulo, presently called the Geological Institute of São Paulo, and appears to be the first tetrapod trackway discovered and collected in South America. However, it was only much later published by Friedrich von Huene (1931).

Shortly after arriving in Brasil, Leonardi started inquiries about the origin of the Pacheco's flagstone and discovered in July 1976 in the municipality of Araraquara, region of Ouro, an abundant and varied ichnofauna consisting mainly of vertebrate tracks and secundarily invertebrate trails, in the above said quarries, then actively worked, as well as in the sidewalks of the town of Araraquara (Leonardi, 1980). Other Leonardi's expeditions followed (11 altogether, cfr. Leonardi, 1994, p. 169), by means of grants from the CNPq (The National Council for Research of Brazil). Between 1976 and 1986 natural exposures, quarries and town pavements throughout the eastern outcrop of the Botucatu Formation, from Minas Gerais (North) to Rio Grande do Sul (South) was explored by Leonardi and collaborators, special attention being paid to those of the São Paulo State. The recovery of fossils was

startling: vertebrate tracks were discovered in five Brazilian states, at Sacramento (Minas Gerais), Rifaina, Franca, Brodósqui, Analândia, Araraquara, São Carlos and Botucatu (São Paulo); Jacarezinho (Paraná), Serra do Rio do Rasto (Santa Catarina), Taquari, Tramandaí and Santa Cruz do Sul (Rio Grande do Sul) a belt 2500 km long (Leonardi, 1977; 1981a-b; 1989; Leonardi & Sarjeant, 1986; Leonardi & Godoy, 1980). Later, two sites were discovered by Leonardi in the western side of the Paraná basin, in Murtinho (Mato Grosso) and Asunción (Paraguay) (Leonardi, 1992, 1994).

Between 1976 and 1983, all the sidewalks of Araraquara and other pavements - a linear extent of 308 km, or an area of 0.77 km^2 - were surveyed by Leonardi, in an urban palaeoichnology expedition being aided by a group of students from the School of Geology of the Federal University of Paraná at Curitiba (*Ibidem*).

Until November 2005, there was a continuous prospection and collection of new slabs that have been lodged at Universidade Federal de São Carlos (UFSCar), Universidade Estadual Paulista (UNESP - Rio Claro) and Rio de Janeiro Federal University (Geology Department).

4. THE ICHNOFAUNA OF THE OURO ICHNOSITE

The tetrapod tracks from the Ouro quarries (and from the sidewalks of the town) are almost always (90-95%) of poor quality, the footprints being simply a rounded or elliptical cavity (convexity in the counterprints or natural casts) furnishing no morphological details (Figures 3 and 4). Characteristically this cavity is accompanied by a crescentic sandstone ridge, always in the direction of foreset dip, representing the sand displaced by the animal's foot during its progression across the slopes of a dune. However, the parameters of such tracks frequently enable them to be classified, despite their poor quality, provided that a good specimen of the same type has been found also. Firm identifications and descriptions depend necessarily on the better specimens, and it is on the basis of these, in the last analysis, that the comments below are made *(Ibidem)*.

The classification is always difficult due to the poor quality of the material and due to the uncertainty as to the age of the formation, because of lack of associated body fossils and because of the endemicity of the ichnofauna.

Presently it appears that the ichnofauna of Ouro covers:

a) Eight dinosauroid forms, all bipedal, digitigrade and tridactylous, with an elevated pace angulation (up to 180°). These tracks are relatively rare. This group includes one form of relatively large dinosaur (within this dwarf desert fauna), with footprints 34 cm long and a stride of 2 meters; two or three forms of medium-sized animals with footprints 12 cm long and strides up to 2 meters; some medium-sized animals, with a stride of 1-1.5 meters; and some very smaller types. One small form is trydactylous but fequently appears monodactylous in the running gait.

