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A NEW TITANOSAUR FROM WESTERN SÃO PAULO STATE, UPPER CRETACEOUS BAURU GROUP, SOUTH-EAST BRAZIL

by RODRIGO MILONI SANTUCCI *and* REINALDO J. BERTINI

IGCE-UNESP, São Paulo State University, Av. 24-A, Nº 1515, Rio Claro 13506-900, CP 178, Brazil; e-mails: rmilonis@rc.unesp.br; rbertini@rc.unesp.br

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Abstract: Material from a new titanosaur from the Bauru Basin (Bauru Group), Brazil is described and compared with well-known titanosaurs. *Adamantisaurus mezzalirai* gen. et sp. nov. is based on six articulated anterior caudal vertebrae and two haemapophyses collected from the Adamantina Formation, which is considered to be Campanian–Maastrichtian? in age. *Adamantisaurus mezzalirai* is characterized by the following combination of characteristics: anterior caudal vertebrae with straight or slightly backwardly-projecting neural spines with strongly expanded distal ends, stout prespinal lamina, very wide pre- and postzygapophyseal articular facets, and concave postzygapophyseal articular facets on anterior caudal vertebrae. Although our cladistic analysis has produced equivocal results, *Adamantisaurus mezzalirai* shares with DGM 'Series B' (Peirópolis titanosaur) and *Aeolosaurus* the presence of postzygapophyses with concave articular facets, and shares with DGM 'Series B' the presence of laterally expanded neural spines and stout prespinal lamina. Additionally, *A. mezzalirai* shares with DGM 'Series' C (other titanosaur from Peirópolis) the presence of short neural spines.

Key words: Titanosaurs, Upper Cretaceous, Bauru Basin, Adamantina Formation, Brazil.

THE Bauru Group is a well-known continental Cretaceous dinosaur-bearing unit in Brazil, where several vertebrate remains have been uncovered, including fishes, frogs, turtles, lizards, crocodyliforms, sauropod and theropod dinosaurs, and mammals (Mezzalira 1989; Bertini *et al.* 1993). Sauropods are the most common dinosaurs, generally represented by unarticulated but well-preserved titanosaur teeth and bones. Despite the large quantity of sauropod bones, almost none has been described. Kellner and Campos (2000) pointed out the limited number of publications not only on sauropods from Bauru Group but also on Brazilian dinosaurs generally.

The first titanosaur from the Bauru Group was uncovered at the beginning of the twentieth century. It is composed of a procelic caudal vertebra from the Adamantina Formation near the city of Colina in São Paulo State. This specimen was described by Pacheco (1913), who misinterpreted it as a crocodile vertebra. Huene (1929, p. 88) later attributed this same vertebra to *Titanosaurus* cf. *T. australis*; however, the material lacks diagnostic features and therefore cannot be regarded as any specific titanosaur taxon. Remarkable titanosaur remains were also recovered in 1947–48: the vertebral series (cervical, DGM 1487-R, 'Series A'; dorsal, DGM 1488-R, 'Series B'; and caudal, DGM 1490-R, 'Series C') from Peirópolis, Uberaba in the state of Minas Gerais (Price 1955). These articulated series from Bauru Group were described in detail by Powell (1987, 2003), who did not assign a formal name to them.

Arid and Vizotto (1971) formally described the first titanosaur from the Bauru Group, *Antarctosaurus brasiliensis* from the Adamantina Formation. Unfortunately this species was based on very fragmentary and non-diagnostic bones (incomplete right humerus, incomplete left femur, and one dorsal centrum). Another taxon, *Gondwanatitan faustoi* (Kellner and Azevedo 1999), was described from the Adamantina Formation in the city of Álvares Machado based on a relatively complete skeleton lacking a skull. Additionally, Campos and Kellner (1999) described some pelves from the Marília Formation (Peirópolis) including part of the vertebral series described by Powell (1987, 2003). Azevedo and Kellner (1998) reported a small, well-preserved osteoderm from Peirópolis. This titanosaur dermal bone was the first to have been reported from Brazil. In a recent contribution, Medeiros (2002) noted a fragmentary anterior caudal vertebra recovered from Alcântara Formation, São Luís-Grajaú Basin, Maranhão state, regarded as Cenomanian in age. He considered it to be from a saltasaur. If this assignment is confirmed, it will change not only the geographical

