Theropod teeth from the Marília Formation (late Maastrichtian) at the paleontological site of Peirópolis in Minas Gerais State, Brazil

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Abstract Theropod teeth can be separated at the family level using the basal cross-section, and by the presence or absence of wrinkles in the enamel of the tooth crowns. Theropods comprise the most common vertebrate remains in the fossil assemblage from the Serra da Galga Member, Marília Formation (late Maastrichtian) in the Bauru Basin Peirópolis paleontological site (Uberaba Town, Minas Gerais State), in southeastern Brazil. In this study, cross-sectional outlines of the teeth and wrinkles on the surfaces of the crowns were used to group the teeth into nine morphological classes. The tooth cross-sections were drawn using a copper wire to contour the outlines of the most proximal portions of the tooth crowns. Other features were analyzed using a microscope. Within the nine morphological classes, morphotypes one and two can be assigned to the Abelisauridae, and morphotypes three to seven belong to the Carcharodontosauridae. This is the most abundant record of Abelisauridae in Minas Gerais State, Brazil. Morphotypes eight and nine were not identified because they do not have any diagnostic features of known Gondwanan or Laurasian taxa. The presence of Carcharodontosauridae teeth in the Member of Serra da Galga (late Maastrichtian) is the youngest record for this family.

Keywords: dinosaur; Late Cretaceous; theropod teeth; Minas Gerais State; Brazil.

INTRODUCTION Theropod teeth (carnivorous dinosaurs) are relatively abundant in the geological record, but they are rarely studied and identified. The main reason for this situation is the lack of sufficiently diagnostic material, as usually only isolated teeth and tooth fragments are recovered. Identification can be difficult in the absence of association with more readily diagnostic cranial bones. Additionally, it is necessary to have complete denitions in order to recognize variation within the jaws (Chandler, 1990; Currie et al., 1990).

Another problem with isolated teeth is the lack of studies that have been done on the taxonomic significance of theropod dental morphology (Currie, 1987; Farlow & Brinkman, 1987; Currie et al., 1990; Farlow et al., 1991). Many studies have been carried out on dentition replacement (Cooper et al., 1970; Osborn, 1971, 1975; Kline & Cullum, 1984; Bolt & Demar, 1986), but most of them focus on the relationships between diet and dentition (Hotton, 1955; Massare, 1987; Tanke & Currie, 1998; Candeiro & Tanke, 2008).

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Theropod teeth are the most abundant cranial material found at the Paleontological Site of Peirópolis (Fig. 1) near Uberaba Town in Minas Gerais State, in Brazil. The exposures at the site are composed of Marília Formation sediments (late Maastrichtian). Other vertebrates from the site include disarticulated bones from fish, turtles, lizards, crocodiliforms, titanosaurs, and theropods (Candeiro et al., 2006, 2008, Candeiro, 2007, 2009 and references therein). However, the only cranial theropod elements found are teeth. These are labiolingually compressed and have carinae with denticles. Previous to this study, the theropod tooth collections from the Paleontological Site of Peirópolis housed in Centro de Pesquisas Paleontológicas Llewellyn Ivor Price (Peirópolis) included 55 specimens. Kellner (1995, 1996) and Candeiro et al. (2004) studied the morphologic aspects of these theropod teeth. Other studies by Franco & Bertini (1997) and Franco (2000) focused on theropod tooth taxonomy. This study presents a detailed description of the teeth from Peirópolis, based on tooth morphology.

Institutional abbreviations
- AMNH: American Museum of Natural History, New York;
- CPP: Centro de Pesquisas Paleontológicas Llewellyn Ivor Price, Peirópolis;
- DG/UFRJ: Departamento de Geologia of Universidade Federal do Rio de Janeiro, Rio de Janeiro;
- MACN: Museo Argentino de Ciencias Naturales, Buenos Aires;
- MCF-PVPH: Museo Municipal Carmen Funes, Paleontología de Vertebrados, Plaza Huincul;
- UNPSJB-PV: Universidad Nacional de la Patagonia, “San Juan Bosco”, Comodoro Rivadavia;
- PVL: Fundación-Instituto Miguel Lillo, Tucumán;
- MUCPV-CH: Museo de la Universidad Nacional de Comahue, El Chocon collection;
- RTMP, Royal Tyrrell Museum of Palaeontology, Drumheller.

MATERIAL AND METHODS Fifty-five isolated theropod teeth were micro-photographed using a scanning electron microscope (SEM) and a ZENIT 12 camera. The following measurements were taken: tooth crown height (TCH); fore aft basal width – FABL (Currie et al., 1990, Farlow et al., 1991; Sankey et al.,...
2002; Smith & Dodson, 2003); and numbers of denticles per millimeter on the proximal and distal portions of the anterior and posterior carina. Cross-sections of each specimen were traced from a copper thread, which had been wrapped around the base of the tooth crown. The geological subdivision of the Bauru Group (Bauru Basin) hereafter follows Fernandes & Coimbra (1996).