b) At least seven theromorphoid (from the morphological point of view) forms that are rarely encountered in the sidewalks and very rarely found in the quarries. It is difficult to recognize the parameters of the trackways (stride, pace, pace angulation etc.) because they are represented mainly by isolated footprints. However, maybe only two teromorphoid trackmakers produced all these variations due the preservation conditions and the variable

moving forms. By the morphology of the footprints and the heteropody, they are attributable to highly specialized quadrupedal animals, with advanced gait. The footprints are semi-plantigrade and their outline points to rounded or elliptical paws, with the transverse axis larger than the antero-posterior. The digits are always very short, pointing to a probable phalangeal formula 2-3-3-3-3. The claws are partially or completely separated from the palm or sole and are sometimes modified into small hooves. The stride is between 15 and 50 cm. The trackway is relatively narrow for a quadrupedal animal and the pace angulation is around 100° to the posterior autopods and about 90° to the anterior autopods. When the hetoropody is absent the pace angulation is about to 160°.

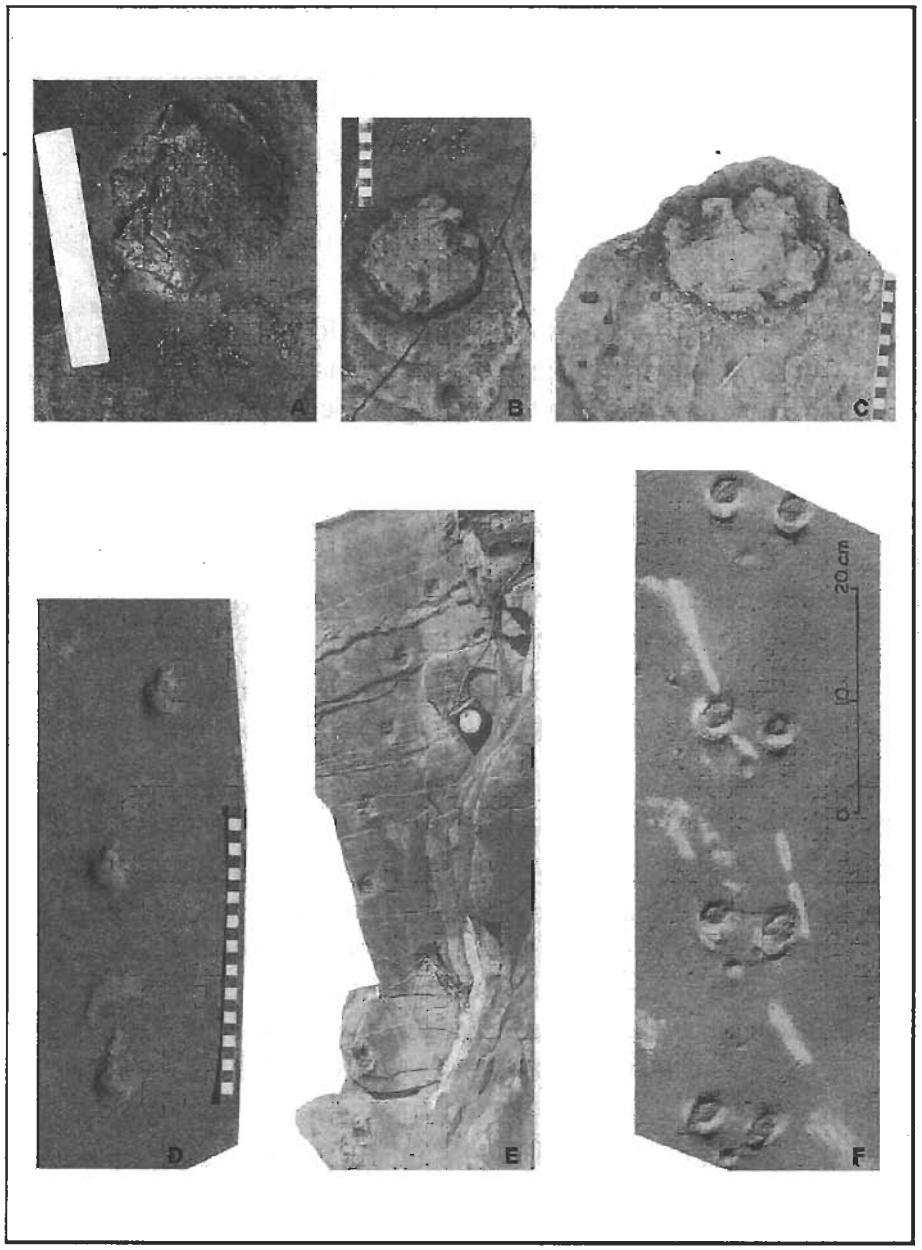


Fig. 3: Fossil footprints from Botucatu Formation. (A), (B), (C) Theromorphoid footprint attibuted to relative bigger mammals; (D), (E) small theropod trackways; (F) mammaloid trackway with galloping gait.

c) At least nine forms, because of their advanced gait, the shape of their autopodia (rounded or elliptical paws, with the transverse axis larger than the antero-posterior, the digits always very short, pointing to a probable phalangeal formula 2-3-3-3-3) and because of their small dimensions can be morphologically defined as mammaloid. The diferences among the trackways may be explained by the differents forms of locomotion or else by distinct preservational conditions (as in dry or damp sand or undertracks), produced several forms of tracks to the same trackmaker. Some of these forms appears to be new; some at the ichnogenus level, others at the morphofamily level. This group includes some rare and interesting trackways with hopping and gallopping gaits. Among these tracks, the most abundant form was classified ***Brasilichnium elusivum*** Leonardi, 1981. This form has a strong heteropody, with the forefeet extremely small.

