

NEW RECORD OF ABELISAUROID THEROPODS FROM THE BAURU GROUP (UPPER CRETACEOUS), SÃO PAULO STATE, BRAZIL

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ABSTRACT – Isolated bones of abelisauroid theropods from the Bauru Group (Late Cretaceous, Brazil), are described. They correspond to three individuals represented by fused ischia and part of the ilium, a partial axis, and a right fibula, respectively. The fossils come from different sites in the municipalities of Ibirá (axis and fibula) and Monte Alto (ilium and ischia), São Paulo State, from Maastrichtian beds of the São José do Rio Preto and the Marília formations (Bauru Group), respectively. The specimens provide new information on abelisauroids which are still poorly known in the Brazilian fossil record, and on the distribution of this diverse group of theropod dinosaurs in South America. These discoveries indicate that abelisauroids were the most common large predatory dinosaurs in the outcrops where they come from.

Key words: Abelisauroida, Theropoda, Late Cretaceous, Marília Formation, São José do Rio Preto Formation, Brazil.

RESUMO – Ossos isolados de terópodes abelissauroides do Grupo Bauru (Cretáceo Superior), Brasil, são descritos. O material consiste de restos de três indivíduos, um representado pelos ísquios fusionados e parte do ílio, outro por um fragmento de eixo e outro por uma fíbula direita. Os fósseis, oriundos dos municípios de Ibirá (eixo e fíbula) e Monte Alto (ílio e ísquios fusionados), Estado São Paulo, foram descobertos em depósitos maastrichtianos das formações São José do Rio Preto e Marília (Grupo Bauru), respectivamente. Os espécimes fornecem novas informações sobre abelissauroides, ainda são pouco conhecidos no registro fóssil brasileiro, e sobre a distribuição deste grupo diverso de dinossauros terópodes na América do Sul. Estas descobertas indicam que os abelissauroides foram os grandes dinossauros predadores mais comuns nos afloramentos de onde eles provêm.

Palavras-chave: Abelisauroida, Theropoda, Cretáceo Superior, Formação Marília, Formação São José do Rio Preto, Brasil.

INTRODUCTION

The Brazilian record of theropods includes diverse lineages such as abelisauroids (Bertini, 1996; Bittencourt & Kellner, 2002; Kellner & Campos, 2002; Candeiro *et al.*, 2004, 2006a,b; Novas *et al.*, 2008; Machado *et al.*, 2013), spinosaurids (Martill *et al.*, 1996; Kellner & Campos, 1999; Kellner *et al.*, 2011), megaraptorans (Méndez *et al.*, 2012; Martinelli *et al.*, 2013), and maniraptorans (Novas *et al.*, 2005; Machado *et al.*, 2008), including some isolated teeth (Bertini *et al.*, 1997; Bertini & Franco-Rosas, 2001; Franco-Rosas, 2002) with questioned assignment (Canale *et al.*, 2007). Isolated teeth attributed to carcharodontosaurids (Silva & Kellner, 1999; Candeiro *et al.*, 2004, 2006b) are currently considered to correspond to abelisauroids (Canale *et*

al., 2009; Souza *et al.*, 2011). However, most recently, new bone remains belonging to carcharodontosaurian theropods have been described (Azevedo *et al.*, 2013). Theropod remains were found in several formations of the Bauru Group (Bittencourt & Langer, 2011). Remains of abelisauroid theropods are restricted to the Bauru Basin in southeastern Brazil. The first materials described for Abelisauroidea from this Group was a fragment of right premaxilla and an isolated tooth (Bertini, 1996) from Santo Anastacio City, São Paulo State (Adamantina Formation). Kellner & Campos (2002) described *Pycnonemosaurus nevesi*, the only named abelisauroid from Brazilian beds, found in the Cambebé area, Mato Grosso State (Adamantina Formation). From the same locality of *Pycnonemosaurus* Kellner & Campos, 2002, Bittencourt & Kellner (2002) described isolated teeth that

they considered to belong to Abelisauridae. Candeiro (2002) identified abelisaurid teeth from the Marília Formation in Uberaba County (Serra do Veadinho, Peirópolis). Novas *et al.* (2008) described several bones belonging to Abelisauridae from three localities in the Peirópolis area (Uberaba County, Minas Gerais State), corresponding to the Serra da Galga Member of the Marília Formation, and more recently, Machado *et al.* (2013) recognized an abelisauroid tibia from the same formation.

The goal of the present study is describe three theropod fossils discovered in two municipalities of São Paulo State (Figure 1), thus enlarging the list of dinosaur record unearthed from rocks of the Bauru Group.

Institutional abbreviations. MACN, Museo Argentino de Ciencias Naturales, Buenos Aires, Argentina; MPMA, Museu de Paleontologia de Monte Alto, São Paulo, Brazil; UA, Université d'Antananarivo, Antananarivo, Madagascar.