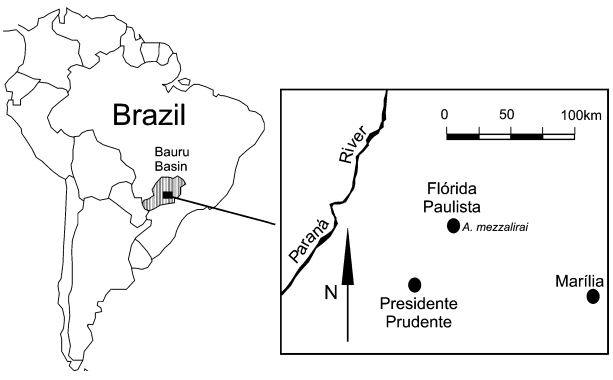
distribution of the saltasaurs, but also their chronological range.

The titanosaur remains described in this paper were collected in 1958 from deposits of the Adamantina Formation near Flórida Paulista, in south-western São Paulo State (Text-fig.1), during the construction of the railway between Adamantina and Irapurú. At the same locality some titanosaur teeth (Mezzalira 1989) and a nearly complete turtle (S. Mezzalira, pers. comm. 2000) were also collected. The turtle has not yet been formally described. The titanosaur remains recovered from Flórida Paulista comprise six well-preserved and articulated anterior caudal vertebrae, two haemapophyses and an isolated femur. All of the material is housed at the Valdemar Lefèvre Geological Museum, Água Branca Park, city of São Paulo. These remains were first mentioned in the literature by Mezzalira (1959). Below, we compare the caudal vertebrae and haemapophyses with well-known titanosaurs and describe a new species, *Adamantisaurus mezzalirai*.

GEOLOGICAL SETTING

The Bauru Group is located in south-east Brazil, distributed through the states of Goiás, Mato Grosso do Sul, Minas Gerais and São Paulo, and, with the Caiuá Group, forms the Bauru Basin, which is approximately 350,000 km^2 in area (Fernandes and Coimbra 2000).

Despite the fact that the Bauru Group is one of the most studied continental Cretaceous units in Brazil, there is no consensus about its stratigraphic subdivision. The most common stratigraphic sequence used in recent papers includes the Araçatuba, Adamantina, Uberaba and Marília formations (Fernandes and Coimbra 1994, 2000; Fulfaro and Perinotto 1996). The Adamantina and Uberaba formations are interpreted as representing fluvial braided systems supplied by the alluvial systems of the Marília Formation (Fernandes and Coimbra 2000). The Araçatuba Formation represents a lake system in the central portion of the Bauru Basin (Fernandes and Coimbra 1996). The deposits of the Adamantina Formation are composed of sequences of massive reddish sandstones that gradually change to beige siltstones. Locally, the sandstones are cross-stratified (Fernandes and Coimbra 2000).



TEXT-FIG. 1. Map showing the location of the fossil site.

Different ages have been proposed for the Bauru Group. Since palynological evidence is not available, most age estimates have relied on the distribution of ostracods and titanosaurs. The most recent papers argue for a late Campanian/early Maastrichtian age (Bertini *et al.* 2000; Gobbo-Rodrigues *et al.* 2000; Santucci and Bertini 2001). This has been suggested for the upper Adamantina Formation near Monte Alto and the lower Marília Formation (Serra da Galga Member) in Uberaba (Bertini *et al.* 2000; Santucci and Bertini 2001). Gobbo-Rodrigues *et al.* (2000) proposed the same chronological interval for the Araçatuba, Adamantina and Marília Formations based on ostracods, whereas Dias-Brito *et al.* (2001) suggested a Turonian/Santonian age for the Adamantina Formation on the basis of charophyte and ostracod assemblages.

