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Dinosaurs remains from western São Paulo state, Brazil (Bauru Basin, Adamantina Formation, Upper Cretaceous)

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Abstract

In this contribution is presented the preliminary results of a paleontological expedition to five Upper Cretaceous fossil sites in the western part of the state of São Paulo, Brazil. Although the material is fragmented, the recovered fossils constitute an important record of the theropod dinosaur; some isolated teeth are the first record of Carcharodontosauridae in the Upper Cretaceous period in Brazil. The authors group the teeth of the theropod into five morphological groups on the basis of the general morphology of each tooth's cross-section and the presence of wrinkles on the crown. Spinosaurid and abelisaurid are also represented in this assembly, though other morph groups remain undetermined. One tooth in particular and a caudal vertebra indicate the presence of sauropods from the family Titanosauridae family.

Keywords: Adamantina Formation; Brazil; Dinosaurs; Upper Cretaceous

Resumo

Neste artigo são apresentados os resultados preliminares de uma expedição paleontológica a cinco sítios fossilíferos de idade Cretáceo Superior, na porção oeste do estado de São Paulo, Brasil. Apesar do material estar fragmentado, os fósseis recuperados se constituem num importante registro de dinossauros Theropoda, sendo alguns dentes isolados o primeiro registro de Carcharodontosauridae para o Cretáceo Superior do Brasil. Os dentes de terópodes foram agrupados em cinco grupos morfológicos baseados na morfologia geral do dente, na forma da seção transversal e na presença de rugosidades na coroa. Spinosaurídeos e abelissaurídeos estão também representados nesta assembléia, enquanto outros morfo-grupos ainda não foram determinados. Um dente isolado e uma vértebra caudal indicam a presença de saurópodos da família Titanosauridae.

Palvras chave: Formação Adamantina; Brasil; Dinossauros; Cretáceo Superior

1. Introduction

In the austral spring of 2001, the Laboratório de Macrofósseis of the Geology Department of the Universidade Federal do Rio de Janeiro organized an expedition to several Cretaceous fossil sites in the state of São Paulo, Brazil (Fig. 1). The expedition recovered numerous fossil remains, including ichnofossils, mollusks, fish, turtles, crocodylomorphs, and dinosaurs. The dinosaur assemblage comprises ten isolated teeth of Theropoda and one tooth and an incomplete vertebra of Sauropoda. The following article is a description and classification of these fossils.

The Adamantina Formation (Soares et al., 1980) is a very rich fossiliferous unit of the Bauru Basin, Brazil. The most important fossil sites of this basin are located in the states of São Paulo, Mato Grosso, and Minas Gerais (Kellner and Campos, 2000), where a diverse fauna composed of fish,

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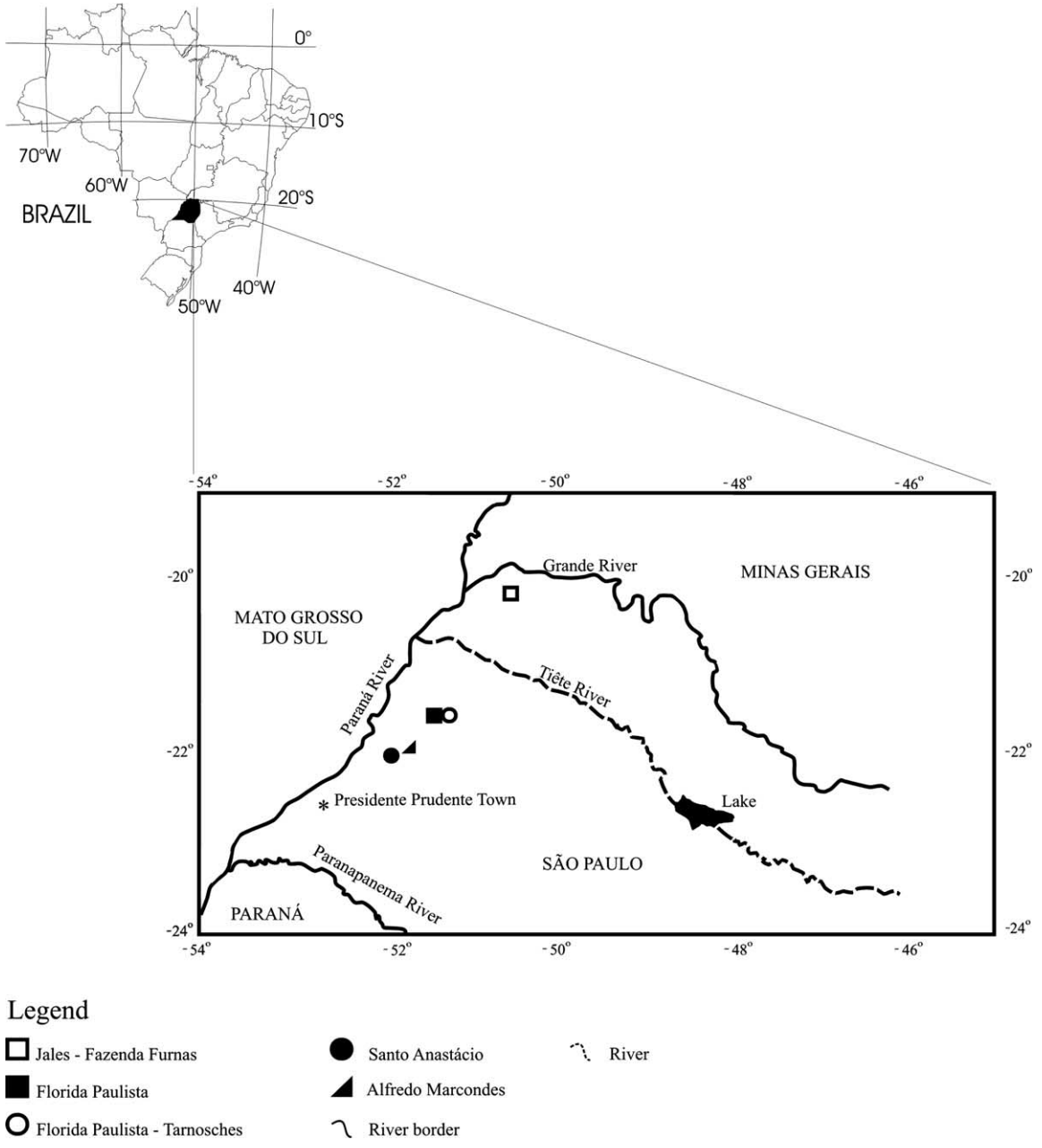