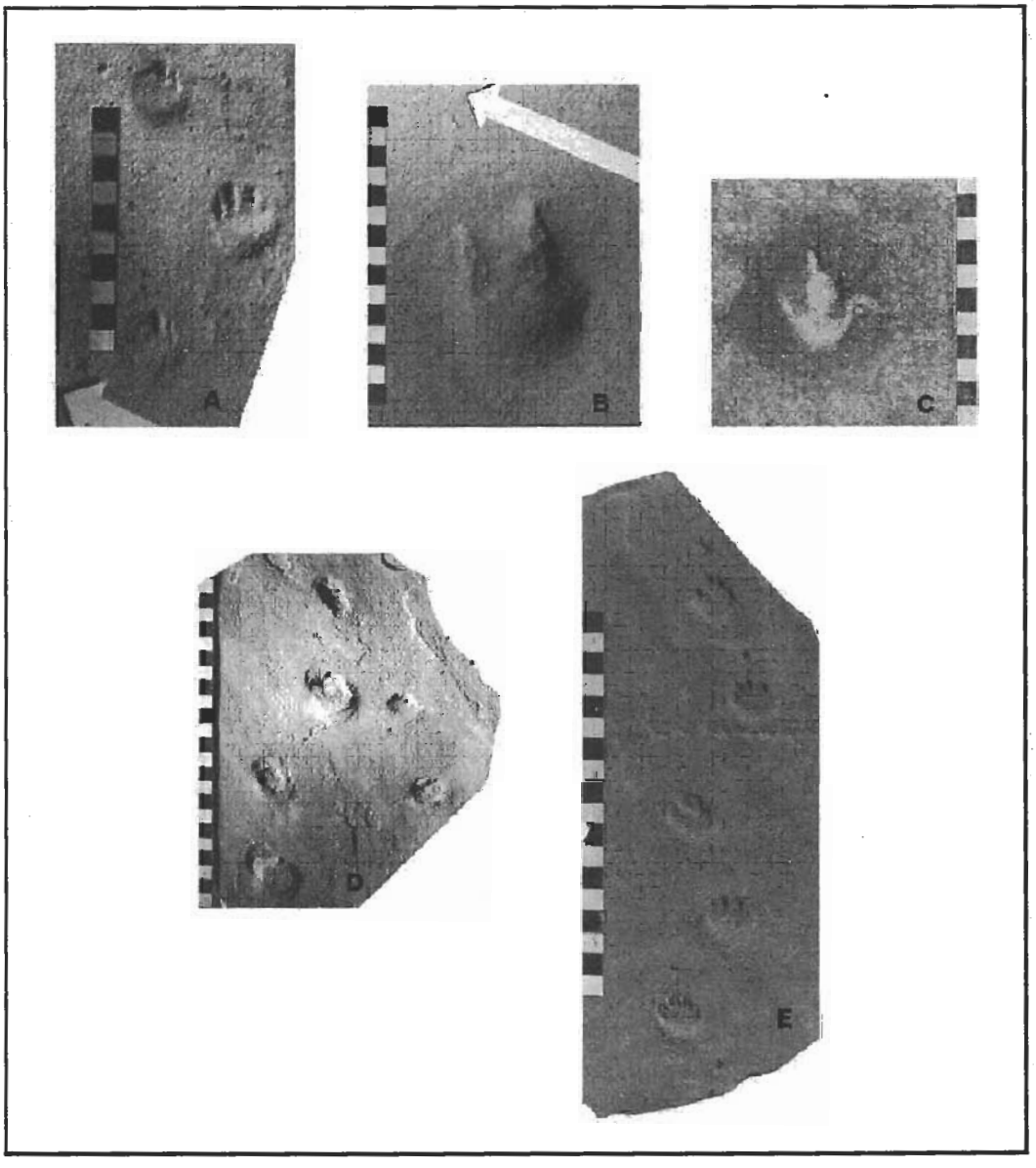


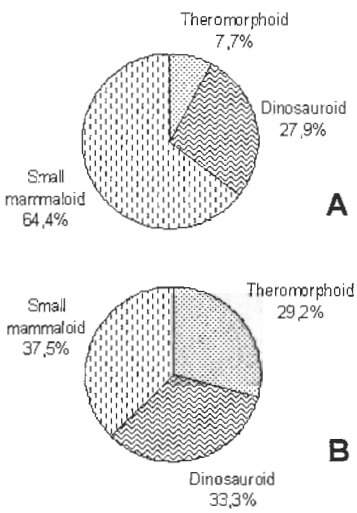
Fig. 4: Fossil footprints from Botucatu Formation. (A) Small mammaloid trackway; (B), (C) Theropod footprints; (D), (E) *Brasilichnium elusivum* trackways referred to small mammals.

d) Ten forms of invertebrate trails, mainly attributable to arthropods (arachnids and insects, adults or larvae). The invertebrate trails are remarkably rarer than the tetrapod tracks.

e) An urolite, a liquid excretion. As it is associate with ornithopod footprints it was attributed by Fernandes *et al.* (2004), maybe produced by an ornithopod dinosaur.

The statistical composition of the Ouro ichnofauna (Figure 5), in a sample of the first 100 collected slabs by Giuseppe Leonardi, is as follows: it includes a small number of theromorphoid individuals but a possible large number of forms (7.7% of the individuals and 29.2% of the forms); a good percentual of dinosauroid tracks as for the individuals (27.9%) and the forms (33.3%); the small mammaloid percent is high as for the individuals (64.4%), not so for the forms (37.5%). Sixty three tracks and 14 forms are quadrupedal; 41 tracks and 10 forms are bipedal. In this ichnofauna, where a number of mammaloid tracks present bipedal hopping gait, bipedalism is rather common (39.4% of the individuals and 41.7% of the forms). The sprawling tracks are completely absent. The mammalian/archosaurian ratio is 2.31; the theropsidian = (theromorphoid + mammaloid)/archosaurian ratio is 2.58. These results are significant; however, they were probably based in the picking up of the slabs, in favour of the quite rarer dinosauroid and theromorphoid tracks.