Despite these determinations, there are currently no useful fossil data on which to date the Flórida Paulista locality. We assume a late Campanian/early Maastrichtian age for the site because this is the age recently proposed most often for localities for the Adamantina Formation in São Paulo State (Bertini *et al.* 2000; Gobbo-Rodrigues *et al.* 2000).

Abbreviations. MUGEO, Museu Geológico Valdemar Lefèvre, São Paulo; DGM, Departamento Nacional da Produção Mineral, Rio de Janeiro.

SYSTEMATIC PALAEONTOLOGY

ARCHOSAURIA Cope, 1869
SAURISCHIA Seeley, 1888
SAUROPODA Marsh, 1878
TITANOSAURIFORMES Salgado *et al.*, 1997
TITANOSAURIA Bonaparte and Coria, 1993

Genus ADAMANTISAURUS gen. nov.

Derivation of name. From the Adamantina Formation in western São Paulo State from which this specimen was collected, and *saurus*, Greek for lizard.

Diagnosis. As for the species.

Adamantisaurus mezzalirai sp. nov.
Plate 1; Text-figure 2

Derivation of name. In honour of Dr Sérgio Mezzalira, the researcher who collected and first mentioned the remains in the literature.

Holotype. MUGEO 1282 (Pl. 1, figs 1–8; Text-figure 2A–H), six articulated anterior caudal vertebrae, the first of which is probably the second caudal vertebra, and MUGEO 1289 and 1295 (Pl. 1, figs 9–10; Text-figure 2I–J), two haemapophyses. As noted above, the material is housed in the Valdemar Lefèvre Museum, São Paulo. Mezzalira (1959, 1966, 1989) referred to it as Titanosauridae indet. However, he did not prepare a detailed description or propose a new species. Santucci and Bertini (2000) considered the remains as belonging to a new species.

Type horizon and locality. Adamantina Formation, Cretaceous, Senonian (Campanian–Maastrichtian?), near the city of Flórida Paulista (railway between Adamantina and Irapurú), São Paulo, Brazil (Text-fig. 1).

Diagnosis. Titanosaur characterized by the following: anterior caudal vertebrae with straight or slightly backward-projecting neural spines, with distal end strongly expanded laterally, stout prespinal lamina, pre- and postzygapophyses with very wide articular facets; concave postzygapophyseal articular facets on anterior caudal vertebrae.

Description. Comparisons with DGM 1490-R, 'Series C' from Peirópolis, which preserves a relatively complete caudal sequence, indicate that the six articulated caudal vertebrae correspond approximately to second through seventh caudal vertebrae.

The first of these (Pl. 1, fig. 1; Text-fig. 2A) is strongly procoelous, although it is the least procoelous of any in the series. The neural spine is relatively short and slightly inclined backwards with a relatively wide base and a strong spinoprezygapophyseal lamina that extends halfway up the neural spine. One of the most distinctive features of this series is the strong lateral expansion at the distal end of the neural spine.

In anterior view the neural spine has a wide, robust prespinal lamina. In posterior view there is a postspinal lamina that extends to the top of the spine to form a protuberance on the posterodorsal margin; however, this lamina is less developed than the prespinal lamina.

The neural arch is wide both anteroposteriorly and laterally, almost occupying the entire extension of the vertebral centrum, but the dorsal portion of the neural arch is thinner than its base. The articular facets of the prezygapophyses are wide and elliptical in shape. The postzygapophyses are located near the base of the neural spine and are taller than wider. They are supported by robust spinopostzygapophyseal laminae. On the lateral margins of the neural spine there is a wide lateral fossa just in front of the postzygapophyses.

The transverse processes are robust and directed horizontally backward with a large attachment area to the lateral face of the centrum. The centrum is relatively short with the posterior articulation rounded in transverse section with a small depression on its dorsal margin. Both ventral and lateral margins are anteroposteriorly concave.