Fig. 1. Location map of paleontological sites investigated in the Adamantina Formation of the Bauru Basin (São Paulo State).

amphibians, crocodylomorphs, lizards, turtles, dinosaurs, and mammals has been recovered (Bertini et al., 1993).

The fossiliferous sites in western São Paulo State (Fig. 1) comprise some of the most interesting Upper Cretaceous localities in Brazil (Mezzalira, 1989). Based on its vertebrate content, the Adamantina Formation has been dated as Santonian–Maastrichtian (Suguio and Barcelos, 1983; Fernandes, 1998). However, Dias-Brito et al. (2001), based on microfossil correlation, isotopic analysis, and sequence stratigraphy, assign the Adamantina Formation to the Turonian–Santonian interval.

Only five Brazilian Cretaceous dinosaurs were formally described so far (Kellner and Campos, 2000; Carvalho et al., 2003), two of which were recovered from western São Paulo sites: '*Antarctosaurus*' *brasiliensis* Arid and Vizotto, 1971, and *Aeolosaurus faustoi* Kellner and Azevedo, 1999. Originally, both were considered members of the Family Titanosauridae, but the former species, described upon fragmented bones, subsequently it had been regarded as Titanosauria indet (Kellner and Azevedo, 1999; Kellner and Campos, 2000).

Although theropod teeth are the most frequent dinosaur remains in Brazilian Cretaceous deposits, all known described species come from northeastern basins (Kellner and Campos, 1996; Martill et al., 1996). The sole prior mention of theropod teeth in the Adamantina Formation was made by Franco (1999), who describes and tentatively classifies some isolated teeth. However, none of these studies employed

a methodology that associates isolated teeth with any of the known theropod taxa. Recently, Candeiro (2002), studying some isolated theropod teeth from the Upper Cretaceous of Minas Gerais, applied the methodology presented by Currie et al. (1990) to Laurasian theropods and assigned the teeth to two Gondwanan theropod families: Abelisauridae and Carcharodontosauridae. Likewise, we employ Candeiro's (2002) methodology to classify the newly discovered material.

The dental specimens studied herein were arranged according to the outline of their basal cross-section, the presence of wrinkles in the enamel of the crown when available, and the shape of the tooth. All teeth included are isolated and lack their roots.

The Systematic used here follows Holtz (1994) and Sereno (1999). All specimens are housed on the fossil collections at the Departament de Geologia/Universidade Federal de Rio de Janeiro.

2. Methodology

The methodology implied follows Candeiro (2002) and consists of measuring the tooth crown height (TCH) and the fore-aft basal width (FABL) and counting the number of denticles per millimeter at the beginning of the distal third of the crown on the anterior and posterior carina (Table 1). A similar methodology and terms have been employed by Currie et al. (1990), Farlow et al. (1991), Sankey et al. (2002), and Smith and Dodson (2003).

Currie (pers. comm.) studied the teeth of Tyrannosauridae, Dromaeosauridae, Carcharodontosauridae, and other Theropoda and observed that tooth cross-sections are unique to theropod families. His observations have been corroborated by the senior author of this article through cross-sections of approximately 1500 theropod teeth housed at the American Museum of Natural History (New York), the Royal Tyrrell Museum of Palaeontology (Drumheller), the Museo Argentino de Ciencias Naturales (Buenos Aires), and the Museu Nacional and Departamento de Geologia/UFRJ (both in Rio de Janeiro). The cross-sections of the specimens were taken by placing a copper thread around the tooth crown, near the base of the tooth. The shape resulted was then traced onto a sheet of paper.