The trackmakers, at Ouro site and especially at the São Bento quarry (Figures 6 and 7), preferred certain directions. Indeed, 76% of the trackways examined *in situ* are oriented in both ways to directions within the 2nd and 4th quadrants of the compass. As a whole, the animals have crossed most frequently (and diagonally) a large transverse dune. The motives that explain this special direction are not known



at present. One could express the working hypothesis that this direction could correspond to a route connecting two watering points or oases.

The ichnofauna seems to be completely endemic. This factor causes problems in the classification and interpretation of the tracks, but adds greatly to their interest. As noted earlier, this was a very arid environment, a desert and/or semi-desert highland and it is known that arid and highland environment ichofaunas and faunas are relatively rare.

Fig. 5: Statistical composition of the vertebrate ichnofauna in 100 slabs. (A) percentual of individuals; (B) percentual of forms.

5. THE TRACKMAKERS

We started, some years ago from the presumption that the Botucatu Formation was Lower Jurassic, as it seemed more probable from the ichnological point of view (Leonardi & Oliveira, 1990). If this was the correct datation, then the small and medium dinosauroid tracks with clawed digits could most probably be attributed to ceratosaurid theropods and the largest dinosauroid tracks, sometimes with hoofed digits, to the ornithopods. The theromorphoid tracks could be attributed to therapsids and, in the Liassic hypothesis, to the Tritylodontoidea, the only group of therapsids present after the end of

the Triassic. The small mammaloid forms probably belong to true early mammals. Nowadays it seems more probable that Botucatu sandstones and their tracks are Upper Jurassic to Lower Cretaceous. If this is true, then the theropodian tracks may be attributed to some more recent South-American family of Theropods and the theromorphoid tracks must probably also be attributed to true relatively large mammals.

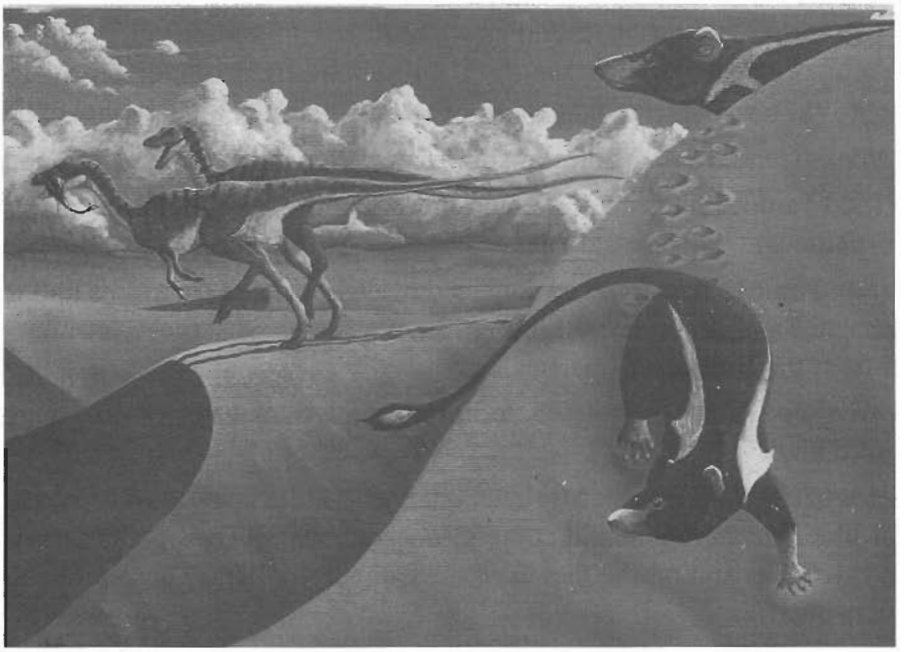


Fig. 6: Reconstruction of the paleoenvironment of Ouro ichnosite. The small mammals *Brasilichnium elusivum* and theropod dinosaurs. Ilustration by Ariel Milani Martine.