SYSTEMATIC PALEONTOLOGY

Subordem THEROPODA Marsh, 1881
 Infraordem CERATOSAURIA Marsh, 1884
 Superfamília ABELISAUROIDEA Bonaparte, 1991
 (Figures 2A-D; 4A-F; 5A-E)

Referred material. MPMA 27-0001-02, partial pelvis consisting of incomplete right ilium and left pubis plus both ischia (Figures 2A-D); MPMA 08-0016-95, partial axis (Figures 4A-F); MPMA 08-0069-13, right fibula (Figures 5A-E).

Locality, horizon and age. MPMA 27-0001-02, Municipality of Monte Alto, São Paulo State, Brazil; Marília Formation, Maastrichtian, Upper Cretaceous. MPMA 08-0016-95 and MPMA 08-0069-13, Municipality of Ibirá, São Paulo State, Brazil; São José do Rio Preto Formation, Maastrichtian, Upper Cretaceous.

Description and comparison. The right ischium MPMA 27-0001-02 is almost complete and proximally fused with the ischiadic pedicle of the ilium. Both ischia are broken distally, lacking the distal foot. The left ischium is broken proximally but fused with the posterior end of the left pubis. The ischia are anteroposteriorly narrower than the same bones in *Carnotaurus* Bonaparte, 1985 (Figure 3), being more similar in shape to the ischia of *Ceratosaurs* Marsh, 1884 and *Masiakasaurus* Sampson, Carrano & Forster, 2001. Each Monte Alto ischium measures 45 cm from the antitrochanter to the preserved distal end, whereas the ischium of *Carnotaurus* measures at least 72 cm. Thus, the Brazilian ischia are at least 37.5% smaller than the same bones in

