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INVERTEBRATE ICHNOFOSSILS FROM THE ADAMANTINA FORMATION (BAURU BASIN, LATE CRETACEOUS), BRAZIL

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ABSTRACT – The Bauru Group is a sequence at least 300 m in thickness, of Cretaceous age (Turonian-Maastrichtian), located in southeastern Brazil (Bauru Basin), and consists of three formations, namely Adamantina, Uberaba and Marília. Throughout the Upper Cretaceous, there was an alternation between severely hot dry and rainy seasons, and a diverse fauna and flora was established in the basin. The ichnofossils studied were found in the Adamantina Formation outcrops and were identified as *Arenicolites* isp., ?*Macanopsis* isp., *Palaeophycus heberti* and *Taenidium barretti*, which reveal the burrowing behavior of the endobenthic invertebrates. There are also other biogenic structures such as plant root traces, coprolites and vertebrate fossil egg nests. The Adamantina Formation (Turonian-Santonian) is a sequence of fine sandstones, mudstones, siltstones and muddy sandstones, whose sediments are interpreted as deposited in exposed channel-bars and floodplains associated areas of braided fluvial environments.

Key words: Bauru Basin, ichnofossils, late Cretaceous, continental palaeoenvironments, Adamantina Formation.

RESUMO – O Grupo Bauru é uma seqüência de pelo menos 300 m de espessura, de idade cretácica (Turoniano-Maastrichtiano), localizada no Sudeste do Brasil (bacia Bauru), e consiste das formações Adamantina, Uberaba e Marília. Durante o Cretáceo Superior houve uma alternância entre estações extremamente quentes e secas e estações chuvosas, com uma fauna e uma flora diversificada que se estabeleceu na bacia. Os icnofósseis estudados são oriundos dos sedimentos da Formação Adamantina, sendo identificados como *Arenicolites* isp., ?*Macanopsis* isp., *Palaeophycus heberti* e *Taenidium barretti*, os quais representam comportamento escavador de invertebrados endobentônicos. Ocorrem também outras estruturas biogênicas, tais como traços de raízes de plantas, coprólitos e ninhos fossilizados de vertebrados. A Formação Adamantina (Turoniano-Santoniano) é uma seqüência de arenitos finos, argilitos, siltitos e arenitos argilosos interpretados como depositados em barras expostas e em planícies de inundação em ambientes fluviais entrelaçados.

Palavras-chave: Bacia Bauru, icnofósseis, Cretáceo superior, paleoambientes continentais, Formação Adamantina.

INTRODUCTION

The Bauru Basin have been widely studied, specially by its fossil content, which is composed of charophyte oogonia algae, pteridophyte sporocarpes (Marsiliaceae), coniferophyte logs, ostracods, gastropods, bivalves, invertebrate and vertebrate ichnofossils occur as well as diversified vertebrate fauna of fishes, amphibians, reptiles (lizards, ophidians, turtles, crocodylomorphs, dinosaurs) and mammals (*e.g.*, Bertini, 1993; Castro *et al*., 1999; Ribeiro & Ribeiro, 1999; Musacchio, 2000). Crocodilomorphs, eggs and dinosaurs compound the fossil record of the Adamantina Formation. Recent studies in continental deposits of the Adamantina Formation revealed the presence of an invertebrate ichnofauna composed of unornamented U-tubes, empty subcylindrical burrows and sinuous meniscated tubes. The aim of this paper is to characterize this invertebrate ichnofauna and to discuss its palaeoecological and palaeoenviromental significance.

GEOLOGICAL SETTING

The Bauru Basin had its origin during the opening of the South Atlantic ocean, through thermo-mechanical subsidence processes (Fernandes & Coimbra, 1996). This inland basin, located in southeastern Brazil, has an area of 370,000 km^2