Table 1
Tooth measurements and denticle count per mm of the specimens

Specimens	TCH	FABL	ADP (mm)	PDP (mm)
UFRJ-DG 354-Rd	8.60	5.97	–	3.0
UFRJ-DG 371-Rd	13.92	10.04	2.5	2.0
UFRJ-DG 372-Rd	18.88	10.56	–	–
UFRJ-DG 373-Rd	20.59	8.60	2.0	–
UFRJ-DG 374-Rd	16.47	9.20	2.5	2.5
UFRJ-DG 375-Rd	10.21	17.36	3.5	3.0
UFRJ-DG 376-Rd	10.12	13.83	3.0	3.0
UFRJ-DG 377-Rd	15.97	9.31	2.0	2.5
UFRJ-DG 378-Rd	14.93	11.48	3.0	2.5
UFRJ-DG 379-Rd	18.91	12.37	–	2.5

TCH, tooth-crown-height; FABL, fore-aft basal length; ADP(mm), anterior denticle per mm, PDP(mm), posterior denticle per mm.

3. Geology

The Bauru Basin is a SAG-type basin (Miall, 1990) developed in the central southern part of the South American platform through thermomechanical subsidence in the Late Cretaceous. This interior basin accumulated an essentially sandy sedimentary siliciclastic sequence that is now approximately 300 m thick. After Dias-Brito et al. (2001), the Bauru Basin comprises the Caiuá (Aptian–Cenomanian), Santo Anastácio (Cenomanian), Adamantina (Turonian–Santonian), Uberaba (Turonian-Coniacian), and Marília (Maastrichtian) Formations. The fossils studied here were recovered from four different localities where the Adamantina Formation outcrops.

The Adamantina Formation is dominated by reddish mudstones and sandstones of fluviolacustrine origin that were deposited during a time of warm, humid climates (Suguio and Barcelos, 1983). The sandstones are usually massive or have plane-parallel laminations alternating with medium- to small-scaled cross-bedding (Dias-Brito etal., 2001). The formation frequently exhibits hydrodynamic structures, such as ripple marks, climbing ripples, cross-lamination, and cut-and-fill structures. It also presents intraformational breccias with siltic-argillaceous intraclasts and normal grading.

The Adamantina Formation covers an area of more than 100,000 km^2 in the states of São Paulo, western Minas Gerais, southern Goias, southeastern Mato Grosso do Sul, and northern Paraná and extends as far as eastern Paraguay (Fernandes and Coimbra, 1996).

3.1. Flórida Paulista—Agrela Suburbs outcrop (21°37′55.6″S/51°09′27.4″W)

The very fine, reddish sandstone sediments of the Flórida Paulista–Agrela Suburbs outcrop are sometimes conglomeratic and cemented by calcium carbonate (Fig. 2). Conglomeratic sandstones are quartzose with well-rounded clasts and sometimes clay intraclasts. They have plane-parallel stratifications from thin to large-scale laminations and low-angle cross-bedding.

Recovered specimen: UFRJ-DG 373-Rd (Titanosauridae tooth).

3.2. Florida Paulista—Fazenda Nelson Tarnorches outcrop (21°35′S/51°11′W)

The Flórida Paulista-Fazenda Nelson Tarnorches outcrop exposes conglomeratic, medium, and fine sandstones, with up to 1 cm quartz pebbles of yellowish to reddish color, though they are whitish at the base. Sandstones and shale

clasts may also occur. Trough cross-beddings are observed in the conglomeratic sandstones with plane-parallel laminations, and small-scale tabular cross-beds are observed in the fine ones.

Recovered specimens: UFRJ-DG 259-R (Titanosauridae caudal vertebra), UFRJ-DG 371-Rd (Abelisauridae tooth), UFRJ-DG 372-Rd (Spinosauridae tooth), and UFRJ-DG 374-Rd (Abelisauridae tooth).