**SYSTEMATIC PALEONTOLOGY**

THEROPODA (Marsh, 1881);
CERATOSAURIA (Marsh, 1884);
NEOCERATOSAURIA (Novas, 1991);
ABELISAURIA (Novas, 1992);
ABELISAUROIDEA (Bonaparte, 1991);
ABELISAURIDAE (Bonaparte & Novas, 1985).

**Morphotype 1**


**LOCALITY** Peirópolis site, near Uberaba Town, Minas Gerais State, Brazil.

**HORIZON AND AGE** All the teeth are from the Serra da Galga Member of Marília Formation – late Maastrichtian (Dias-Brito et al., 2001).

**DESCRIPTION** Teeth of morphotype one (Figs. 2A to D) are characterized by slightly convex labial and lingual surfaces, which are compressed along the margins where they have contact at the carina. The denticles at the proximal end of the anterior carina are smaller than those in the posterior carina, but the middle denticles of the anterior carina are larger than at either end. All the denticles at the distal ends of both carinae point towards the apex of the crown, but this is less pronounced in the proximal and middle denticles. All the denticles of both carinae are restricted to the enameled part of the crown. The denticles of the proximal and distal regions of the posterior carina are the same size, while the middle ones are larger.

**Morphotype 2**

REFERRED MATERIAL CPP 123, 129b, 129c, 131, 132, 135, 154, 161/1, 198, 211, 372, 375/2, 446, 451/1, 452/1, 476, 478.

**Figure 2** – Abelisauridae teeth. (A and C) SEM microphotograph of anterior and posterior denticles, CPP 20 (Labial); (D) cross-section of base; (B) labial view. (E and G) SEM microphotograph of posterior and anterior denticles, CPP 123 (lingual); (F) labial view; (H) cross-section of base. (I and K) SEM edge microphotograph edge with absence of denticles, CPP 129b (lingual); (F) labial view; (L) cross-section of base. (M and O) SEM of posterior and anterior denticles, CPP 131 (lingual); (N) lingual view; (P) cross-section of base. (Q) lingual view; (R) cross-section. (S and U) SEM of posterior and anterior denticles CPP 452/22 (lingual); (T) lingual view; (V) cross-section.
DESCRIPTION Teeth classified as morphotype two (Figs. 2E to V) are characterized by slightly convex lingual and labial surfaces, which are compressed where they meet at the posterior carina. The denticles on the proximal portion of the anterior carina are smaller than those of the distal part, but denticles in the middle are the largest. All the denticles near the tooth tip point toward the apex of the crown. The denticles on the proximal and middle parts of the anterior carina point toward the apex of the crown. Each dентicle of either carina is proximodistally longer than its basal width in labial or lingual views. The denticles of the proximal and distal parts of the posterior carinae are the same size, and those in the middle are larger. The cross-section (Figs. 2F, J, N, R, V) shows the anterior face compressed and posterior face slightly convexes. Cross-sectional shape has already been used to study theropod teeth (Bakker et al., 1988; Currie et al., 1990; Farlow et al., 1991; Sankey et al., 2002), and it is useful for identifying teeth from Brazil. The cross-sections of teeth in the jaws of Aucasaurus garridoi (MCF-PVPH-236), Carnotaurus sastrei (MACN 894), Noasaurus leali (PVL-4061), Indosuchus raptorius (AMNH 1960), and an unidentified Carnotaurinae (UNPSJB-PV-247) are similar to the Peirópolis teeth. Morphotypes one and two have convex lingual and labial faces of the crown, but are compressed along the carina margins. This type of cross-section is different from that of a carnarodontosaurus (Stromer, 1931; DG/UFRJ S/N; RTMP 94.43.1, 94.43.2, 94.43.3, 94.43.4, Giganotosaurus MCPV-CH-1). Abelisaurid (Aucasaurus garridoi, Carnotaurus sastrei and Indosuchus raptorius) teeth are more compressed labiolingually than those of Carnarodontosaurus (Fig. 3). Dentary teeth of Carnotaurus sastrei and Indosuchus raptorius (AMNH 1960) are labiolingually compressed and slightly recurved on the posterior carina whereas in Noasaurus leali and Masiakasaurus knopfleri (Carrano et al., 2002) they are curved more strongly along the posterior carina. Morphotypes one and two have similar characteristics to those in the jaws of Carnotaurus sastrei and Indosuchus raptorius – both have slightly convex lingual and labial faces and compressed edges.