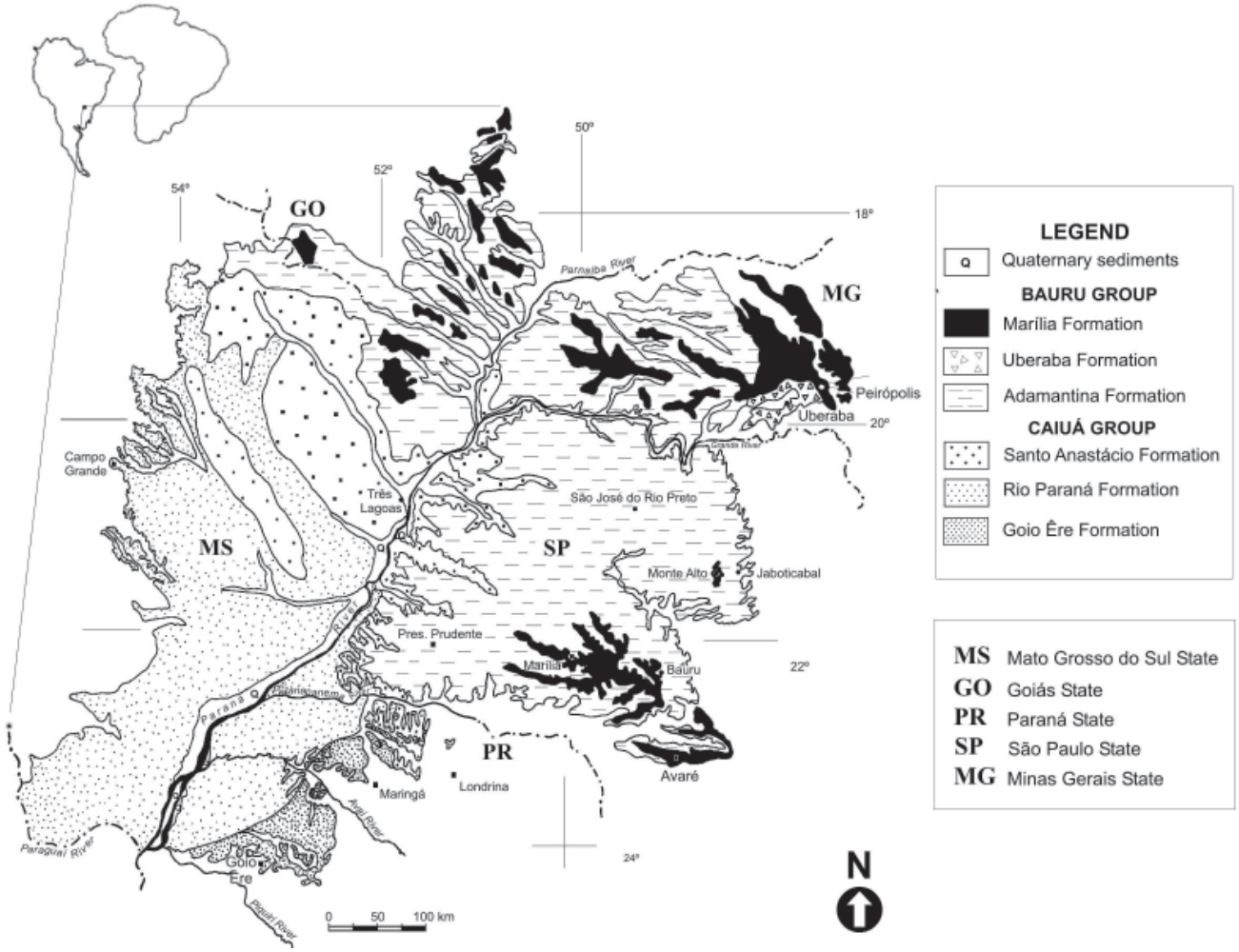

Figure 1. Location map of the Bauru Basin (modified from Fernandes & Coimbra, 1996).

(Figure 1) comprising a Cretaceous sequence (Figure 2), with at least 300 m of siliciclastic sediments (Fulfaro *et al*., 1994; Fernandes & Coimbra, 1996, 1999). The age of the Bauru Basin ranges from Aptian to Maastrichtian (Fulfaro *et al*., 1994) and the sediments are generally included into the Caiuá and Bauru groups.

The Bauru Group was divided by Fernandes & Coimbra (1996) into three formations, namely Adamantina, Uberaba and Marília. The Adamantina Formation (Turonian-Santonian age, Castro *et al*.,1999; Dias-Brito *et al*., 2001) is a sequence of fine-grained sandstones intercalated by mudstones, siltstones and muddy sandstones. The lowermost part of this unit was redefined by Batezelli *et al*. (1999) as the Araçatuba Formation. The Uberaba Formation (Coniacian-Campanian, Goldberg & Garcia, 2000) is composed of fine-grained green sandstones interbedded by siltstones, coarse sandstones, mudstones and volcaniclastics. The Marília Formation (Maastrichtian, Dias-Brito *et al*., 2001) was formally proposed by Soares *et al*. (1980) as a succession of coarse to conglomeratic sandstones, mudstones and carbonate beds.

Throughout the Late Cretaceous, there was an alternation between severely dry and hot rainy seasons, and a diverse fauna and flora was established in the basin. Plant root traces, invertebrate burrows and vertebrate coprolites and egg nests are found in the Bauru Basin deposits. They occur in distinct stratigraphic levels generally in fine-grained sandstones.

SEDIMENTARY FACIES

The ichnofossils discussed in this paper occur in fine-grained sandstones of the Adamantina Formation deposited during sudden floods on alluvial plains under a dry and hot season. They were collected from three localities SW of São Paulo State (Figure 3). The locality A is exposed at km 595 in SP-294 road, municipality of Adamantina. The local succession (Figure 4A) is 1.3 m thick and consists of fine-grained sandstones with climbing ripples. The locality B occurs in the SP-463 road, 1 km from the crossing with the SP-320 road nearby the city of Jales, municipality of Jales. The deposits (Figure 4B) are 7.0 m thick and consist of a succession of fine-grained sandstones intercalated with coarse-grained sandstones and thinner levels of mudstones. Climbing ripples are present in the fine-grained sandstones, along with ostracods and theropod teeth remains. The locality C crops out at Fazenda São José, in Prudêncio e Morais district, municipality of General Salgado. The outcrop (Figure 4C) comprises a 6.0 m thick succession of coarse-grained sandstones with trough cross-stratification intercalated with