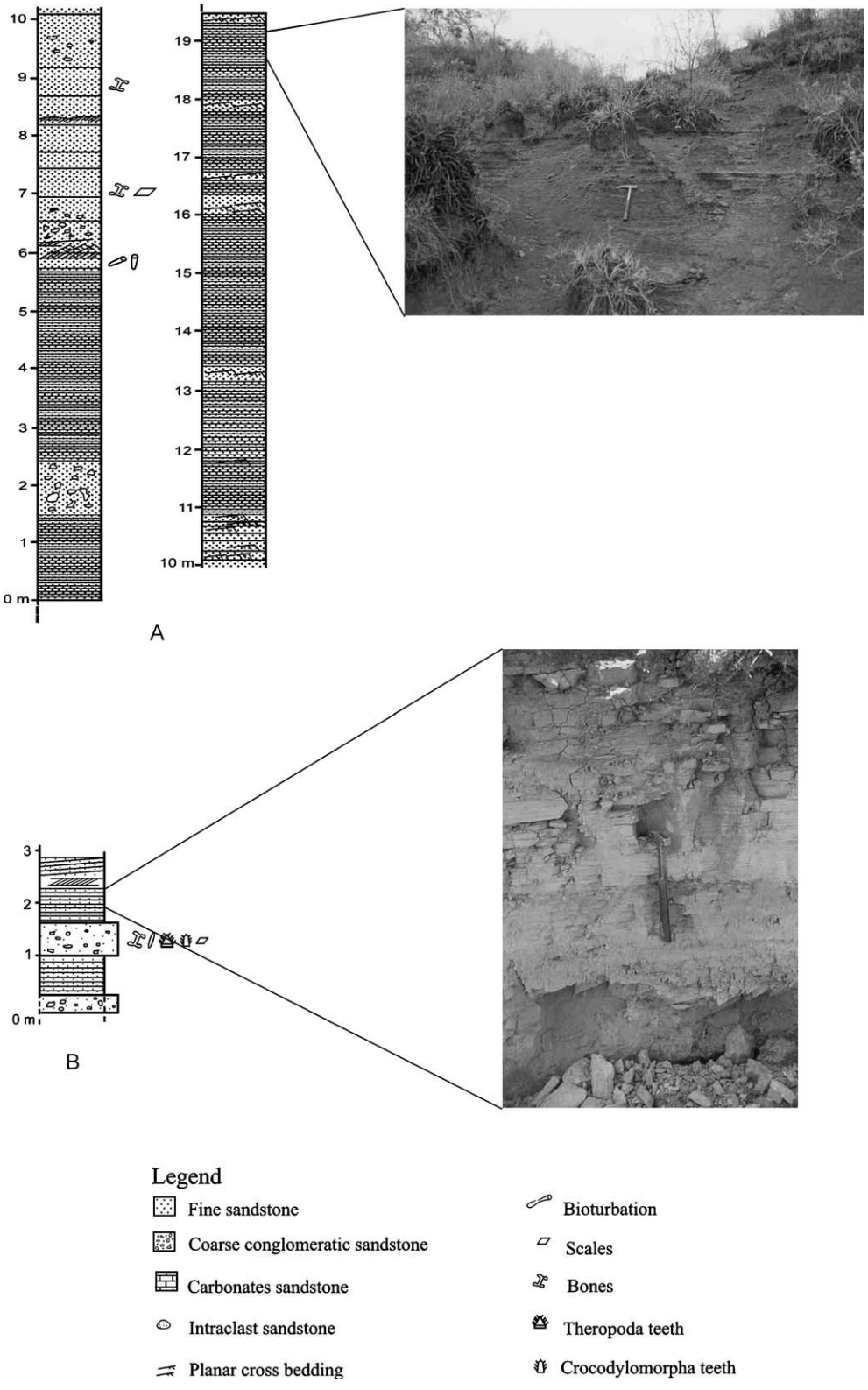

Fig. 2. Lithological profiles of the Adamantina Formation, Bauru Basin, of Jales (A) and Florida Paulista (B) sites (São Paulo State).

3.3. Santo Anastácio outcrop (21°56′39″S/51°22′23″W)

The Santo Anastácio outcrop displays fine, reddish sandstones, sometimes conglomeratic, with trough cross-bedding (Fig. 3).

Recovered specimens: UFRJ-DG 354-Rd (Spinosauridae tooth) and UFRJ-DG 377-Rd (Theropoda tooth).

3.4. Alfredo Marcondes outcrop (21°56′39″S/51°22′23″W)

The Alfredo Marcondes outcrop shows fine, reddish sandstones, sometimes conglomeratic, with plane-parallel laminations (Fig. 3).

Recovered specimens: UFRJ-DG 333-Rd (Titanosauridae tooth), UFRJ-DG 375-Rd (Theropoda tooth), UFRJ-DG 376-Rd (Theropoda tooth), UFRJ-DG 378-Rd (Abelisauridae tooth), and UFRJ-DG 379-Rd (Carcharodontosauridae tooth).

4. Description of specimens

4.1. Carcharodontosauridae

UFRJ-DG 379-Rd (Fig. 4A) is an incomplete tooth that lacks the tip and part of the lingual face. The anterior carina is missing, and the posterior one is smoothly curved. Sharp wrinkles are present on the labial face but these are more marked near the posterior border. The posterior surface is partially preserved. The cross-section could not be drawn from this specimen.

4.2. Spinosauridae

Both UFRJ-DG 354-Rd and UFRJ-DG 372-Rd (Fig. 4B) are more robust and conical than UFRJ-DG 379-Rd and have almost round cross-sections. The proximal half of the anterior edge of UFRJ-DG 372-Rd is broken.

