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A new basal titanosaur (Dinosauria, Sauropoda) from the Lower Cretaceous of Brazil

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A B S T R A C T

Although dinosaurian ichnofaunas are common in the Northeastern Brazilian Interior Basins, osteological remains are poorly represented in these areas. One of the main challenges in vertebrate paleontology in the Lower Cretaceous of this region is to recognize body-fossils, which can unveil the anatomy, functional morphology and paleoecological aspects of the dinosaurian fauna recorded until now only by footprints and trackways. The discovery of a new dinosaur specimen in the Rio Piranhas Formation of the Triunfo Basin opens new perspectives into the comprehension of paleogeographical and temporal distribution of the titanosaur sauropods. Titanosaurs are common in Upper Cretaceous rocks of Brazil and Argentina. The age of the Rio Piranhas Formation is considered to range from Berriasian to early Hauterivian. Thus, the description of this new species opens new viewpoints concerning the paleobiogeographical aspects of these sauropod dinosaurs.

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1. Introduction

Titanosaurs were the most common and diversified group of neosauropods throughout the Cretaceous (Curry Rogers, 2005). Although their remains are present in almost all continents, in South America their fossil record is more abundant and complete (Santucci and Bertini, 2001; Powell, 2003; Poropat et al., 2016). In Brazil, titanosaurs are best recorded in the Upper Cretaceous deposits of the Bauru Basin, being represented mostly by body fossils (Kellner and Azevedo, 1999; Campos et al., 2005; Kellner et al., 2005, 2006; Santucci and Bertini, 2006; Salgado and Carvalho, 2008; Santucci and Arruda-Campos, 2011; Bandeira et al., 2016). In the São Luís-Grajaú Basin, northern South America, titanosaurs are badly preserved in the lower-Upper Cretaceous (Albian-Cenomanian) strata (Medeiros and Schultz, 2001, 2002; Castro et al., 2007; Freire et al., 2007; Lindoso et al., 2013; Medeiros et al., 2014).

Intriguingly, the fossil record of these sauropods in the Lower Cretaceous (Berriasian to Hauterivian) of Equatorial deposits of Brazil are represented almost entirely by footprints (Leonardi, 1979; Carvalho, 1996, 2000; Leonardi and Carvalho, 2000, 2007; Leonardi and Santos, 2004). The only titanosaur species described from this interval comes from the Sanfranciscana Basin (Aptian, Areado Group) (Zaher et al., 2011). Recently, the first titanosaur body fossil has been discovered from the Rio do Peixe Basin complex (Ghilardi et al., 2016). Among the interior basins situated in the Northeastern Brazil, those located in the region of Rio do Peixe, specially Sousa and Triunfo, stand out due to their prolific dinosaur fossil record, in particular on their paleoichnological aspects (Carvalho, 2001; Leonardi and Carvalho, 2002). Footprints and trackways, mainly of large theropods, sauropods and ornithopods and invertebrate ichnofossils, such as traces and burrows produced by arthropods

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and annelids, are also common (Fernandes and Carvalho, 2001; Carvalho et al., 2017).

The paleontological-geological relevance of Sousa and Triunfo basins lies on the abundance of dinosaurian ichnofaunas that represent an extensive Lower Cretaceous megatracksite (Viana et al., 1993; Carvalho, 2000; Leonardi and Carvalho, 2000, 2002) established during the early stages of the South Atlantic opening. In this area, 37 sites and approximately 96 individual stratigraphic levels preserve occurrences of more than 535 individual dinosaurian trackways, as well as rare tracks and traces of the vertebrate mesofauna (Leonardi, 1989, 1994; Leonardi and Carvalho, 2000; Carvalho et al., 2013). On the other hand, dinosaur remains are poorly represented in these basins. Then, one of the main challenges in the vertebrate paleontology in northeastern Brazil is to find dinosaur body-fossils, which can unveil the anatomy, functional morphology and paleoecological aspects of the dinosaurian fauna recorded until now only by footprints and trackways (Carvalho, 2004; Carvalho et al., 1993a,b).

This paper presents a new species of a titanosaur from the Lower Cretaceous (Berriasian to lower Hauterivian) of Brazil and one of oldest worldwide. Additionally, it provides new insights regarding the pattern of distribution of this successful group of sauropods in the equatorial Gondwana.