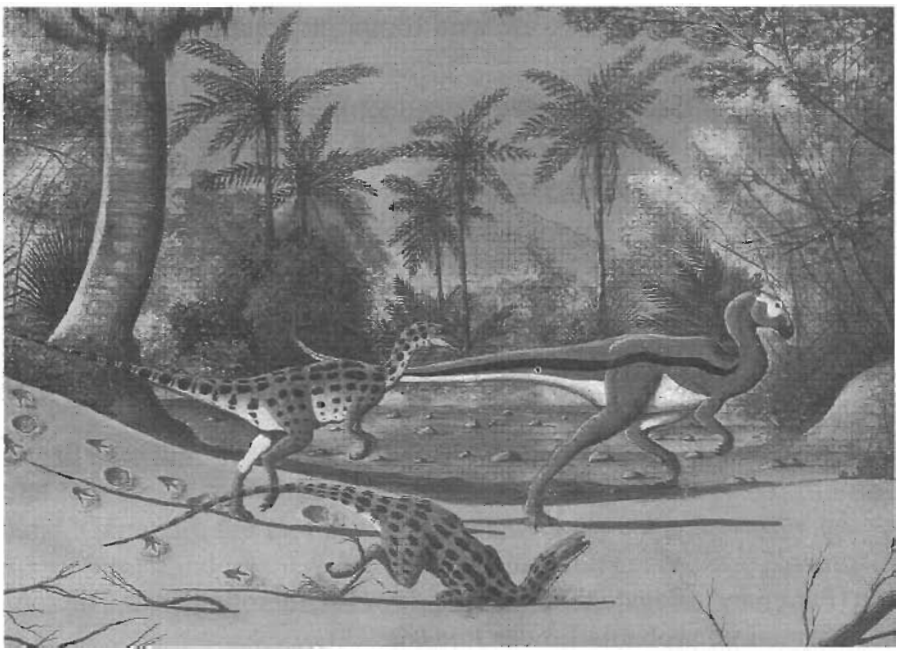


Fig. 7: Reconstruction of the paleoenvironment of Ouro ichnosite. Ornithopod and theropod dinosaurs at the Botucatu desert border. Ilustration by Ariel Milani Martine.

6. OTHER ICHNOSITES OF THE BOTUCATU FORMATION

A number of ichnosites analogous to that of Ouro site were discovered by Leonardi, along the strip of nearly 2,500 km where the Botucatu Formation sandstones outcrop along the eastern side of the Paraná Basin and more rarely along the western side. The sites are the following, from north to south:

Eastern side:

a) Sacramento (Minas Gerais) - flagstones of some sidewalks; undetermined tetrapods.
b) Frutal (Minas Gerais) - flagstones of some sidewalks; undetermined tetrapods.
c) Rifaina (São Paulo) - flagstones of some sidewalks; isolated footprints and trackways of the theromorphoid and dinosauroid kind.
d) Franca (São Paulo) - flagstones of some sidewalks; isolated footprints and trackways of the theromorphoid and dinosauroid kind on the flagstones of some sidewalks; these probably proceed from the Brodósqui quarries.
e) Brodósqui (São Paulo) - isolated footprints and trackways of the theromorphoid and dinosauroid kind.
f) São Carlos (São Paulo) - in Migliato quarry, some trackways attributed probably to a mammal like *Brasilichinum* and some insect trackways. Theropodian tracks on flagstones of some sidewalks and on the facing of the cathedral pillars. These probably proceed from Araraquara quarries.
g) Analândia (São Paulo) - some trackways of the mammaloid kind, one of them with the ricochet gait.
h) Rio Claro (São Paulo) - flagstones of some sidewalks; undetermined tetrapods.
i) Botucatu range (São Paulo) - two isolated footprints, relatively large size *in situ*, perhaps attributable to ornithopods.
j) Jacarezinho (Paraná) - tracks of undetermined tetrapods on flagstones found in other Paraná towns were procured in quarries near this town.
k) Ponta Grossa and Curitiba (Paraná) - flagstones of some sidewalks; undetermined tetrapods. The flagstones probably come from the Jacarezinho quarries.
l) Serra do Rio do Rasto (Santa Catarina) - record of a tetrapod trackway, not seen.
m) Taquari (Rio Grande do Sul) - record of tetrapod trackways, not seen.
n) Santa Cruz do Sul (Rio Grande do Sul)- a flagstone with two parallel trackways, one of a small theropod, the other of *Brasilichnium elusivum*.
o) Tramandaí (Rio Grande do Sul) - one theropod isolated footprint, on a flagstone in the town sidewalks.