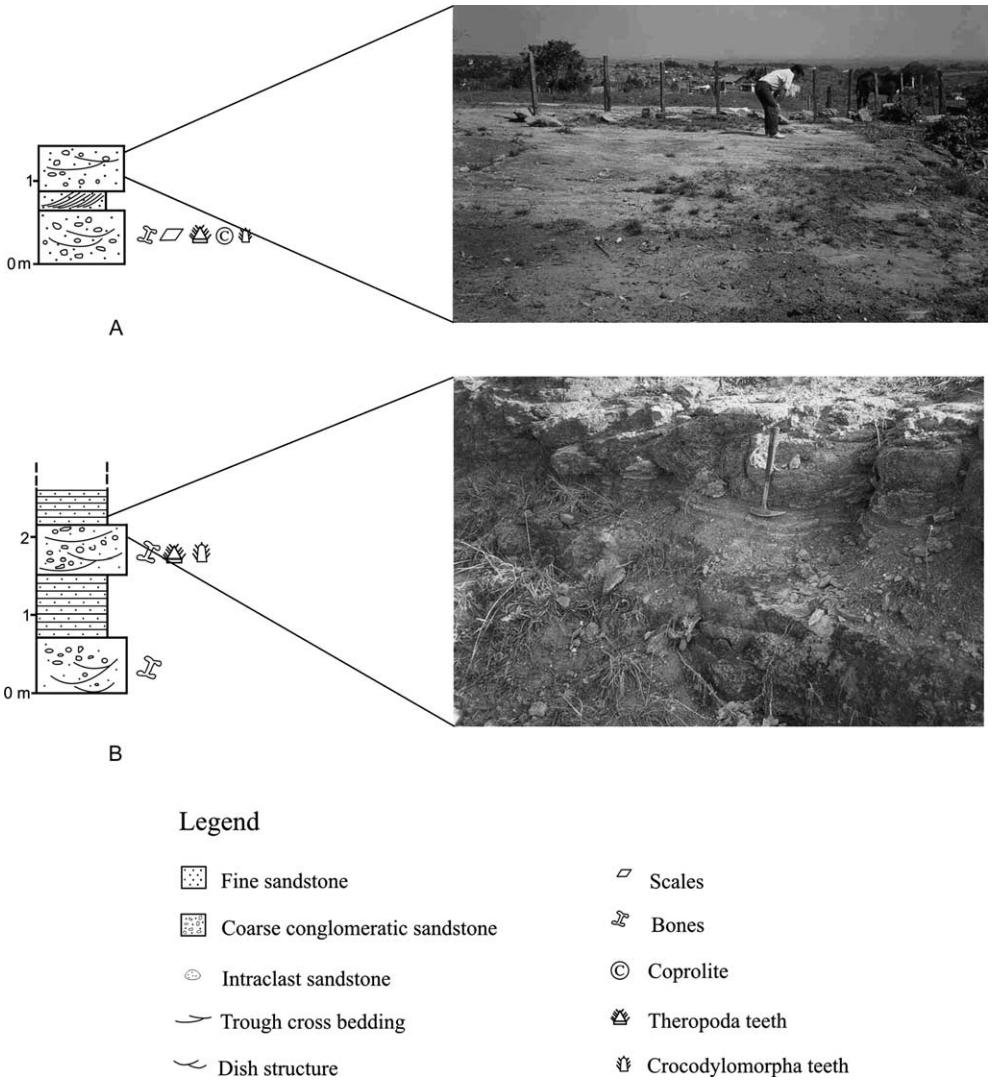

Fig. 3. Lithological profiles of the Adamantina Formation, Bauru Basin, of the Santo Anastácio (A) and Alfredo Marcondes (B) sites (São Paulo State).