2. The Triunfo Basin

2.1. Geological and paleontological setting

Located in the west of Paraíba State in the counties of Uiraúna, Poço, Brejo das Freiras, Triunfo and Santa Helena, this basin of 480 km^2 is an asymmetric graben that was controlled by a northwest transcurrent fault system (Fig. 1). The Precambrian basement is composed of igneous (granites, gabbros and diorites) and metamorphic (migmatites, gneisses, quartzites and marbles) rocks (ANP, 2008; Carvalho, 2000).

In the basin, the main lithologies are clastic rocks: breccias, conglomerates, sandstones, siltstones, shales and mudstones. Limestones are rare, occurring as nodules or as centimeter-thick levels in marls. The lithostratigraphic terms used in the Triunfo Basin are the same as for the Sousa Basin. The total thickness of these deposits is unknown. Besides the breccias and conglomerates near the faulted margins, there are coarse arkosic sandstones and medium-fine quartzose sandstones with an argillaceous matrix or siliceous cement in the Antenor Navarro Formation. The main sedimentary structures are cross-channel and planar stratification (Mabesoone and Campanha, 1973; Carvalho and Leonardi, 1992; Mabesoone, 1994; Carvalho, 2000).

As the basin is an asymmetric graben, the finer-grained lithologies are distributed in the south-southeast region of the basin, where tilting was greater than elsewhere. Such deposits are referred to the Sousa Formation, which comprises shales and mudstones interbedded with sandstones and siltstones. The main sedimentary structures are ripple marks, climbing ripples, mudcracks, convolute lamination and liquefaction features (Carvalho, 2000).

The last macroclastic succession is the Rio Piranhas Formation, composed of coarse grained immature sandstones, medium grained sandstones, breccias and polymictic conglomerates. Trough-cross bedding is common with paleocurrents mainly from N/NW to S/SE. This unit interfingers with the Antenor Navarro and Sousa formations. The origin of this basin, like others in the interior of Northeastern Brazil, was a result of reactivation of basement transcurrent faults. Deposition of coarse grained sediments on the margins occurred under the strong influence of tectonic activity. The tilted blocks created a pronounced rupture in terrain topography, and in the southern part of the basin, the decrease in gradient favored the establishment of meandering fluvial and lacustrine environments (Machado et al., 1990; Lima Filho, 1991; Mabesoone et al., 2000).

Excepting the dinosaur footprints, which are located close to the northern margin, the fossiliferous localities are in the central-south region of the basin. The paleoenvironmental interpretation suggests coalescing alluvial fans and an anastomosing fluvial system. Córdoba et al. (2008) concluded – based on the analysis of sysmic sections – that Rio Piranhas Formation is chronocorrelated to the Sousa Formation. Furthermore, the relatively rare footprints and

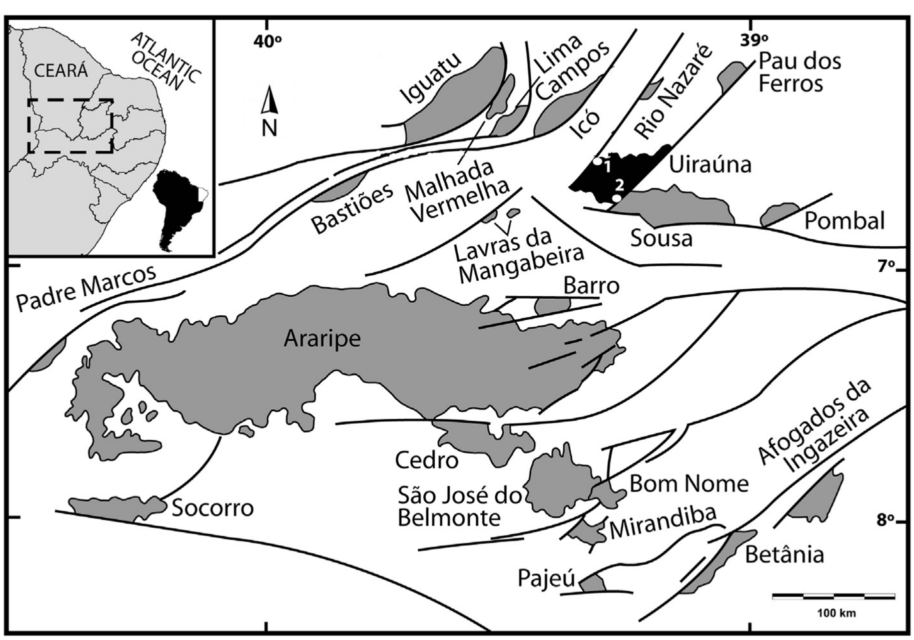

Fig. 1. Location of Triunfo Basin, northeastern Brazil (black area on the right); Triunfo town, Paraíba State (1); Areias Farm, Paraíba State, site where the fossils comes from (2).