Western side:

a) Assunción (Paraguay) - flagstones of some sidewalks; theropodian and theromorphoid tracks; Missiones Formation, probably Lower Jurassic.
b) Murtinho (Mato Grosso do Sul) - flagstones of the platforms of the railway station; undetermined tetrapods.

The Botucatu Formation distribution area is surely one of the world's largest megatracksites (Leonardi & Mietto, 2000).

7. INVERTEBRATE TRACKS

The first description of invertebrate trace fossils was presented by Pacheco (1913) that recognized "worm tunnels" in the sandstones of Botucatu Formation. Later, Almeida (1954), Bjornberg & Tolentino (1959) also identified new "worm trails" in these sandstones. Paraguassu (1970) proposed that these ichnofossils were produced by conchostraceans. Leonardi (1980, 1984), Leonardi & Godoy (1980) and Leonardi & Sarjeant (1986) considered them as "worm" and arthropod tracks.

The following localites with invertebrate ichnofossils in Botucatu Formation was presented by Fernandes *et alii* (1990):

a) Quarry 3 - 4 km from São Carlos (São Paulo) - worm tunnels (Pacheco, 1913).

b) Botucatu Range (São Paulo) - worm tunnels (Almeida, 1954).

c) Pacaembu, São Carlos (São Paulo) - worm trails (Bjornberg & Tolentino, 1959).

d) Quarry of São Tomás Farm, Ibaté county (São Paulo) - conchostraceans trails (Paraguassu, 1970).

e) Quarries of Araraquara (São Paulo) - worm trails and arthropod tracks (Leonardi, 1980).

f) São Bento Quarry, Araraquara (São Paulo) - arthropod trails (Leonardi, 1984).

g) São Bento Quarry, Araraquara (São Paulo) - trails and invertebrate burrows (Leonardi & Godoy, 1980).

h) Quarry of Itaguaçu Farm, São Carlos (São Paulo) - worm trails (Leonardi & Godoy, 1980).

The study presented by Fernandes *et al.* (1990) classified some trace fossils of Botucatu Formation as ***Taenidium satanassi*** D'Alessandro & Bromley, 1987 and ***Taenidium serpentinum*** Heer, 1897, besides "U" shaped burrows. Ethological interpretation of ***Taenidium*** trails attributes them as feeding traces, whose burrow fills could be considered as faecal material or the packets of surrounding sediments by earthworms and insects; the "U" - shaped burrows are probably evidence of insect or earthworms dwelling tubes.

8. PROTECTION

The tetrapod ichnofossils from Ouro site have been collected and housed in Museums and Universities of São Paulo and Rio de Janeiro states. There isn't any kind of protection in the quarry were these material are found. Generally the more conspicuous tracks were selected by the workers of the São Bento quarry (Ouro Site) standing there until some institution get it; since November 2005, the quarry is out of work due to the lack of ambiental and governmental permissions.

Nowadays Araraquara municipality intend to preserve some sidewalks with tracks in the historical streets, like an open sky museum, with references of trackmakers.

9. ACKNOWLEDGMENTS

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