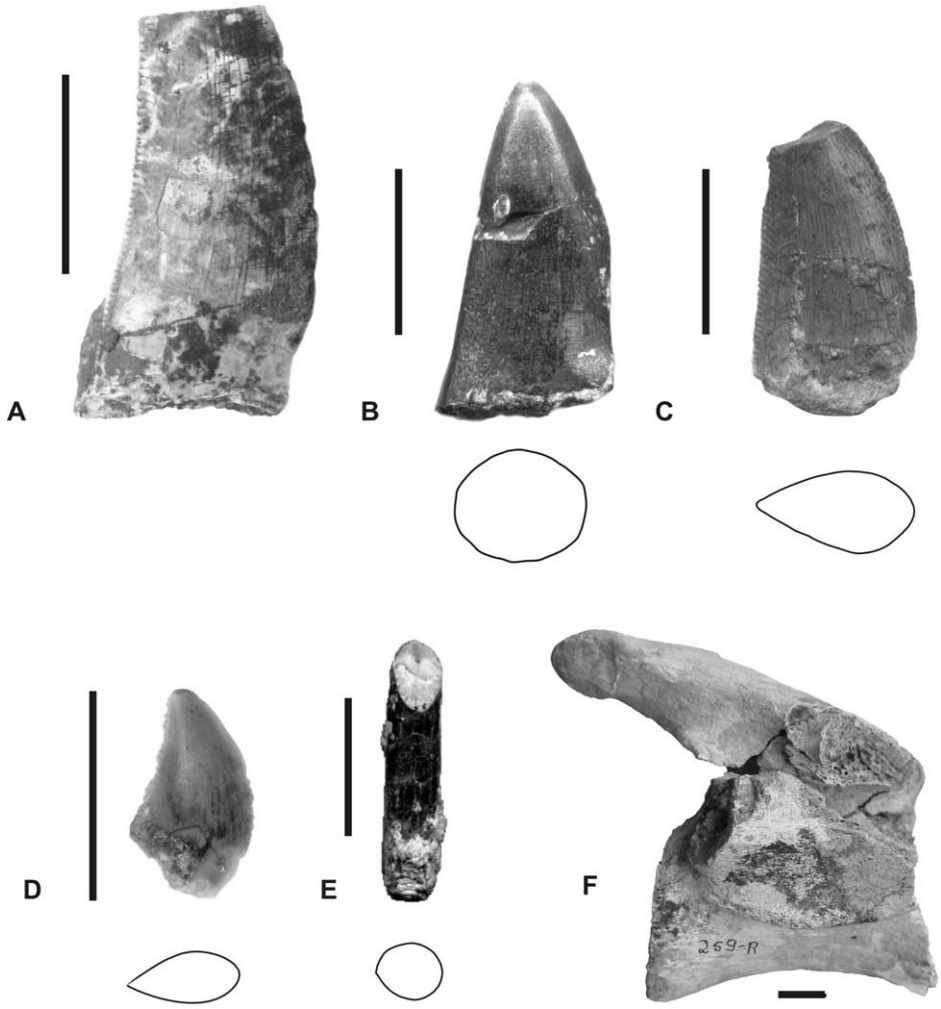

Fig. 4. Labial view and cross-section of theropod (A–E) and sauropod (F) teeth and a sauropod caudal vertebra (G) from the Adamantina Formation, Bauru Basin, São Paulo State. (A) UFRJ-DG 379-Rd; (B) UFRJ-DG 372-Rd; (C) UFRJ-DG 371-Rd; (D) UFRJ-DG 377-Rd; (E) UFRJ-DG 333-Rd; and (F) UFRJ-DG 269-R. Scale bar 10 mm.

The denticles are pointed occlusally . Denticles from the anterior carina are smaller and less rounded than those from the posterior carina. The distal denticles are worn out on both carinae. UFRJ-DG 354-Rd lacks its distal extremity, and its denticles are worner than those in UFRJ-D6 372-Rd. In both specimens, the labial and lingual faces are strongly convex. The enamel is textured.

4.3. Abelisauridae

UFRJ-DG 371-Rd (Fig. 4C), UFRJ-DG 374-Rd, and UFRJ-DG 378-Rd are more transversely compressed than the teeth referred here to Spinosauridae. UFRJ-DG 371-Rd lacks the distal end. In each tooth, the posterior edge is straight, and the anterior is convex. Anterior and posterior carinae bear denticles that are pointed occlusally. Both labial and lingual faces are more convex in cross-section near the anterior edge and flatter posteriorly; the lingual face is also slightly concave proximodistally.

4.4. Theropoda indet

UFRJ-DG 375-Rd and UFRJ-DG 376-Rd are slightly more robust than the teeth assigned to Abelisauridae but less robust than those attributed to Spinosauridae. Like UFRJ-DG 371-Rd, UFRJ-DG 374-Rd, and UFRJ-DG 378-Rd, the posterior carina is straight, but the anterior carina is not strongly convex. In both carinae, the denticles point occlusally. The cross-section is elliptical, but the labial surface is slightly more convex than that of the lingual surface.

UFRJ-DG 377-Rd (Fig. 4D) has a cross-section similar to the Abelisauridae tooth specimens identified herein, it has a more complex anterior edge and it is slightly concave posteriorly (Fig. 4D). In terms of the size of the tooth, the denticles are large and occlusally pointed in both carinae. Like Abelisauridae teeth from the Adamantina Formation, the labial and lingual faces are convex anteriorly and flat posteriorly, though less convex.

UFRJ-D6 375-Rd is very fragmentary, making it possible to determine to which of the theropod teeth it belongs.

4.5. Titanosauridae

UFRJ-DG 333-Rd (Fig. 4E) is cylindrical, straight, unserrated, and has a 'chisel-like' tip. Its base is irregularly broken and filled with sediment, suggesting that at least the base of the tooth is hollow.

UFRJ-DG 259-R (Fig. 4F) is a fragmentary and eroded caudal vertebra, lacking the posterior half of the centrum, one prezygapophysis, and the neural spine (Fig. 4F). The centrum is dorsoventrally compressed and displays spongy bone internally. The anterior articular facet is deeply concave, possibly indicating a well-developed posterior articular ball (procoelous condition), as found in titanosaurid sauropods. The right prezygapophysis has a rounded anterior articular facet that is oriented medially. The transverse process is limited to a lateral, anteroposteriorly directed ridge on the base of the neural arch.