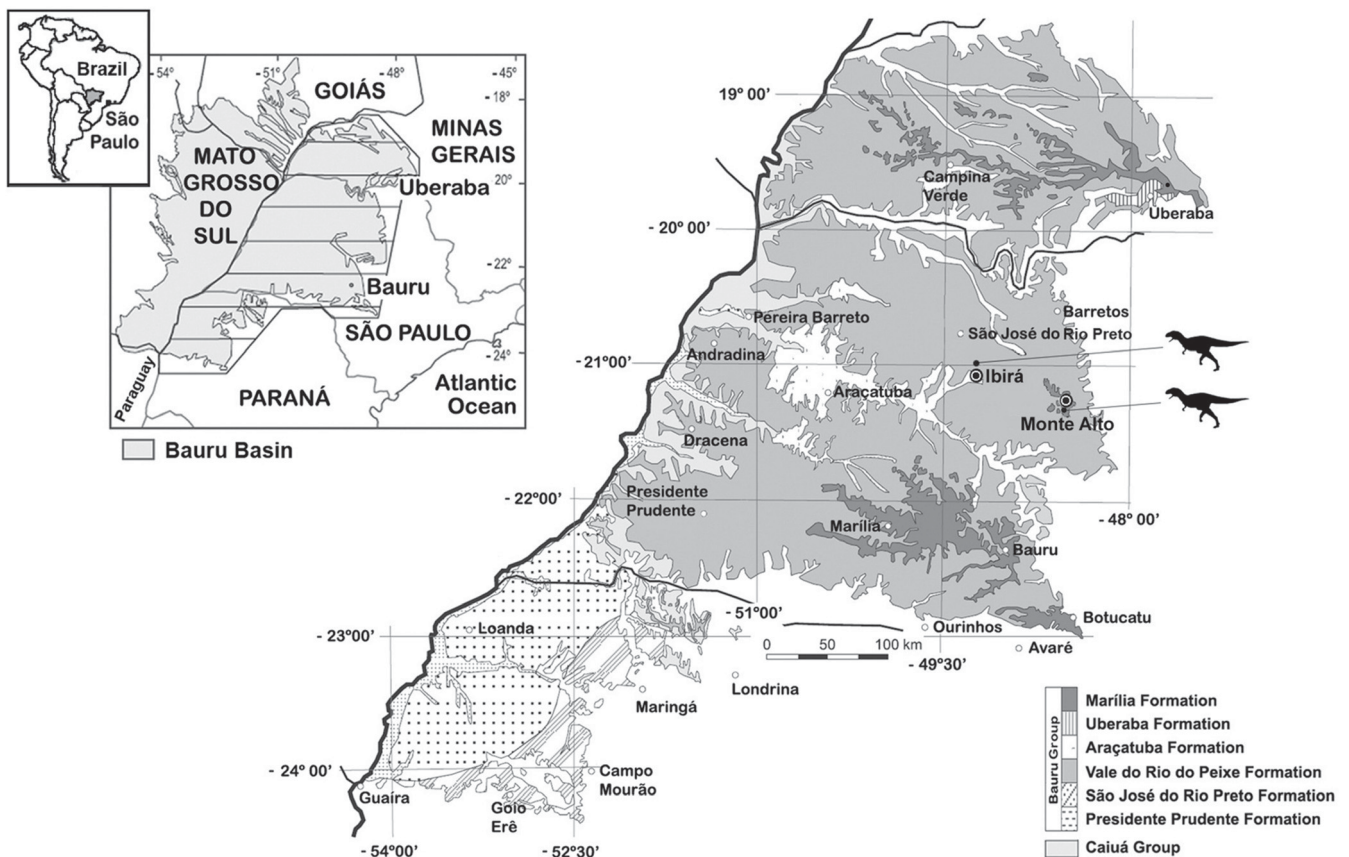


Figure 1. Geological map of the Bauru Basin, with the locations of the abelisauroid finds at the Ibirá and Monte Alto fossil sites (modified from Fernandes & Coimbra, 2000).

Carnotaurus. The ischiadic antitrochanter is well developed and continues within the ilium (Figure 2B). The ventral margin of the acetabulum is also preserved, being mediolaterally narrower (almost laminar) than the antitrochanter, similar to the condition observed in abelisaurids and *Tyrannosaurus* Osborn, 1905 (Brochu, 2003), whereas in *Allosaurus* Marsh, 1877 the base of the acetabulum is wide (Madsen, 1976). The supracetabular crest continues posteriorly and connects with the brevis-shelf, a morphology observed in most abelisauroids (e.g. *Masiakasaurus* Carrano *et al.*, 2011; *Majungasaurus* Carrano, 2007; *Eoabelisaurus* Pol & Rauhut, 2012; although not in *Rajasaurus* Wilson *et al.*, 2003). This contrasts to the condition in most theropods, in which there is a gap between the crest and the lateral margin of the brevis fossa (Carrano & Sampson, 2008). The contact between the ilium and ischium seems to have a peg-and-socket morphology which is typical of abelisauroids (Carrano & Sampson, 2008), and is also present in the carcharodontosaurids *Giganotosaurus* Coria & Salgado, 1995 and *Mapusaurus* Coria & Currie, 2006 (Coria & Currie, 2006; Canale, 2010). The obturator process is only represented by its base, and it seems different from the triangular shape present in *Allosaurus* and *Tyrannosaurus*. Its lateral surface exhibits a distally curved ridge which appears to coincide with the distally pointed process of the obturator process (Figures 2B,C). The latter process continues distally into a narrow ridge, with strong muscle scars, that extends to middle of the ischial shaft (Figures 2B,C). This ridge probably corresponds to the attachment site of the *puboischiotibialis* muscle (PIT), which arises on the anterolateral surface of the ischium, over the proximal end of the obturator process, and inserts on the proximomedial aspect of the tibia. The PIT aids in adducting the leg (Hutchinson & Gatesy, 2000).

The ischiadic peduncle is broad anteroposteriorly and narrow lateromedially, whereas the opposite condition is present in *Tyrannosaurus*. MPMA 27-0001-02 lacks an ischial tuberosity as observed in *Tyrannosaurus*, *Sinraptor* Currie & Zhao, 1994, and *Elaphrosaurus* Janensch, 1920 (Brochu, 2003). Distal to this point, the anterior surface of the bone is well excavated, with this excavation being distally bounded by the fused distal feet (Figure 2A). The posterior surface of the ischial shaft is mediolaterally convex along most of its length (Figure 2D). The ischia are narrow in posterior view (18 cm wide taken approximately at the level of the antitrochanter, and 7 cm immediately proximal to the distal foot). The fusion of the pelvic elements observed in the Brazilian specimen is characteristic of abelisauroids (Coria *et al.*, 2006; Carrano & Sampson, 2008) and coelophysoids (Tykoski & Rowe, 2004) and is present among others in *Carnotaurus*, *Aucasaurus* Coria, Chiappe & Dingus, 2002, *Eoabelisaurus* Pol & Rauhut, 2012 and *Elaphrosaurus*. The distal foot must have been prominent, although possibly less so than that of *Carnotaurus*, forming a strongly acute angle with the anterior margin of the ischial shaft. Distal foot expansion is a feature also present in *Eoabelisaurus* and *Elaphrosaurus* as well as in *Deltadromeus* Sereno *et al.*, 1996 and *Neovenator* Hutt, Martill & Barker, 1996 (Carrano & Sampson, 2008), in basal tetanurans (e.g. *Allosaurus*) the distal end of the ischium is barely expanded and rounded, whereas in coelurosaurs (e.g. *Tyrannosaurus*), the distal foot is reduced (Rauhut, 2003).