trackways identified in this unit are similar to those of Sousa Formation (Carvalho, 2000), reinforcing this chronocorrelation. The age of this later unit is well established based on ostracods and paleopalynology (Braun, 1969, 1970; Mabesoone and Campanha, 1973; Lima and Coelho, 1987; Ponte et al., 1991; Arai, 2006). According to Arai (2006), the palynological association of Sousa Formation is composed of *Dicheiropollis etruscus* and lacking of *Transitoripollis crisopolensis* (= *Tucanopollis crisopolensis*), indicating a Rio da Serra-Aratu stage (Berriasian-lower Barremian) (Ponte et al., 1991). According to Depeche et al. (1986) and Regali (1990), the species *T. crisopolensis* araised in the early Aratu age, suggesting that the Sousa Formation may be related exclusively to the Rio da Serra-lower Aratu stage (Berriasian-lower Hauterivian) or even only to the Rio da Serra stage (Berriasian-Valanginian). The presence of the ostracod *Cypridea vulgaris* (Rio da Serra-Aratu range) reinforces the lower Neocomian age of the Sousa Formation and, consequently, of the Rio Piranhas Formation.

By analogy with the sediments dated by ostracods and palynology in the Sousa Basin, and considering the similarities among the ichnofaunas, the main depositional phase in the Triunfo Basin probably dates from between the Rio da Serra and Aratu local stages (Berriasian-Hauterivian) as already observed by, Lima and Coelho (1987) and Regali (1990). A review presented by Arai (2006) considered that this sedimentary succession accumulated mainly during the Berriasian-Valanginian (local age Rio da Serra) by the presence of the pollinic association containing *Dicheiropollis etruscus* and laking *Transitoripollis crisopolensis* although the possibility that this succession extends until earliest Hauterivian is not excluded (local age Aratu).

There are a few instances of vertebrate fossils in the Triunfo Basin. They occur in the towns of Poço and Triunfo. In these localities, the material is extremely fragmentary, with a severely limited distribution in the Antenor Navarro and Rio Piranhas formations. At the Poço locality (Poço County), bone fragments belonging to Crocodylomorpha, were identified in a succession of fine sandstones with clay intraclasts. The rocks are within the local stages of Rio da Serra and Aratu (Berriasian-lower Hauterivian, Lower Cretaceous). This fossil is a rare occurrence in the geological context of the Rio do Peixe basins, given the absence of other tetrapod skeletal elements.

An important occurrence, analyzed in this study, comes from Rio Piranhas Formation (Berriasian-lower Hauterivian, Lower Cretaceous). Skeletal elements assigned to Dinosauria (Sauropoda) were recognized at the Triunfo region (State of Paraíba, Brazil), from arkose sandstones in a trough-cross bedding structure with N/NW to S/SE direction of flow (Fig. 2). The material consists of a set of three articulated caudal vertebrae (including neural spines), one right ischium and two isolated chevrons, whose characters indicate their assignment to a titanosaur sauropod. These fossils are aligned in the south-southeast direction, in the context of gravel bars in the same direction of channeled flows (Fig. 3). The characteristics of this new fossil are analyzed in the next section.

3. Systematic paleontology

DINOSAURIA Owen, 1842.
SAUROPODA Marsh, 1878.
TITANOSAURIFORMES Salgado et al., 1997.
TITANOSAURIA Bonaparte and Coria, 1993.
Triunfosaurus gen. nov.
Type species. *Triunfosaurus leonardii* sp. nov.

Derivation of name. For the type-locality where the specimen comes from; plus *saurus*, Greek for lizard, reptile.

Diagnosis. Titanosaur characterized by the following characters (the characters indicated with the asterisks are autapomorphies recovered in the phylogenetic analysis): middle-anterior caudal vertebrae with short and robust prezygapophyses, directed anteriorly and slightly inclined upward; neural spine small, possessing a sagittal process expanded at its distal ends; transverse process inclined upward, slightly oriented posteriorly; posterior half of the centrum with lateral faces strongly concave having a small pleurocoels; anterior haemal arch straight with articular surfaces placed dorsally; middle haemal arch compressed anteroposteriorly with articular surfaces of the proximal processes directed posterodorsally and distal process reduced; *anteroposterior pubic pedicel of the ischium divided by the total length of the ischium larger than 0.5; *close angle (less than 70°) formed between the shaft and the acetabular line of the ischium.