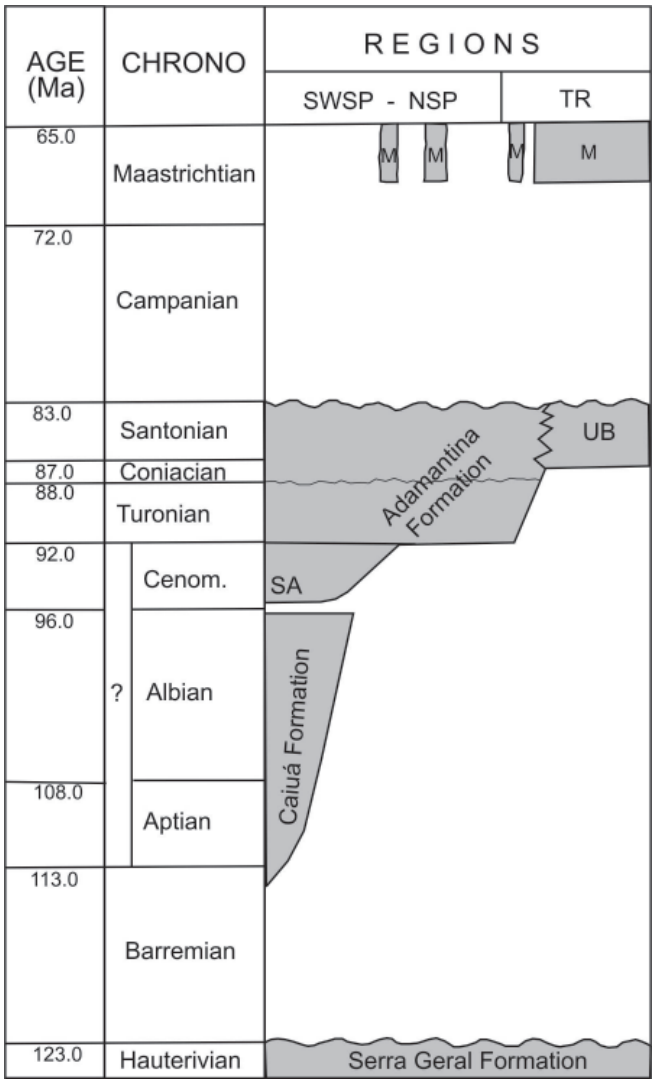

Figure 2. Diagramatic stratigraphic chart of the Bauru Basin. **Abbreviations: SWSP**, Southwest of São Paulo State; **NSP**, North of the São Paulo State; **TR**, Triângulo Mineiro region; **M**, Marília Formation; **SA**, Santo Anastácio Formation; **UB**, Uberaba Formation (modified from Dias-Brito *et al*., 2001).

fine-grained sandstones with planar cross-stratification, muddy siltstone, and a caliche horizon at the lower part of the sequence. Vertebrate bones occur in the fine-grained sandstones.

Collected specimens are housed in the collection of the Departamento de Geologia, Instituto de Geociências, Universidade Federal do Rio de Janeiro (UFRJ-DG).

SYSTEMATIC ICHNOLOGY

Ichnogenus *Arenicolites* Salter, 1857
Arenicolites isp.
(Figure 5)

Material. UFRJ-DG 203-Ic, several specimens recorded in the field and one slab with nine specimens. Associated in the same slab there are *Taenidium* specimens.

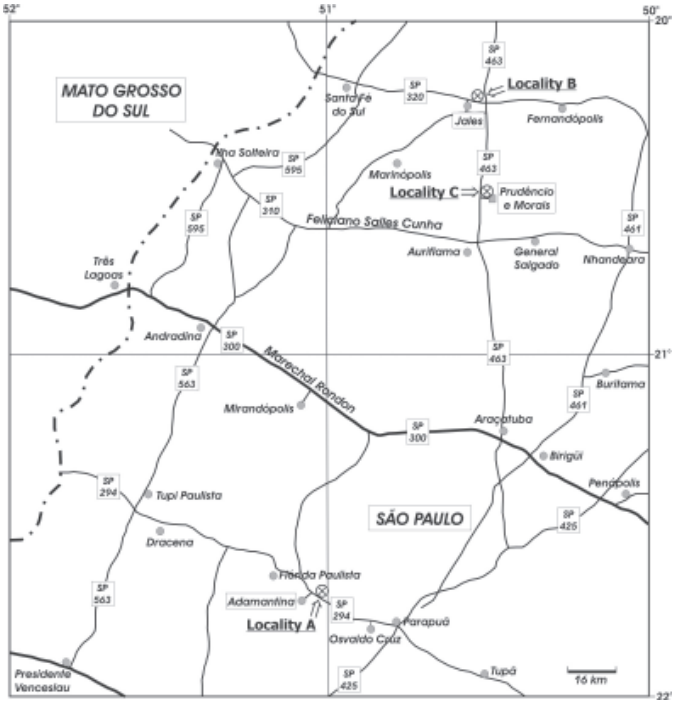

Figure 3. Location map of the invertebrate ichnofossil localities of the Adamantina Formation in São Paulo State.

Collecting site. Locality A.

Description. Simple, unornamented U-tubes without spreite, perpendicular to beds, with some specimens reaching 10 cm down in the substrate. When observed in the bedding planes (Figure 5A), they are seen as paired circular structures with variable diameters between 8-10 mm. In the Figure 5B, a vertical cross section through the paired circular structures (although the lowermost portion is broken) shows the connection as a U-tube, without linning.