In MPMA 08-0016-95 only the anterior third of the axis is preserved, including the odontoid process, the axial intercentrum, and the anterior portion of the centrum and neural canal (Figure 4). The axis is known in the abelisaurids *Carnotaurus* (Bonaparte *et al.*, 1990), *Majungasaurus*

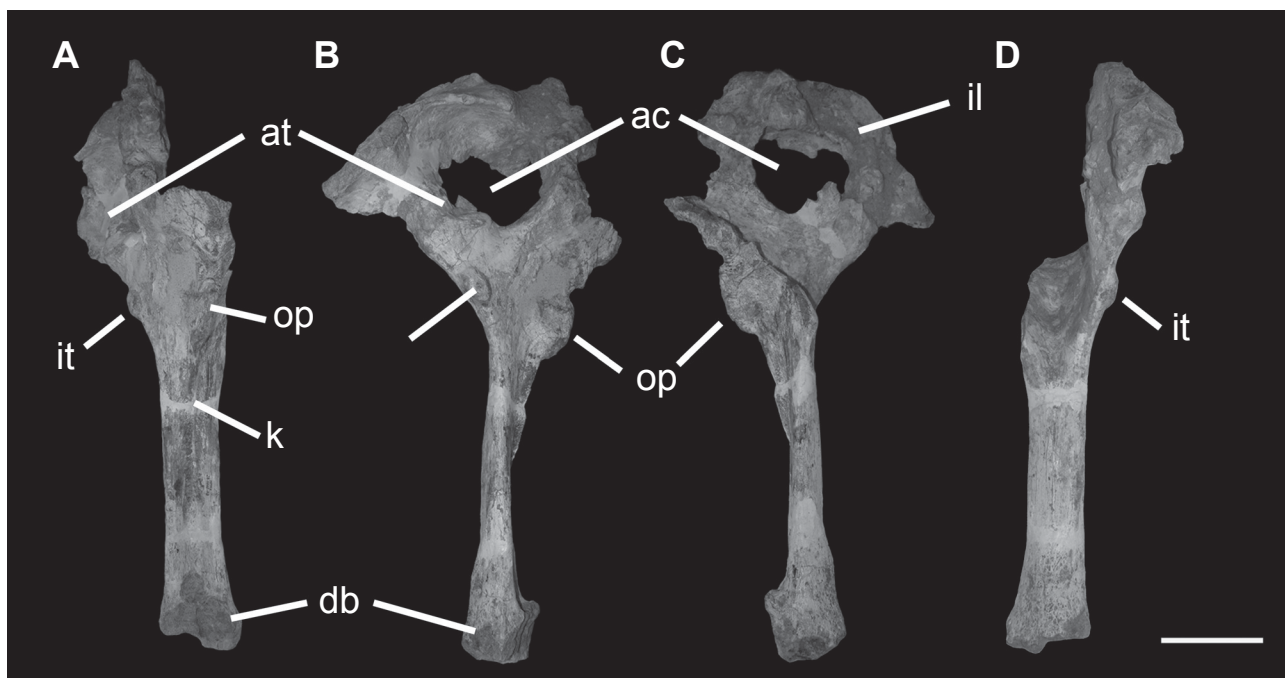


Figure 2. Abelisauroid partial pelvis MPMA 27-0001-02 in (A) anterior, (B) right lateral, (C) left lateral, and (D) posterior views. **Abbreviations:** ac, acetabulum; at, antitrochanter; db, distal boot; il, ilium; it, ischiadic trochanter; k, keel; op, obturator process. Scale bar = 10 cm.



Figure 3. Abelisauroid partial pelvis MPMA 27-0001-02 (A-C) and fused ischia of *Carnotaurus sastrei* (MACN-PV-CH 894; D-F) in (A,D) anterior, (B,E) right lateral, and (C,F) posterior views, respectively. Not to scale.

Lavocat, 1955 (O'Connor, 2007), and *Rahiolisaurus* Novas *et al.*, 2010 (Novas *et al.*, 2010). MPMA 08-0016-95 is similar to the axes of *Carnotaurus*, *Ceratosaurus* and *Masiakasaurus* (Carrano *et al.*, 2011) in that the odontoid process surpasses the anterior edge of the axial intercentrum (Figure 4), whereas in *Majungasaurus*, *Rahiolisaurus* and *Composuchus* Matley & Huene, 1933 (Novas *et al.*, 2004), the anterior edge of the axial intercentrum is reached but not exceeded by the odontoid process (Méndez, 2010). The

axial intercentrum and the preserved part of the centrum are firmly fused. The axial intercentrum is wide and almost flat ventrally, as in *Ceratosaurus*, *Masiakasaurus*, *Majungasaurus*, *Rahiolisaurus* and *Carnotaurus*. A slight ventral keel is present in the preserved part of the centrum, as in *Carnotaurus*, *Majungasaurus*, *Masiakasaurus*, whereas in *Ceratosaurus* the ventral keel is much pronounced. The parapophyses are slightly pronounced, located on the anteroventral border of the centrum (Figure 4A), as also