The second vertebra, probably the third in the caudal series (Pl. 1, figs 2–4; Text-fig. 2B–D) is well preserved and very similar to the previous one; however, the procoely is better developed and the centrum is wider, with a rounder transverse section. The neural spine is lower, less posteriorly directed, and has a less-developed lateral fossa than the preceding vertebra. The neural arch is considerably lower than in the previous vertebra, but equally wide. Unlike the previous vertebra, the prezygapophyses are projected more forward than upward and their articular facets are also slightly wider. The spinoprezygapophyseal laminae are completely preserved, as are the prespinal lamina, which are less developed than in the preceding vertebra. The postspinal lamina is wider and more developed than in the previous vertebra.

The third vertebra (Pl. 1, figs 5–6; Text-fig. 2E–F) is slightly deformed, but is very similar to the preceding vertebra. The main differences are in the neural spine, which is shorter and more posteriorly directed; however, it does not have lateral fossae. The postzygapophyseal articular facets are dorsoventrally concave in posterior view. The left transverse process is directed posterolaterally, while the right one is just directed laterally, but it is not possible to determine whether one side is deformed, or if the asymmetry is a morphological anomaly.

The fourth vertebra (Pl. 1, fig. 7; Text-fig. 2G), probably the fifth caudal, is similar to the third, with the same type of morphological variation in the transverse processes. However, the neural arch is lower and the neural spine is narrower laterally than previous vertebra. It also has prezygapophyses that are longer and more anteriorly projecting than in the third vertebra. There are incipient depressions on posterior face for the haemapophyseal articulation.

The fifth vertebra (Pl. 1, fig. 8; Text-fig. 2H) is similar to the preceding one, but both transverse processes are directed posterolaterally.

The final vertebra, probably the seventh caudal, lacks a neural spine, postzygapophyses and transverse processes. In comparison to the other vertebrae, it possesses a longer centrum with a less-rounded transverse section. The neural arch is relatively low and the prezygapophyses are more developed.

A feature common to all the vertebrae is the presence of small pits, principally in the lateral faces of the first five.

Only one haemapophysis is completely preserved (Pl. 1, fig. 9; Text-fig. 2I); the other (Pl. 1, fig. 10; Text-fig. 2J) does not possess part of the left proximal articulation. Both are long, with a typical Y shape, and are flattened laterally at the distal end.

DISCUSSION

Mezzalira (1966, 1989) associated a left femur (approximately 1·1 m in length) with this caudal series (MUGEO 1282, 1289, 1295). He informed us (pers. comm. 2000) that the femur was collected by workers who built the railway line between Adamantina and Flórida Paulista. The vertebrae were collected subsequently from the same location, but there is no certainty about the association. Due to the small size of the femur and its different state of preservation when compared to the vertebrae, we believe that it belonged to a different individual. Since it

is common to find isolated bones from two or more species together in deposits of the Adamantina Formation, we did not include this femur in the holotype description and have not referred it to the same species.