5. Discussion

Gondwanan Cretaceous saurischians include Abelisauria, Allosauroidea, Spinosauroidea, Coelurosauria, Titanosauriformes, and Diplodocoidea (Mcintosh, 1992). In South America, Abelisauridae, Noasauridae, Carcharodontosauridae, Spinosauridae, Alvarezasauridae, Titanosauridae, Rebbachisauridae, and Dicraeosauridae are the only taxa presently recorded (Mcintosh, 1992; Salgado et al., 1997; Candeiro, 2002). Some authors (Franco, 1999; Vilas-Bôas et al., 1999) have assigned isolated theropod teeth from Brazilian Cretaceous beds to the Laurasian Dromaeosauridae, despite its biogeographical implications. These teeth were later reviewed and reassigned to South American taxa (Abelisauridae and Carcharadontosauridae) by Candeiro (2002). Although some Gondwanan-isolated teeth may resemble Laurasian forms, the presence of these forms in the Bauru Group is less probable and must be considered with caution. Until now, the fauna associated with theropod teeth in Bauru Group has been composed strictly by Gondwanan forms (Candeiro, 2002).

The number of denticles per millimeter and the FABL, commonly employed to characterize theropod families (Currie et al., 1990; Farlow et al., 1991; Fiorillo and Currie, 1994; Franco, 1999; Vilas-Bôas et al., 1999; Ryan et al., 2000; Sankey et al., 2002), are not diagnostic for most theropods, because the number of denticles is size dependent and can be the same for different taxa. One exception is the troodontid tooth, in which the denticles are relatively large in relation to its body size (Currie et al., 1990). The denticle number and FABL are useful for describing tooth morphology but cannot be used to identify most theropod teeth.

Carcharodontosaurus teeth have been reported in Brazil, first recovered from the Late Cenomanian of Lage do Coringa, São Luís Basin, in the northeastern Brazilian state of Maranhão (Vilas-Bôas et al., 1999; Medeiros, 2001). Due to the incompleteness of the tooth, the specimen UFRJ-DG 379-Rd from the Adamantina Formation cannot be classified as carcharodontosaurid only by its cross-section. However, it presents enamel wrinkles on the preserved portion of the crown, a diagnostic feature of Carcharodontosauridae according to Larsson (1996) and Sereno et al. (1996). Wrinkles also are present to a lesser degree in *Tyrannosaurus rex* and other tyrannosaurids, but their teeth are much more robust than the specimen studied herein. This specimen would be the first reported occurrence of a carcharodontosaurid in the Latest Cretaceous of Brazil.

The cross-sections of the specimens UFRJ-DG 354-Rd and 372-Rd are very similar to a Spinosauridae tooth. However, the major problem in assigning them to Spinosauridae is the restriction of this family to Early Cretaceous. Two spinosaurids are currently known from the Santana Formation (Aptian–Albian, Maisey, 1991) Araripe Basin, Brazil: *Angaturama limae* Kellner and Campos, 1996, and *Irritator challengeri* Martill et al., 1996. Sereno et al. (1998) suggest that *I. challengeri* is the only valid species for Brazil, a proposal followed by Sues et al. (2002). An autapomorphy of *I. challengeri* is the absence of denticles (Sues et al., 2002). No comparison could be made to *A. limae* (=*I. challengeri*) because no teeth were preserved in the holotype (Kellner and Campos, 1996). However, the denticle morphology of specimens UFRJ-DG 354-Rd and 372-Rd are similar to the pattern presented by the subfamily Baryonychinae, mainly in the denticle patterns observed in the North African *Suchomimus* (*sensu* Sereno et al., 1998). It is therefore possible that these specimens could represent a new form of Spinosauridae in Brazil.

Some crocodile teeth also present a cross-section similar to spinosaurids, but they differ from this theropod in being less conical and possessing only incipient anterior and posterior edges. Some crocodile teeth also have denticles, but they are less robust, and there is no variation in size and general aspect throughout their carina, as is observed in theropod teeth. Charig and Milner (1997), Sereno et al. (1998), and Sues et al. (2002) note that small marginal serrations and textured enamel are characteristic of spinosaurid teeth. Although the textured enamel is smoother than in known Spinosauridae, both diagnostic features are clearly observed in specimens UFRJ-DG 354-Rd and 372-Rd.

The Abelisauridae are characterized by low crowns and slightly curved teeth (Bonaparte, 1996; Lamanna et al., 2002; Wilson et al., 2003). The cross-sections of Abelisauridae teeth have never been described (e.g. Bonaparte and Novas, 1985; Lamanna et al., 2002), but the senior author of this article is conducting an analysis of this feature in some abelisaurid (*Indosuchus* AMNH 1960 and *Carnotaurus* MACN 894). He has observed that they are characterized by

a convex labial and slightly convex lingual cross-section. The cross-sections of specimens UFRJ-DG 371 Rd (Fig. 4C), UFRJ-DG 374 Rd, and UFRJ-DG 378 Rd are exactly as in Abelisauridae.