Remarks. *Arenicolites* is interpreted as a dwelling burrow of suspension feeders in marine environments (Fillion & Pickerill, 1990) and by oligochaete worms (Bromley & Asgaard, 1979) or insects (Rindsberg & Kopaska-Merkel, 2005) in continental environments. Rindsberg & Kopaska-Merkel (2005) revised and analysed the four ichnospecies of *Arenicolites*: *A. carbonarius* (Binney, 1852), *A. sparsus* Salter, 1856, *A. curvatus* Goldring, 1962 and *A. longistriatus* Rindsberg & Kopaska-Merkel, 2005. The studied sample illustrated in the Figure 5B resembles the diagnostic characteristic of *A. sparsus* as a simple, regular U-shaped burrow with vertical limbs and lacking a thick lining (Rindsberg & Kopaska-Merkel, 2005). Therefore, the preservation of the specimen UFRJ-DG 203-Ic does not allow an accurate identification of this ichnospecies. *Arenicolites* is known only from three Brazilian Mesozoic continental lithostratigraphical units: Sanga do Cabral and Caturrita formations (Triassic of the Paraná Basin; Gandini *et al*., 2004; Netto, 1989, 2000; Netto *et al*., 1994), and Sousa Formation (Lower Cretaceous of the Sousa Basin; Carvalho, 1989).

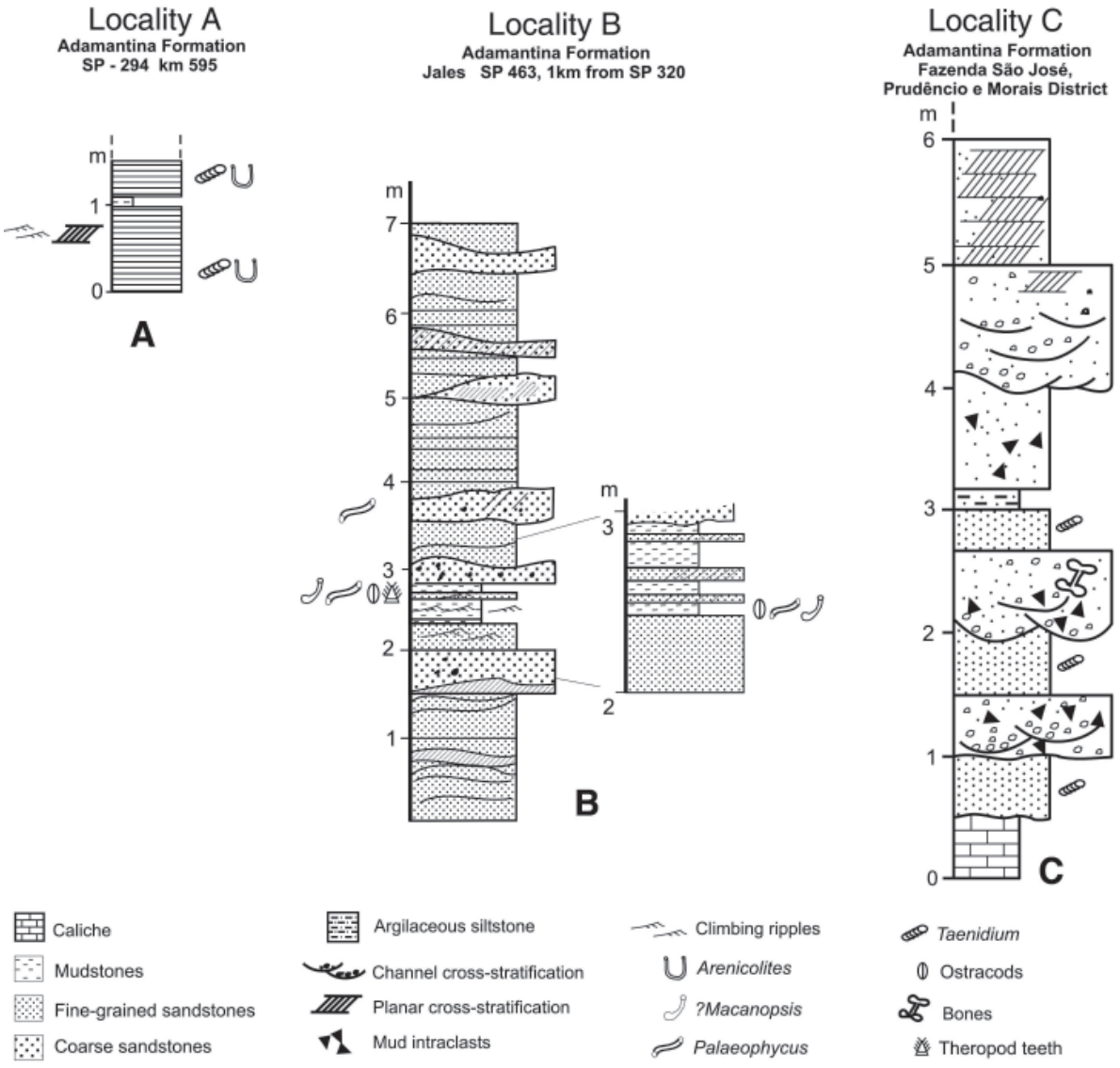

Figure 4. Stratigraphic sections of the localities: **A**, the 1.3 m thick sequence of the locality A. Fine-grained sandstones with tubes of *Arenicolites* are intercalated with a thin mudstone level. **B**, in the locality B, the deposits consist of fine-grained sandstones intercalated with coarse-grained sandstones and mudstones. The bioturbation occurs in the fine-grained sandstone, whereas the ostracods and theropod teeth are present in the mudstone levels. **C**, the 6.0 m thick deposits of the locality C consist of coarse-grained sandstones with channel cross-stratification and vertebrate bones and eggs. These horizons are intercalated with fine-grained sandstones with *Taenidium* burrows and mudstone levels. The 0.5 m thick layer of caliche is restricted to the base of the section.