We characterize the new species by comparing its remains with well-known Titanosauria. Because only anterior caudal vertebrae are preserved, its remains have been compared with species where caudal vertebrae are available. Upchurch (1998) provided an extensive systematic analysis of sauropods, which includes some titanosaur taxa. Unfortunately, most of the synapomorphies he listed for Titanosauroidea and Titanosauridae cannot be assessed in *Adamantisaurus mezzalirai*. The presence of dorsoventrally-compressed middle caudal centra, suggested by Upchurch (1998) as one of the seven synapomorphies uniting Titanosauridae, also occurs in the most distal caudal preserved in *A. mezzalirai*. To the extent to which we are able to make comparisons, *A. mezzalirai* has two of the synapomorphies proposed by Wilson (2002) for Titanosauria: procoelous anterior caudal centra and absence of forked chevrons. Additionally, *A. mezzalirai* shows one synapomorphy for Opisthocoelicaudiinae; namely the first caudal neural arch with coel on lateral aspect of the neural spine. However, the most anterior caudal vertebra preserved in *A. mezzalirai* probably corresponds to the second one in the caudal series. When compared to the data presented by Salgado *et al.* (1997) in a systematic analysis of the largest number of titanosaurs to date, *A. mezzalirai* possesses only one titanosaurid synapomorphy: strongly procoelous anterior caudal vertebrae with 'ball and socket' articular faces that differ from the slightly procoelous condition in basal titanosaurs, such as *Andesaurus delgadoi* (Calvo and Bonaparte 1991) and *Malawisaurus dixeyi* (Jacobs *et al.* 1993). Jacobs *et al.* (1993) considered the anterior caudal vertebrae of *M. dixeyi* as strongly procoelous; however, this state is considered here to be less developed than in *A. mezzalirai*. The strongly procoelous state also differentiates *A. mezzalirai* from *Opisthocoelicaudia skarzynskii*, which has opistocoelic/amphiplatyan caudal vertebrae (Borsuk-Bialynicka 1977). Because only the anterior caudal vertebrae are available in *A. mezzalirai*, the other synapomorphies proposed by Salgado *et al.* (1997) for Titanosauridae cannot be assessed. It is excluded from the Saltasaurinae by the lack of depressed anterior caudal centra (Salgado *et al.* 1997), and in having pre- and postzygapophyses with more horizontally directed articular surfaces in the anterior elements (Sanz *et al.* 1999) and well-developed spinoprezygapophyseal laminae (or crest) on the caudal vertebrae. Additionally, it has no centra with ventral crests on the anterior caudal vertebrae, as in *Saltasaurus loricatus* (Powell 2003) and *Rocasaurus muniozi* (Salgado and Azpilicueta 2000). The absence of hyposphene-hypantrun on the caudal vertebrae distinguishes it from *Epachthosaurus* (Martínez *et al.* 1989).