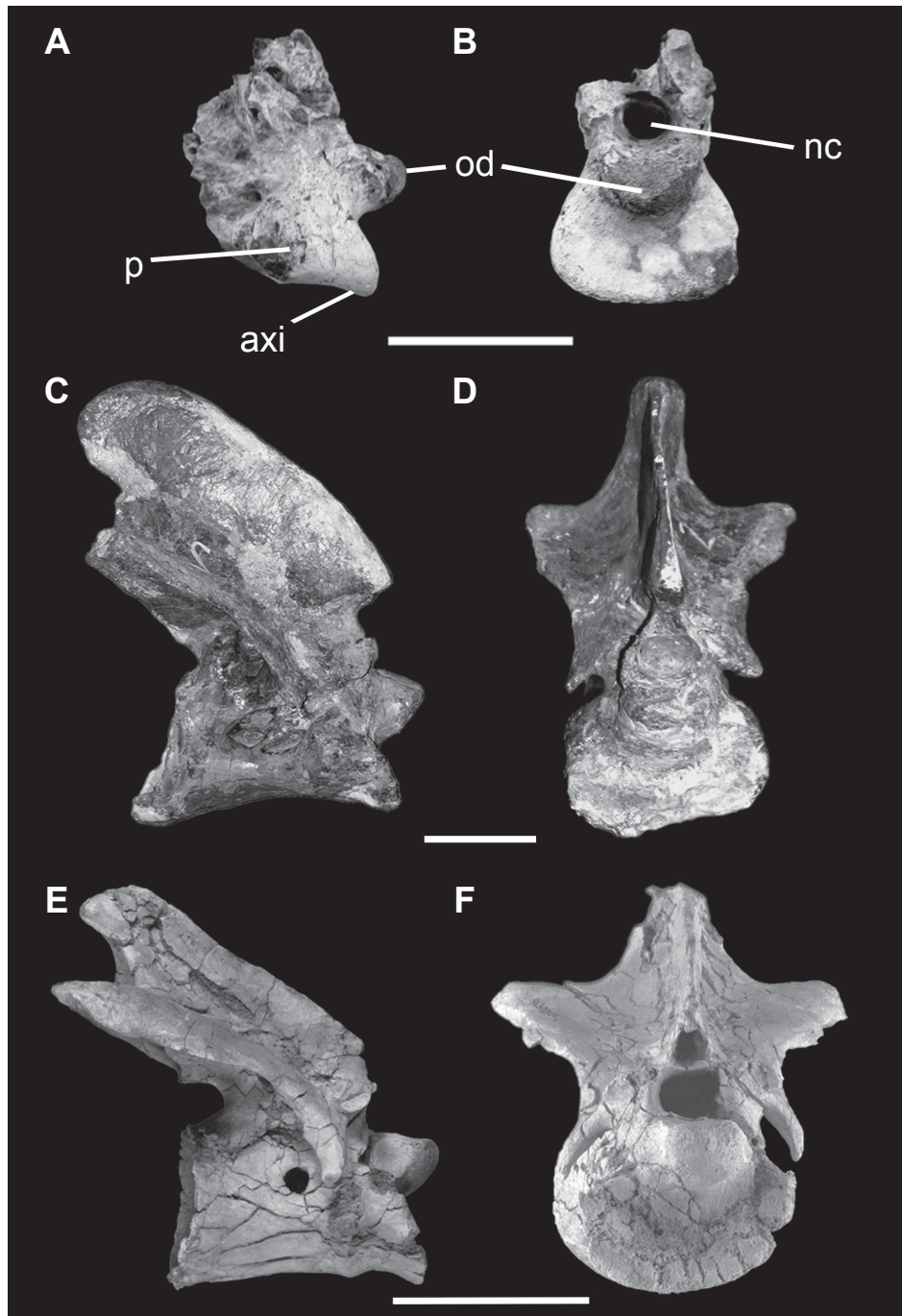


Figure 4. A-B, Abelisauroid axis MPMA 08-0016-95; C-D, *Carnotaurus sastrei* (MACN-PV-CH 894); E-F, *Majungasaurus crenatissimus* (UA 8678). A, C, E in right lateral and B, D, F in anterior views, respectively. **Abbreviations:** axi, axial intercentrum; nc, neural canal; od, odontoid; p, parapophysis. Scale bars: A-B = 10 cm; C-F = 5 cm

occurs in *Carnotaurus*, whereas in *Majungasaurus* they are dorsally placed (Figure 4E). Although broken, the preserved part of the centrum has a foramen that, based on its location and shape, could correspond to a pneumatic foramen. This type of pneumatic opening is also present in the axis of the abelisauroid *Masiakasaurus* (Carrano *et al.*, 2002, 2011) and the abelisauroids *Carnotaurus* (Bonaparte *et al.*, 1990; Méndez, 2014), *Majungasaurus* (O'Connor, 2007), *Rahiolisaurus* (Novas *et al.*, 2010), and *Composuchus* (Novas *et al.*, 2004)