Ichnogenus *Macanopsis* MacSotay, 1967
?*Macanopsis* isp.
(Figure 6)

Material. UFRJ-DG 190-Ic, one specimen.
Collecting site. Locality B.
Description. Vertical, curved, unbranched, empty subcylindrical burrows, with a hemispherical hollow extremity. The specimen has a continuous diameter of 10 mm, with a bend of 90º before the hemispherical hollow which has a diameter of 15 mm.
Remarks. Though the type materials of *Macanopsis* described by Macsotay (1967) are certainly marine (Bown & Kraus, 1983), it was also recorded in the fluvial floodplain deposits of the lower Eocene Willwood Formation (Bown & Kraus, 1983; Hasiotis *et al*., 1993). Similar structures were recorded in Oligocene point bar deposits of the nearshore fluvial Jebel Qatrani Formation in Egypt (Bown, 1982). They were interpreted as a dwelling trace of insects or spiders (Bown & Kraus, 1983). *Macanopsis*-like burrows in Holocene sediments are attributed to a variety of invertebrates including insects, spiders, decapods and mollusks (see Bown & Kraus, 1983 to references). There are known two ichnospecies of *Macanopsis*, *M. pagueyi* Macsotay, 1967 and *M. astreptum* Bown & Kraus, 1983. The Brazilian specimen described herein has a characteristic similar to *M. plagueyi* that is the curve of the burrow in the confluence with the bulbous termination, which is vertical tubular in *M. astreptum*. *Macanopsis* is

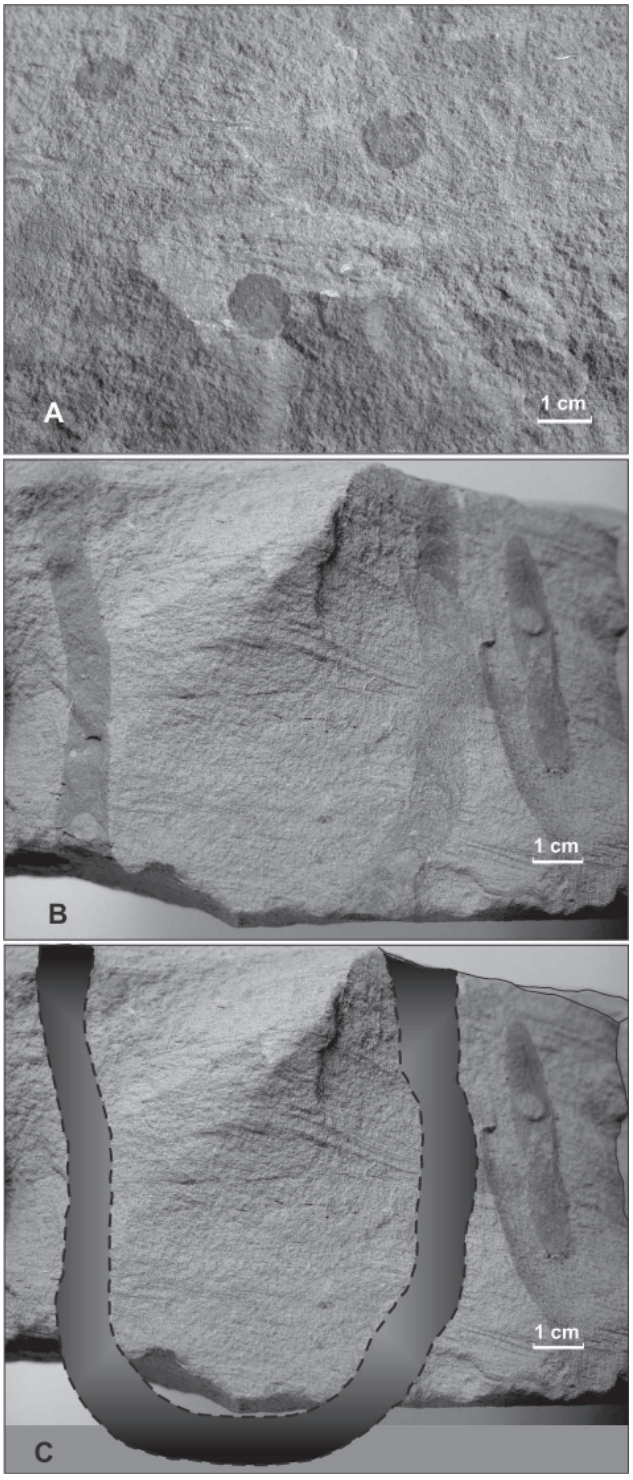

Figure 5. *Arenicolites* isp. UFRJ-DG 203 Ic: **A**, paired circular structures observed in the bedding plane; **B**, vertical cross section where is observed the vertical limbs of the U-tube; **C**, hypothetical reconstruction of the U-tube shown in the picture B.

known from lower Tertiary deposits (Macsotay, 1967; Häntzschel, 1975; Bown & Kraus, 1983), but it was also recorded in the Cretaceous sediments of the Marilia Formation of the Bauru Group (Fernandes, 2001; Fernandes *et al*., 2002). Its presence in the sediments of the Bauru Basin comprises the only known occurrences of this ichnogenus in Brazil.