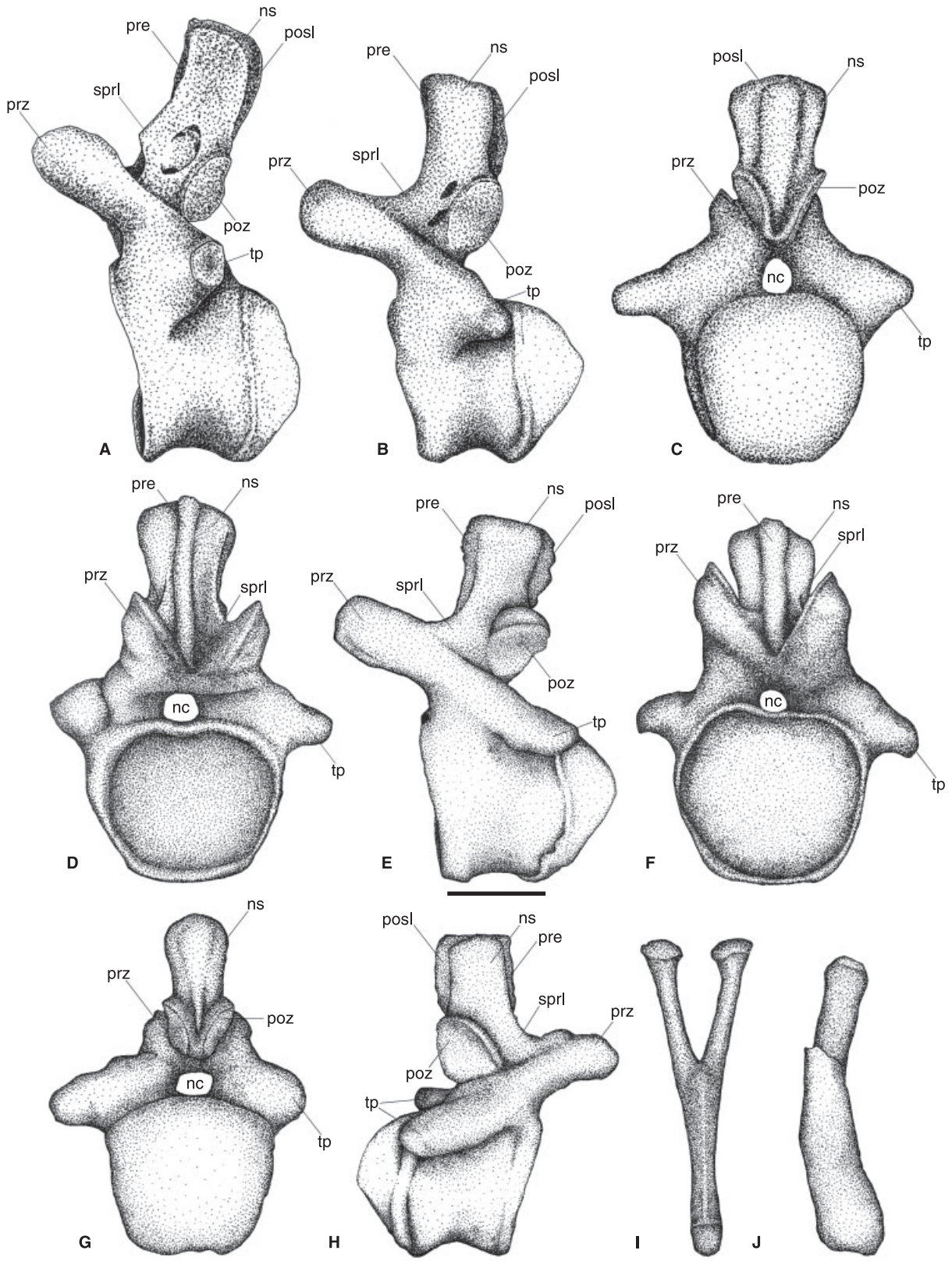
Adamantisaurus mezzalirai possesses short neural spines and neural arches that are more anteriorly positioned on the anterior caudal vertebrae than those of *Titanosaurus colberti* (Jain and Bandyopadhyay 1997). Unfortunately, the available caudal vertebrae of *Lirainosaurus astibiae* are more anterior or more posterior than those preserved in *A. mezzalirai*. As far as they can be compared, *L. astibiae* differs in that it has a prominent eccentric posterior articular facet in anterior caudal vertebrae (Sanz *et al.* 1999), and the anterior caudal centrum is relatively longer. A less developed spinoprezygapophyseal lamina distinguishes *A. mezzalirai* from *Rapetosaurus krausei*, in which the lamina is strongly developed in the anterior caudal vertebrae (Curry Rogers and Forster 2001). Although there are no caudal vertebrae of the holotype of *Alamosaurus sanjuanensis*, the anterior caudal vertebrae attributed to it by Gilmore (1946) differ from those of *A. mezzalirai* in having shorter prezygapophyses, a thinner prespinal lamina and shorter centra.

Despite the lack of anteriorly-directed neural spines on the anterior and middle caudal vertebrae, *A. mezzalirai* shares with *Aeolosaurus* lateral expansions on the distal portion of the neural spines with robust prespinal laminae. These features are not available in *Gondwanatitan faustoi*, but this differs from *A. mezzalirai* in its possession of a heart-shaped caudal centrum in cross-section (Kellner and Azevedo 1999). The caudal vertebrae of *A. mezzalirai* are more similar to DGM 1488-R, 'Series B', 'Peiropólis titanosaur', in that they have laterally expanded neural spines, stout prespinal lamina, and prezygapophyses with wide articular facets, but *A. mezzalirai* has more laterally expanded neural spines and prezygapophyseal articular facets that are wider. *A. mezzalirai* also shares with DGM 1488-R, 'Series B', and *Aeolosaurus* the presence of postzygapophyses with concave articular facets. DGM 1490-R, 'Series' C, one of the most complete and well-preserved titanosaur caudal series ever found,