Triunfosaurus leonardii sp. nov. Figs. 4–8.

Diagnosis. Same as for genus.

Derivation of specific name. In honor of the paleontologist Giuseppe Leonardi, which dedicated greater part of his life to the study of the reptile ichnofauna from the northeastern Brazil.

Holotype. Three middle-posterior articulated caudal vertebrae (UFRJ-DG 498-K-R); one right ischium (UFRJ-DG-498-a-R); three isolated haemal arches (UFRJ-DG-498-b-R; UFRJ-DG-498-d-R; UFRJ-DG-498-f-R); and three isolated neural spines (UFRJ-DG-498-g-R; UFRJ-DG-498-h-R, UFRJ-DG-498-i-R).

Type locality. Areias Farm (6º41′53,8″S 38º32′25″W), Triunfo County, Paraíba State, Brazil.

Stratigraphic horizon. Rio Piranhas Formation, Triunfo Basin. Lower Cretaceous (Berriasian-lower Hauterivian).

UFRJ-DG, Universidade Federal do Rio de Janeiro, Departamento de Geologia, Brazil.

3.1. Description

The specimen UFRJ-DG 498- K-R (Fig. 4) is 31.5 cm length and consists of a sequence of three partially preserved middle-posterior articulated caudal vertebrae partially preserved, which have centra without any internal camellate pattern. Although the posterior articular faces of the centrum are flat, their anterior articular faces cannot be determined due to preservational condition (i.e. they are obliterate). These features contrast with the condition observed in caudal vertebrae of derived lithostrotians (Upchurch et al., 2004), although caudal procoelia is not a uniform characteristic for this clade of titanosaurs (e.g. *Rinconsaurus caudamirus* Calvo and Gonzáles Riga, 2003). The neural arches are located on the anterior half of the vertebral centrum, as in most titanosaurids, and the prezygapophyses are directed anteriorly and slightly inclined forward as in the Aeolosaurini (sensu Franco-Rosas et al., 2004).

The specimen UFRJ-DG-498-a-R (Fig. 5) is 90 cm length and consists of a relatively well preserved right ischium, which lacks part of the pubic articular surface and the distal lamina. The ischiatic bone is twisted in mesio-anterior view. On the internal ischial lamina there is a median protuberance (origin site for *M. flexor tibialis internus* 3).

The specimen UFRJ DG-498-b-R (Fig. 6A–B) is 22 cm long and consists in an anterior haemal arch relatively well preserved. It is straight with the haemal canal narrow and a single facet joint on each of the proximal processes. The distal process (Fig. 6C) has a rounded distal end in lateral view and is anteroposteriorly expanded. The specimen UFRJ DG-498-d-R (Fig. 6D–F) is 19 cm length and represents a middle haemal arch. It is strongly compressed anteroposteriorly (but not laminar) with reduced distal process compressed anteroposteriorly, haemal canal shorter and open than anterior haemal arches. In anterior view (Fig. 6D), the haemal arch is slightly concave and presents articular surfaces of proximal processes located posterodorsally. In posterior view (Fig. 6E), two crests form a small shelf on the base of the haemal arch.