THEROPODA (Marsh, 1881)
TETANURAE (Gauthier, 1986)
NEOTETANURAE (Sereno, 1994)
ALLOSAUROIDEA (Currie and Zhao, 1993)
cf. CARCHARODONTOSAURIDAE (Stromer, 1931)

Morphotype 3
REFERRED MATERIAL CPP 124, 129a, 208, 375/1.

DESCRIPTION Morphotype three (Figs. 3A to D) has a convex lingual face in cross-section, whereas the labial face is almost flat. The posterior part of the crown is labiolinguually compressed, especially at mid-height. Enamel wrinkles are present on both faces of the crown. The denticles on the distal portions of the carinae are smaller than those on the middle and proximal parts. The denticles are larger at mid-height of the crown. All of the distal denticles of both carinae point toward the apex of the crown, while the proximal and middle denticles are directed perpendicular to the longitudinal axis of the tooth. All the anterior denticles have the same heights and widths. The posterior denticles are proportionally the same size in the proximal and distal regions of the carina, whereas the middle ones are larger. All the denticles of this carina are proximodistally higher than their corresponding basal widths. In cross-section, the base of morphotype three is oval.

Morphotype 4
REFERRED MATERIAL CPP 447.

DESCRIPTION Morphotype four (Figs. 3F to H) has a smoothly convex lingual face, and a strongly convex labial one. The anterior region is labiolingually compressed, while the posterior part of the tooth is broadly rounded (Fig. 3D, H). Enamel wrinkles occur on both faces of the crown. The wrinkles originate proximally from the center of the vertical convex ridge on each side, and extend toward the carina. The denticles on the proximal and distal ends of the posterior carina are equivalent in size, while the middle ones are larger. The anterior denticles are smaller than the posterior ones. All the denticles of both carinae point perpendicular to the longitudinal axis of the tooth, and they are proximodistally higher than basally wide. The cross-section of the tooth (Fig. 3H) is shallowly convex on the lingual surface and strongly convex on the labial face. It is compressed towards the front and thick posteriorly so that the cross-section looks roughly like an isosceles triangle.

Morphotype 5
REFERRED MATERIAL CPP 156.

DESCRIPTION Morphotype five (Figs. 3I to L) is peculiar in that the lingual face is smoothly convex whereas the labial face is strongly convex. The posterior part
of the cross-sectional outline of the tooth is somewhat compressed. The tooth has a double posterior carina, with both parts converging toward the tip of the tooth. Smooth enamel wrinkles occur on both faces of the crown. They originate on the surface of the vertical convex ridge on each of the lingual and labial surfaces, and they extend towards the anterior and posterior carinae. The paired posterior carina is formed by a large, almost straight component, and a smaller secondary part (Fig. 3J). The anterior denticles on the proximal and middle portions of the carina point perpendicular to the longitudinal axis of the tooth. The anterior denticles are smaller at the proximal end of the carina, and the middle denticles are the largest. The distal denticles of both carinae point toward the apex of the crown. The denticles on the proximal and middle portions of the anterior carina point away from the longitudinal axis of the crown. The denticles are basally wider than proximodistally high on the anterior carina, while they are higher than wide posteriorly. The posterior denticles are larger at the mid-
height of the crown. The cross-section (Fig. 3L) is anteriorly compressed, and is posteriorly thicker.

**Morphotype 6**

**REFERRED MATERIAL** CPP 152, 199, 216, and 376.

**DESCRIPTION** Morphotype six (Figs. 3M to P) is characterized in cross-section by having a shallowly convex labial and a strongly convex lingual surface (Fig. 3N). The anterior part of the tooth is labiolingually compressed, whereas the posterior edge is thicker in the cross-section. Enamel wrinkles are similar to those of morphotypes three, four, and five. Denticles on the proximal and distal portions of each carina are of equal size, while the middle ones are larger. All anterior denticles are slightly larger than the posterior ones. On both carinae, the denticles point toward the apex of the crown. The denticles of the proximal and mid-height portions of the anterior carina are perpendicularly to the longitudinal axis of the tooth. All of the denticles are proximodistally higher than basally wide on both carinae. Slender blood grooves originate between adjacent denticles. The cross-section is relatively convex on the lingual side, but it is broadly expanded between the posterior carinae.