The first evidence of Abelisauridae in Brazil is a premaxilla with a tooth from the Adamantina Formation (Bauru Basin) Bertini (1996). However, no comparisons to this material could be made so far, because the tooth was not described in detail or clearly figured. Recently, several abelisaurid teeth were recovered from the Bauru basin in Mato Grosso (Bittencourt and Kellner, 2002). Further comparison with these specimens is required.

No family assignment could be made for specimens UFRJ-DG 377-Rd, UFRJ-DG 375-Rd, or UFRJ-DG 376-Rd, but there is no doubt that they belong to carnivorous dinosaurs, because they are strongly labiolingually compressed and show denticles with great variation in size and shape throughout the carina. Their cross-sections are different from any of the known Gondwanan Theropoda, but it is important to note that some Gondwanan dinosaurs teeth are still unknown (Novas, 1997, 1998).

UFRJ-DG 333-Rd was the only sauropod tooth recovered. Its elongated shape and sharply inclined wear facet are typical features of titanosaurid teeth (Salgado and Calvo, 1997).

The fragmentary nature of the caudal vertebra does not allow a specific identification, especially because it lacks the posterior portion of the centrum, which is diagnostic for dinosaur systematics (Powell, 2003). However, Powell (1986, 2003) argues that the titanosaurid vertebrae are characterized by spongy bone, clearly observed on this specimen.

The dinosaur fauna of the Bauru Group indicates a mixture of northern African–northern South American and Patagonian communities. Spinosaurid and carcharodontosaurid dinosaurs, as well as rebbachisaurids, are characteristic of the Early Cretaceous of northern African–northern South American dinosaur communities (Carvalho et al., 2003). Carcharodontosaurids and rebbachisaurids also were recovered in the Upper Cretaceous of Argentina (Bonaparte, 1996; Wilson and Sereno, 1998; Apesteguía, 2002), but they are absent in Lower Cretaceous beds of this country (Rich et al., 1999; Apesteguía, 2002). Some members of the northern African-northern South American dinosaur community may have extended their distribution all the way through austral South America during the middle Cretaceous (Aptian–Early Cenomanian). If carcharodontosaurid and rebbachisaurid have been recovered in the Late Cretaceous of central (Candeiro, 2002) and southern South America, why not expect the same with Spinosauridae? Thus, the record of Spinosauridae in the Late Cretaceous of central Brazil is reasonable.

However, there is no record of Abelisauridae in any of the Lower Cretaceous beds of northern South America, but in the Upper Cretaceous, they were found throughout Gondwana (Wilson et al., 2003). Bonaparte (1996) suggests that Abelisauridae originated in southern South America; thus, we believe that Abelisauridae extended its distribution from the southern parts of South America to central northern South America during the middle Cretaceous (Aptian–Eocenomanian) in a reverse pattern of that of Carcharodontosauridae, Spinosauridae, and Rebbachisauridae.

Intense tectonism, associated with the opening of the South Atlantic, occurred during the Late Jurassic–Early Cretaceous throughout Gondwana and led to the Serra Geral magmatism, the origin of new interior sedimentary areas (Sanfraciscana and Bauru basins), and the uplifting of structural arches (Fúlfaro and Perinotto, 1996; Mussachio, 2000). As a result, no biota interchange could have occurred between southern and northern South America until the Early Cretaceous, because the Serra Geral magmatism acted as an extrinsic barrier for both faunas. However, as Serra Geral magmatism ceased, a faunal interchange took place during the middle Cretaceous (Aptian–Eocenomanian), and the Bauru Group fossil record should be consider a relict of this time.

These results challenge arguments suggesting that the Bauru Group fauna are endemic (Bertini, 1993). Further studies of Bauru dinosaurs should add support to the hypothesis that the composition of the Bauru Group fauna is a result of a mixture of northern African–northern South American and Patagonian communities.

6. Conclusions

This contribution indicates the great diversity of dinosaurs in western São Paulo state during the Late Cretaceous and also states the usefulness of isolated theropod teeth. The following Theropoda families are reported in the Upper Cretaceous of western São Paulo state: Abelisauridae, Carcharodontosauridae, and Spinosauridae. Abelisauridae is recognized on the basis of three teeth; Carcharodontosauridae, for the first time recorded in São Paulo, is represented by one fragmentary tooth. Conical cross-section and textured enamel suggest the presence of Spinosauridae, a family not reported yet in the Latest Cretaceous. Some of the teeth described were not assigned to any known theropod family, which may indicate that the carnivorous dinosaur diversity of the Bauru Group is greater than previously believed. An isolated tooth and a fragmentary caudal vertebra of titanosaurids are also reported. For some time, Serra Geral magmatism represented an extrinsic barrier to the dispersion of northern fauna to southern South America, and vice versa. The end of this tectonic event enabled the interchange of both endemic faunas. The presence of Spinosauridae, Carcharodontosauridae, and Abelisauridae teeth in the Bauru Basin imply that some members of the northern African–northern South American and Patagonian communities of dinosaurs survived through the Late Cretaceous in central austral South American. Thus, the carnivorous dinosaur fauna recorded in

the Bauru Basin is considered a consequence of the mixture of the fauna of those communities.

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