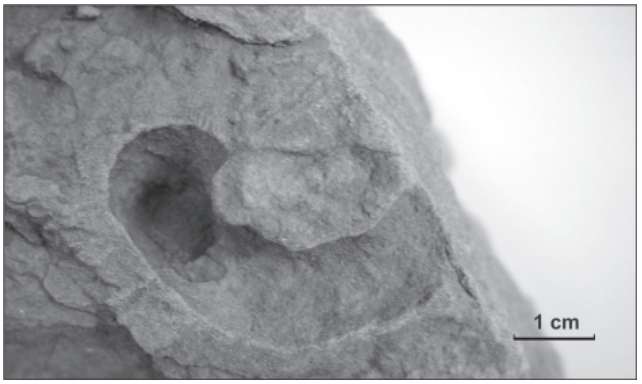

Figure 6. ?*Macanopsis* isp., UFRJ-DG 190 Ic, showing the empty subcylindrical burrow with a hemispherical hollow extremity.

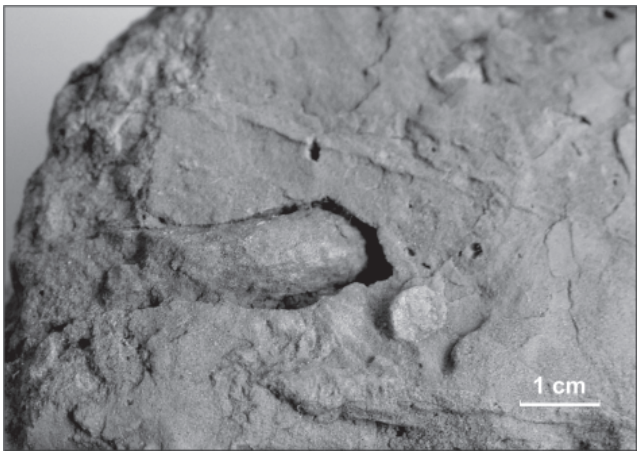

Figure 7. *Palaeophycus heberti,* UFRJ-DG 189 Ic, characterized by the unbranched, smooth, slightly curved and cylindrical burrow.

Ichnogenus *Palaeophycus* Hall, 1847
Palaeophycus heberti (Saporta, 1872)
(Figure 7)

Material. UFRJ-DG 189-Ic, a slab with one specimen.
Collecting site. Locality B.
Description. Unbranched, smooth, slightly curved, cylindrical burrow, with diameter between 1.0 cm and 1.5 cm. Burrow fill identical to the host rock. The specimen shows a thick space between the burrow fill and the host rock. Preserved as endichnia.
Remarks. There are five recognized ichnospecies of *Palaeophycus*: *P. tubularis* Hall, 1847, *P. striatus* Hall, 1852, *P. heberti* (Saporta, 1872), *P. sulcatus* (Miller & Dyer, 1878) and *P. alternatus* Pemberton & Frey, 1982. *P. tubularis* and *P. heberti* are comprised by smooth and unornamented straight to slight curved burrows. *P. tubularis* is thinly lined, and *P. heberti* is composed by thick-lined cylindrical burrows (Pemberton & Frey, 1982), a feature recognized in the studied specimen. *Palaeophycus* is considered a dwelling burrow constructed by a predaceous or suspension-feeding animal (Pemberton & Frey, 1982),

produced in marine environments probably by polychaetes. In nonmarine environments, it is probably produced by insects and other arthropods (Buatois & Mángano, 1993), ranging in age from Precambrian to Holocene (Pemberton & Frey, 1982). The occurrence of *P. heberti* in the Adamantina Formation is the first record of this ichnospecies in the Cretaceous non-marine sediments of the South America. In continental Mesozoic stratigraphic units of Brazil, *Palaeophycus* isp. was only identified in the Cariri Formation, Lower Cretaceous, Araripe Basin (Fernandes *et al*., 2002).

Ichnogenus *Taenidium* Heer, 1877
Taenidium barretti (Bradshaw, 1981)
(Figure 8)

Material. UFRJ-DG 262-Ic to 274-Ic, Several specimens recorded in the field and 17 slabs with 38 specimens.
Collecting site. Localities A and C.
Description. Sinuous and cylindrical unwalled burrows with distinct back-fill containing alternations of meniscus-shaped packets of sediment. The menisci are thin and strongly curved, variably-spaced. The traces have variable diameter from 1.0 to 2.0 cm, which is apparently constant in each specimen, and with variable preserved length, up to 22.0 cm.
Remarks. *Taenidium barretti* differs from other ichnospecies of *Taenidium* by its more curved and thin menisci, and its variable diameter and more sinuous burrows. Probably produced by insect larvae or other arthropods with an exoskeleton in non-marine sediments, the ichnogenus *Taenidium* has a distribution from the Lower Cambrian to probably the Quaternary (Uchman, 1995), being a common component of the Cruziana Ichnofacies in the marine realm, and a typical component of the Scoyenia Ichnofacies, in non-marine settings (Buatois *et al*., 2002). *Taenidium barretti* has been recorded mainly from non marine environments (Keighley & Pickerill, 1994), such as the Lower Cretaceous Wealden Group of southern England (Goldring & Pollard, 1995) and Cretaceous/Tertiary beds of Central Utah, USA (Bracken & Picard, 1984). This is the first occurrence of *Taenidium barretti* in Brazilian Cretaceous deposits.

Taenidium is the most common continental invertebrate ichnofossil registered in Brazilian Mesozoic stratigraphic units. In Paraná Basin, the Triassic sediments of the Sanga do Cabral Formation contain *Taenidium serpentinum* Heer, 1877 (Netto *et al*., 1994), wich also occurs in the aeolian sediments of the Botucatu Formation (Lower Cretaceous), as well as *Taenidium satanassi* D´Alessandro & Bromley, 1987 (Fernandes *et al*., 1990).