The right fibula, MPMA 08-0069-13, is almost completely preserved (Figure 5). The bone is 40 cm in total length, almost 10 cm in proximal width, and 5 cm in transverse length. The proximal end has a marked anteroposterior expansion. It shows a rounded posterior margin and a more angular anterior margin (Figures 5A,D). This is also observed in the abelisauroids *Xenotarsosaurus* Martínez *et al.*, 1986 (Martínez *et al.*, 1988), *Majungasaurus* (Carrano, 2007) and *Masiakasaurus* (Carrano *et al.*, 2002, 2011) as well

as in *Ceratosaurus* (Madsen & Welles, 2000) *Neovenator* (Brusatte *et al.*, 2008) and *Tyrannosaurus* (Brochu, 2003). In *Allosaurus* this expansion is less developed (Madsen, 1976). The proximal end is transversely thicker than the distal one (Figures 5B,E). This is similar to that observed in *Majungasaurus*, whereas in *Ceratosaurus* this difference is smaller. In *Neovenator* both ends are nearly equal in size and proportions (Brusatte *et al.*, 2008). The fibular shaft is straight, although the distal end has a slight medial curvature. This is similar to those observed in the abelisaurids *Majungasaurus*, *Xenotarsosaurus*, *Rahiolisaurus*, the noosaurid *Masiakasaurus* and *Ceratosaurus*. However, this is not observed in the fibular morphology of *Allosaurus*, *Tyrannosaurus*, and *Neovenator* in which the distal end is not curved. A well-developed iliofibularis tubercle is observed in both lateral and medial view (Figures 5A,D), similar to that observed in the abelisaurids *Majungasaurus* (Carrano, 2007), *Rahiolisaurus*, *Xenotarsosaurus* (Martínez *et al.*, 1988) and the abelisauroid K27/620 (Novas *et al.*, 2004). This process

is present but less developed in *Ceratosaurus* (Gilmore, 1920) and the abelisauroids *Berberosaurus* Allain *et al.*, 2007 (Allain *et al.*, 2007) and *Masiakasaurus* (Carrano *et al.*, 2011). In *Allosaurus* (Madsen, 1976) and *Neovenator* (Brusatte *et al.*, 2008) this process is barely visible (Figure 6). In anterior view this process shows a very rough surface, for the insertion of the iliofibularis muscle (Figure 5B). The distal end of the fibula shows a slight anterior expansion. This feature is similar to that present in *Majungasaurus*, *Berberosaurus* and *Tyrannosaurus*, and is more developed in *Allosaurus* and *Neovenator*. In *Ceratosaurus*, the distal end of the fibula exhibits an anterior and posterior expansion, whereas in *Pycnonemosaurus* this expansion is not observed (Kellner & Campos, 2002). In medial view, most of the proximal expansion is occupied by a fibular fossa which has an inverted teardrop shape (Figure 5D). This fossa is similar in shape and size to the one described in the abelisaurids *Majungasaurus*, *Rahiolisaurus*, *Xenotarsosaurus* and the abelisauroid K27/620. In *Tyrannosaurus* and *Neovenator*