**Morphotype 7**

**REFERRED MATERIAL** CPP127, 197, 200, 241, 448, 449, 474, 475.

**DESCRIPTION** Morphotype seven (Figs. 3Q to Z) have shallowly convex lingual and labial surfaces, and are labiolingually narrow at the anterior and posterior carinae. Enamel wrinkles (Figs. 3T and Y) are present on both labial and lingual faces of the crown, and morphologically are similar to those of morphotypes three to six. Denticles from the proximal portions of the carinae are smaller than the distal ones, and both are smaller than the middle ones. Denticles of both carinae point toward the apex of the crown. The denticles from the proximal and mid-height areas of the anterior carina are perpendicular to the longitudinal axis of the tooth. All denticles are proximodistally higher than they are basally wide. The lingual and labial surfaces of the tooth are shallowly convex in cross-section, and the tooth is narrow and bladelike.

The presence of wrinkles on a theropod tooth crown has been considered a diagnostic feature for Carcharodontosauridae (e.g., *Carcharodontosaurus saharicus*, *Giganotosaurus carolinii* and *Mapusaurus roseae*) by many authors (Larsson, 1996; Sereno et al., 1996; Vickers-Rich et al., 1999). In *Giganotosaurus carolinii*, different forms of wrinkles occur (Calvo pers. com), which can be strong or shallow in relief. These features may also extend close to the carinae (e.g., *Carcharodontosaurus* and *Giganotosaurus*), which are also characteristic of morphotypes three to seven. Morphotypes three, four, six, and seven have compressed cross-sections, giving each tooth a knife-like appearance as in *Carcharodontosaurus saharicus* (Stromer, 1931) and *Giganotosaurus* (MUCPV-CH-1). THEROPODA (Marsh, 1881)

**Morphotype 8**

**REFERRED MATERIAL** CPP 128, 243, 271, and 371.

**DESCRIPTION** A morphotype eight (Figs. 4A to B) is characterized by a shallowly convex lingual face and a more strongly convex labial surface in cross-section. The anterior and posterior margins of the tooth are relatively thick in cross-section. On the anterior carina, the proximal denticles are smaller than the distal ones, and the mid-height denticles are larger than both proximal and distal denticles. The distal denticles on both carinae pointed toward the apex of the crown. The denticles on the proximal and mid-height portions of the anterior carina are perpendicular to the longitudinal axis of the tooth. All denticles are as high as they are wide on both carinae. Slender blood grooves are present. The posterior carina forms an angle of almost 90° with the crown teeth base. The denticles of the proximal and distal regions of the posterior carina are equal; however, they are smaller than the mid-height denticles. The denticles on the proximal and mid-height regions of the posterior carina are perpendicular to the longitudinal axis of the tooth. The cross-section (Fig. 4B) has all the sides with concave or oval shapes.

**Morphotype 9**

**REFERRED MATERIAL** CPP 374.

**DESCRIPTION** Morphotype nine (Figs. 4C to F) has a relatively flat lingual surface and a more strongly convex labial face. The anterior part of the tooth base is labiolingually compressed and the posterior part is thicker and has a more strongly convex profile in section.

The proximal and distal denticles are subequal in size, although all anterior denticles are slightly larger than the equivalent posterior ones. Both anterior and posterior denticles near the tip of the tooth...
point toward the apex of the crown. More proximal denticles are more or less perpendicular to the longitudinal axis of the tooth.

CONCLUSIONS  Morphotypes eight and nine do not have any of the characteristics (cross-section, presence of wrinkles, and tooth shape) typical of known Gondwanan theropods, nor do they resemble the teeth of Laurasian theropods. Gondwanan theropods are represented mainly by Abelisauridae, Alvarezsauridae, Carcharodontosauroidae, Spinosauridae, and Coelurosauria. Amongst South-American taxa, teeth are not known for example *Alvarezsaurus calvoi*, *Neuquenornis volans*, *Yungavolucris brevipedalis*, *Lectavis breliola*, *Patagopteryx deferasi*, *Patagonykus puertai*, *Miraschis asymetria*, and *Santanaraptor placidus*, nor are they known for *Cristatusaurus lapparenti* of Africa. Morphotypes nine and ten might represent any of these Gondwanan taxa, or might represent new taxa.

Thus, in the present work theropod teeth records were reported. They are from the Peirópolis Site, in Minas Gerais State, a place that has yielded a great number of bones of titanosaurid sauropods (*Baurutitan britoi* and *Uberabatitan riberoi*) and crocodylomorphs (*Itasuchus jesuoinoi*, *Peirosaurus tormini* and *Uberabasuchus terrificus*). In contrast, to the theropoda record is only represented by teeth (this work), an Abelisauridae vertebra (Novas et al., 2008), a tetanuran scapula (Machado et al., 2008), and a maniraptoran claw (Novas et al., 2005). The present Abelisauridae and Carcharodontosauroidae reports from Peirópolis indicates that this group has a larger geographical distribution in the Gondwanalandmasses, which is the most extensive theropod tooth assemblage from Brazil.

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