EXPLANATION OF PLATE 1

Figs 1–10. *Adamantisaurus mezzalirai* gen. et sp. nov., holotype, Upper Cretaceous Adamantina Formation. 1–8, anterior caudal vertebrae (MUGEO 1282). 1, second? caudal vertebra, left lateral view. 2–4, third? caudal vertebra, left lateral, posterior and anterior views. 5–6, fourth? caudal vertebra, left lateral and anterior views. 7, fifth? caudal vertebra, posterior view. 8, sixth? caudal vertebra, right lateral view. 9–10, haemapophyses (MUGEO 1289 and 1295) in posterior and left lateral views. All × 0·18.

SANTUCCI and BERTINI, *Adamantisaurus*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differs from *A. mezzalirai* in having more slender prezygapophyses and more posteriorly directed neural spines. On the other hand, the neural spines of *A. mezzalirai* are short like those in DGM 1490-R, 'Series' C.

Adamantisaurus mezzalirai was scored and inserted in the data matrix published by Salgado *et al.* (1997). A new analysis was performed by us using the same protocol and software. The strict consensus tree contained a polytomy at the Titanosauriformes node, where almost all taxa were collapsed except for *Alamosaurus sanjuanensis*, *Neuquensaurus australis* and *Saltasaurus loricatus*. This leaves the phylogenetic relationship of *A. mezzalirai* within Titanosauria unclear.

CONCLUSIONS

After the break-up of Gondwana, the continental South American fauna experienced a period of isolation at the end of the Cretaceous Period. Santucci and Bertini (2001) showed that some Bauru Group titanosaurs are more related to Argentinean titanosaurs than those of other continents, principally through the presence of the genus *Aeolosaurus* in Late Cretaceous deposits. Although our cladistic analysis produced inconclusive results, *Adamantisaurus mezzalirai* shares with DGM 1488-R, 'Series B' and *Aeolosaurus* the presence of postzygapophyses with concave articular facets, and with DGM 1488-R, 'Series B' the presence of laterally expanded neural spines and a stout prespinal lamina, albeit not to the same degree. Additionally, *A. mezzalirai* shares with DGM 1490-R, 'Series' C the presence of short neural spines.

The cladistic analyses of Salgado *et al.* (1997) and Upchurch (1998) showed that Titanosauridae, a clade composed of more derived titanosaurs, is well-supported by eight and seven synapomorphies, respectively. On the other hand, Wilson and Upchurch (2003) pointed out that the name Titanosauridae, as well as *Titanosaurus*, Titanosaurinae and Titanosauroidea, must be abandoned because the type species (*Titanosaurus indicus*) on which it has been based is invalid.

Finally, although not tested by strict cladistic analysis, the characters shared by *A. mezzalirai* and other South American titanosaurs, principally DGM 1488-R, 'Series B', appear to be synapomorphies that support a subclade within Titanosauria, because they are not present in more basal titanosaurs.

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TEXT-FIG. 2. *Adamantisaurus mezzalirai* gen. et sp. nov., holotype, Upper Cretaceous Adamantina Formation. A–H, anterior caudal vertebrae (MUGEO 1282); I–J, haemapophyses (MUGEO 1289 and 1295). A, second? caudal vertebra, left lateral view. B–D, third? caudal vertebra, left lateral, posterior and anterior views. E–F, fourth? caudal vertebra, left lateral and anterior views. G, fifth? caudal vertebra, posterior view. H, sixth? caudal vertebra, right lateral view. I–J, haemapophysis in posterior and left lateral views. Abbreviations: ns, neural spine; prz, prezygapophysis; nc, neural canal; poz, postzygapophysis; tp, transverse process; sprl, spinoprezygapophyseal lamina; pre, prespinal lamina; posl, postspinal lamina. Scale bar represents 10 mm.

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