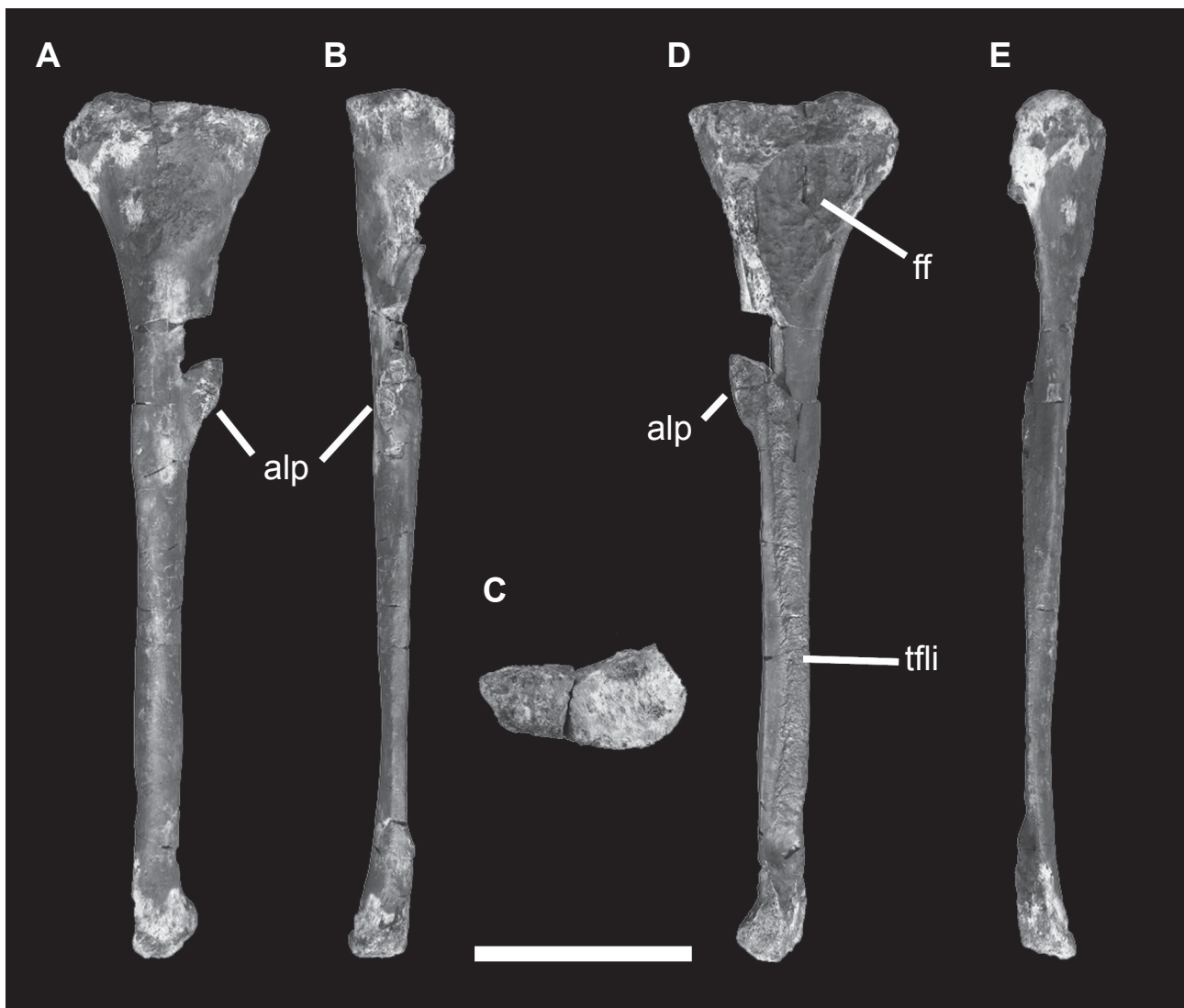


Figure 5. Abelisauroid right fibula MPMA 08-0069-13 in (A) lateral, (B) anterior, (C) dorsal, (D) medial, and (E) posterior views. **Abbreviations:** alp, anterolateral process; ff, fibular fossa; tfli, tibiofibular ligament insertion. Scale bar = 10 cm.

is less developed and is even more reduced in *Allosaurus*, *Ceratosaurus* and *Berberosaurus*. On the other hand, the fibular fossa has an extreme development in the noosaurid *Masiakasaurus* (Figure 6). The fibular shaft exhibits a strong and broad roughness area corresponding to the tibiofibular interosseous ligament insertion (Figure 5D), as seen in *Majungasaurus*, *Rahiolisaurus*, *Xenotarasaurus*, *Masiakasaurus* and *Berberosaurus*. This roughness area is less developed in *Neovenator* and *Tyrannosaurus* (Brochu,

2003), whereas in *Ceratosaurus* and *Allosaurus* the rugosity is nearly absent, and in the latter a deep concavity along the shaft is present (Madsen, 1976).

CONCLUSIONS

The rocks exposed at the Monte Alto and Ibirá municipalities have yielded abundant remains of titanosaur sauropods (Bertini & Campos, 1987; Kellner & Azevedo, 1999; Bertini *et al.*, 1999a,b, 2001; Santucci & Bertini, 2001; Candeiro *et al.*, 2006a; Martinelli *et al.*, 2011). However, this is the first time in which abelisauroid bone remains have been reported from these localities. Abelisaurid theropods have already been documented in the Bauru Group on the basis of numerous isolated teeth and bones (Bertini, 1996; Bittencourt & Kellner, 2002; Kellner & Campos, 2002; Candeiro *et al.*, 2002, 2004, 2006a,b; Novas *et al.*, 2008; Machado *et al.*, 2013) but never from the localities listed above.