Taenidium isp. was recorded in the Lower Cretaceous deposits of the Arajara Formation (Araripe Basin, Fernandes *et al*., 1998; Carvalho, 1989), and in the Antenor Navarro and Sousa formations (Sousa Basin, Fernandes & Carvalho, 2001) *Arenicolites* and *Taenidium* are reported in association from the Sanga do Cabral Formation.

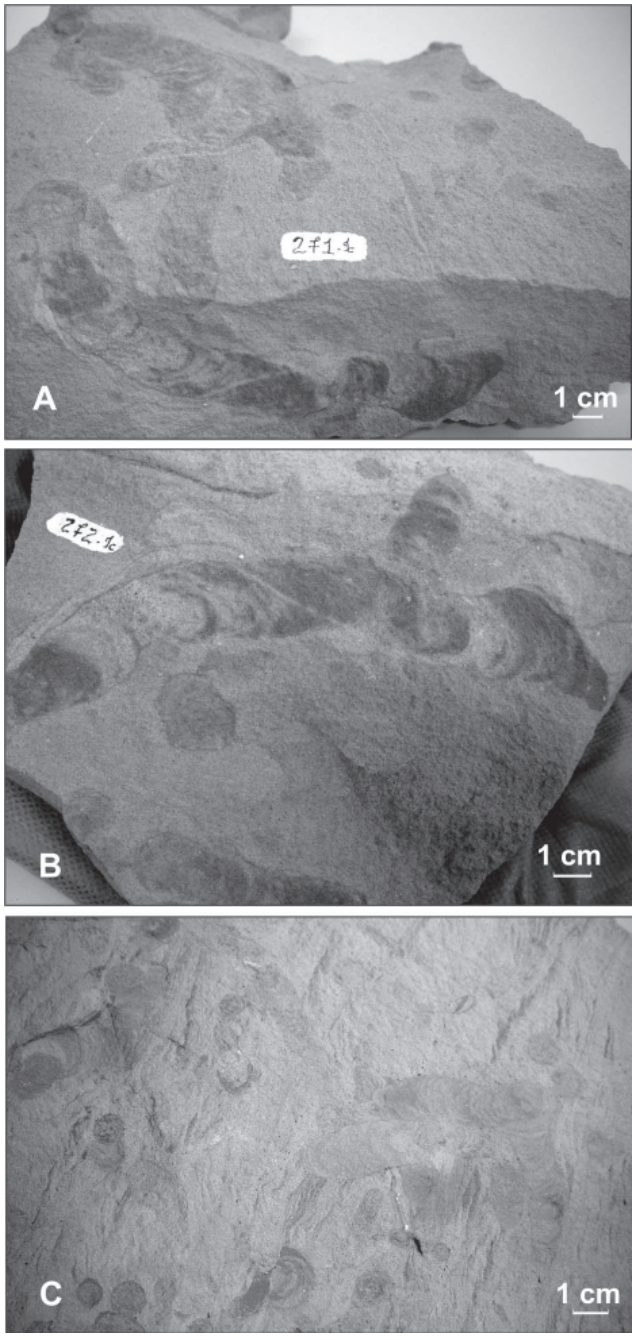

Figure 8. *Taenidium barretti*. **A**, UFRJ DG-271 Ic; **B-C**, UFRJ-DG 272 Ic. Both samples show the sinuous and cylindrical unwalled burrows with thin and strongly curved menisci.

OTHER FOSSIL REMAINS FROM THE ADAMANTINA FORMATION

Vertebrate fossils and ichnofossils have also been collected in the Adamantina Formation, and they comprise reptile bones, coprolites as well as egg nests. The coprolites are known from several outcrops of the Adamantina Formation and are attributed to turtles and sauropod dinosaurs (Souto, 2003). The egg nests are interpreted as produced by crocodylomorphs (Ribeiro *et al*., 2004) and they occur in the same locality (Fazenda São José, municipality of General Salgado) of the *Taenidium* specimens described here.