The isolated fossils described here are referable to Abelisauroidea due to following characters: fusion of pelvic elements, supraacetabular crest continuous with the brevis shelf, peg-and-socket morphology of the contact between ilium and ischium, well development of the distal foot expansion of ischium, axial pneumatic features, general morphology of the axial intercentrum, the remarkable development of the anterolateral process for insertion of the iliofibularis muscle in the fibula, the morphology of the fibular fossa, and the presence of a strong roughness on the medial surface of the fibular shaft. According to their size (all specimens correspond to medium-sized individuals), possibly would be referable to Abelisauridae although ischia and axis might belong to some kind of large noosaurid. Because the bones come from different sites within the basin, they certainly represent three different individuals. No autapomorphies were identified in the available elements, so the materials cannot be referred to a particular genus or species within Abelisauroidea.

Discoveries made in the Monte Alto and Ibirá regions demonstrate that during the Late Cretaceous abelisauroids inhabited along with maniraptorans (Bertini *et al.*, 1997; Bertini & Franco-Rosas, 2001; Franco-Rosas, 2001, 2002; Novas *et al.*, 2005; Machado *et al.*, 2008), megaraptorans (Méndez *et al.*, 2012), and possibly carcharodontosaurids (Azevedo *et al.*, 2013). Based on the relative abundance of carnivorous dinosaurs, abelisaurids were probably the most numerous theropods in the Bauru Basin as was also the case in Late Cretaceous paleoecosystems in most other parts of Gondwana (e.g. Patagonia, Madagascar, India; Bonaparte, 1991; Novas *et al.*, 2008, 2010; Canale *et al.*, 2009).

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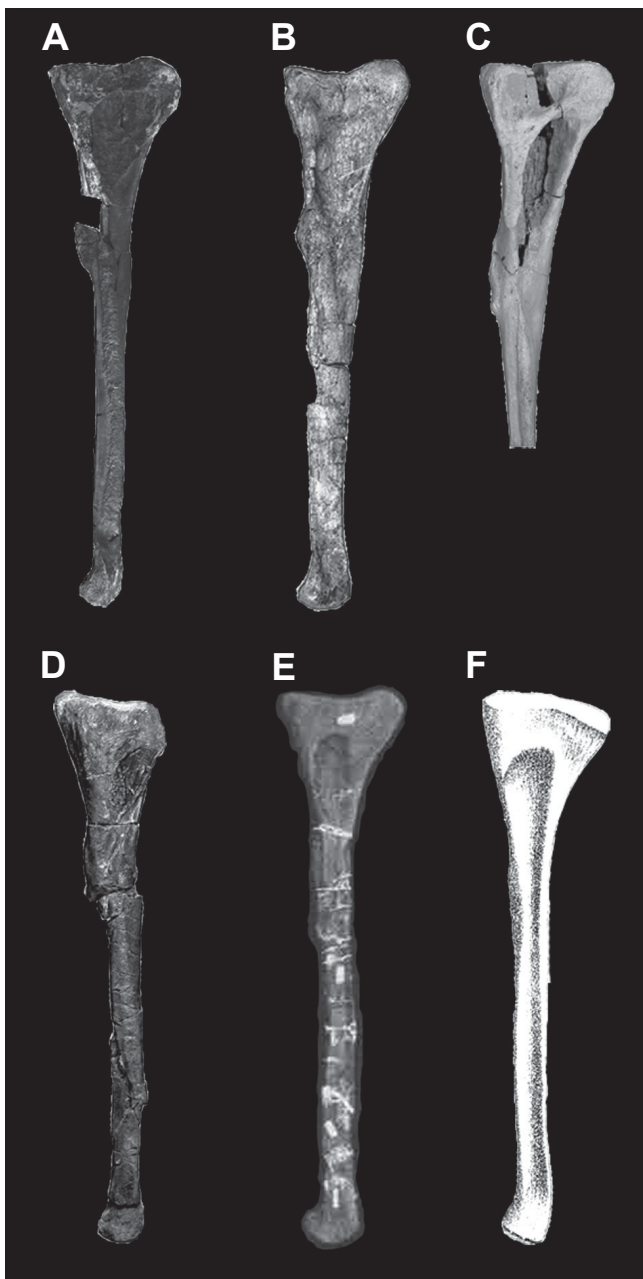


Figure 6. A, Abelisauroid fibula MPMA 08-0069-13; B, *Majungasaurus crenatissimus* (modified from Carrano, 2007); C, *Masiakasaurus knopfleri* (modified from Carrano *et al.*, 2011); D, *Berberosaurus liassicus* (modified from Allain *et al.*, 2007); E, *Neovenator salerii* (modified from Brusatte *et al.*, 2008); F, *Allosaurus fragilis* (modified from Madsen, 1976), in medial view. B, D, E, and F are left fibulae inverted. Not to scale.

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