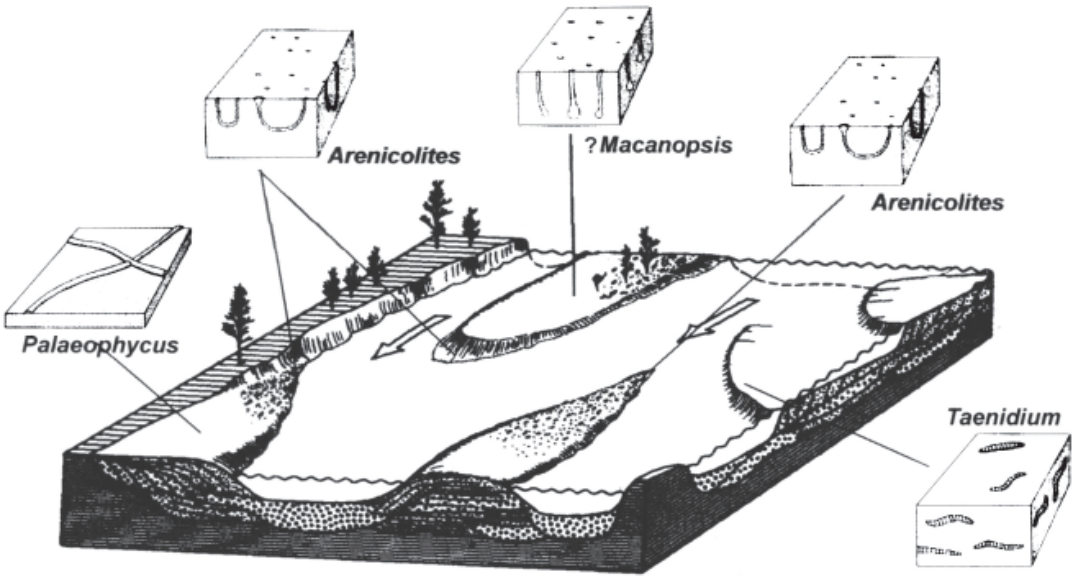

Figure 9. Trace fossil distribution in the alluvial plain sediments of Bauru Basin, Adamantina Formation.

DISCUSSION

In the continental environments, the bioturbation can be produced by several groups of invertebrate organisms, including nematodes, annelids, bivalves, gastropods and arthropods. Through their tracks and excavations, vertebrates are also able to rework the sedimentary deposits.

There is usually a large variety of ichnofossils in continental sediments, an aspect also observed by other authors in the analysis of non-marine ichnocoenoses (Ratcliffe & Fagerstrom, 1980; Fitzgerald & Barrett, 1986; D'Alessandro *et al*., 1987; Genise *et al*., 2000). The trace fossils described by D'Alessandro *et al*. (1987) in the meandering and braided stream deposits of the Duchesne River Formation (Eocene, Uinta Basin – U.S.A) are restricted to few invertebrate ichnogenera and rhizoliths. These were interpreted as endostratal traces, mainly preserved in floodplain sediments, unaltered or partially modified by soil development. As observed by Ratcliffe & Fagerstrom (1980) in Holocene floodplain sediments, the biogenic activity of insects and arachnids are generally abundant locally, producing structures similar to the ichnogenus *Macanopsis*, that are also found in the Cretaceous sediments of Bauru Basin.

Throughout the Upper Cretaceous, due to the persistence of a hot climate and to surrounding topographic heights, there was a progressive increase in aridity in the Bauru Basin. This allowed the establishment of alluvial plains, braided rivers and small temporary ponds (Mezzalira, 1980; Campanha *et al*., 1992, Etchebehere *et al*., 1999; Goldberg & Garcia, 2000). The invertebrate ichnofossils of the Adamantina Formation were collected in fine-grained sandstones, in the context of floodplain and channel-bar deposits (Figure 9). Some ichnogenera (*Taenidium* and *Palaeophycus*) reflect the activity of terrestrial and aquatic invertebrates through feeding and locomotion in the substrate. *Arenicolites* is a dwelling structure, while *Macanopsis* is a nesting trace. The trace fossils occur in sediments interpreted as deposited during sudden floods on alluvial plains under a dry and hot climate. Associated or in nearby correlated stratigraphic levels there are plant root traces, a great amount of crocodylomorph eggs and eggshells, that are indicative of a nesting area exposed for a long period of time.

The identification of a specific ichnofacies occurrence in the Adamantina Formation is a difficult task. *Arenicolites* is rare in the Scoyenia and Mermia Ichnofacies, but common in the Arenicolites Ichnofacies (*sensu* Bromley & Asgaard, 1991; Bromley, 1996), and it occurs in the marine Skolithos, Cruziana and Glossifungites Ichnofacies. At present three ichnofacies are recognized in continental environments, the Coprinisphaera, Scoyenia and Mermia Ichnofacies. The Coprinisphaera Ichnofacies is characterized by a moderate to relatively high ichnodiversity with breeding structures of insects as bees, ants and beetles. Meniscate tubes, mammal burrows, and rhizoliths are also found. It comprises ecosystems of terrestrial herbaceous communities with paleosols developed in a wide range of depositional environments, such as alluvial plains, desiccated floodplains and vegetated aeolian deposits (Genise *et al*., 2000). The Scoyenia Ichnofacies comprises the transition from a terrestrial to a subaqueous setting, containing vertebrate tracks and invertebrate burrows such as *Scoyenia*, *Beaconites*, and *Taenidium* (Pemberton *et al*., 1992). The ichnofacies is characterized by horizontal and small burrows, related to feeding activities, as well as trackways and vertical cylindrical burrows. The Mermia Ichnofacies was proposed by Buatois & Mángano (1995) for permanently subaqueous, lacustrine environments where ichnofossils such as *Mermia*, *Helminthopsis*, *Cochlichnus*, *Planolites*, *Lockeia* and *Gordia* can be found.

The frequent occurrence of numerous specimens of *Taenidium*, *Arenicolites* and *Palaeophycus* in the sandstones of the Adamantina Formation, and their association with vertebrate coprolites and egg nests, suggest the establishment of the Scoyenia Ichnofacies in these floodplain deposits.

CONCLUSIONS

The Cretaceous invertebrate ichnofauna of the Adamantina Formation is composed of *Arenicolites* isp., ?*Macanopsis* isp., *Palaeophycus herberti* and *Taenidium barretti*. Plant root traces, vertebrate bones, coprolites and egg nests are also found associated with these ichnofossils. Their frequent occurrence in distinct stratigraphic levels of the Adamantina Formation fine-grained sandstones, interpreted as exposed channel-bars and floodplain areas of braided rivers, suggest the establishment of the Ichnofacies Scoyenia.

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