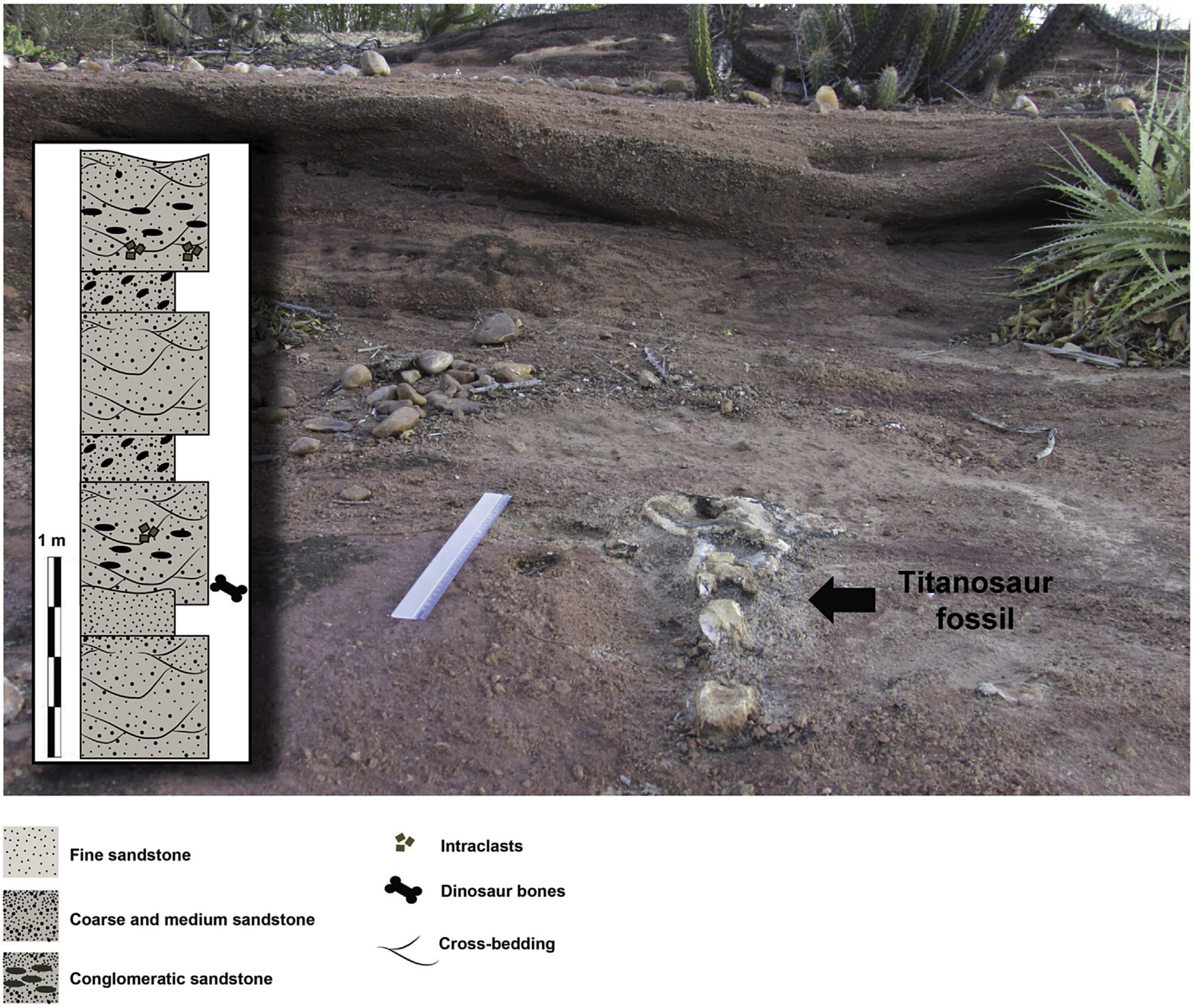

Fig. 2. Stratigraphic log in the Areias Farm exhibiting the typical lithologies of the Rio Piranhas Formation.

3.2. *Taphonomic remarks*

The material described herein (Fig. 7) presents minor macroscopical taphonomic alterations. Inspite of being found in a fluvial setting, rounding is not observed in the specimens. This evidence, associated with the articulation of the vertebrae, suggests that the skeletal elements experienced short-distance hydraulic transport from the source area (place of death) to their burial place (peripheral assemblage, *sensu* Araújo-Júnior, 2016). Furthermore, this evidence – associated with the homogeneous superficial blackish and reddish staining observed in all elements – indicates the assignment of all specimens to the same individual.

Signs of weathering, trampling or boring produced by insects were not observed in the specimens, indicating that the bones were relatively rapidly buried after the death of the individual (Behrensmeyer, 1978, 1991). The association between the taphonomic signatures observed herein (absence of trampling, desiccation and insect marks; articulation of the vertebrae; absence of abrasion) can be associated with a context of intense sedimentary supply into the basin, possibly in a condition of strong tectonic activity in the area. Besides, the absence of desiccation marks – which occur and evolve rapidly in humid conditions (Tappen, 1994) – and boring, associated to the faciological data, is suggestive of an arid climate during the deposition of the Rio Piranhas Formation.

4. Discussion

In spite of the fragmentary condition of the material, it is possible to assess the affinities of the new sauropod. The pubic articulation of the ischium of *Triunfosaurus leonardii* gen. et sp. nov. is longer than the anteroposterior length of the iliac peduncle, as in Camarasauromorpha (Salgado et al., 1997). Within Camarasauromorpha, *Triunfosaurus leonardii* gen. et sp. nov. is a member of the clade formed by *Europasaurus* plus more derived sauropods because of the presence of caudal neural arches positioned on the anterior part of the centrum (a character of *Europasaurus* and more the derived sauropods, Carballido and Sander, 2014: character 211). Unlike *Europasaurus*, the neural spine is vertical and

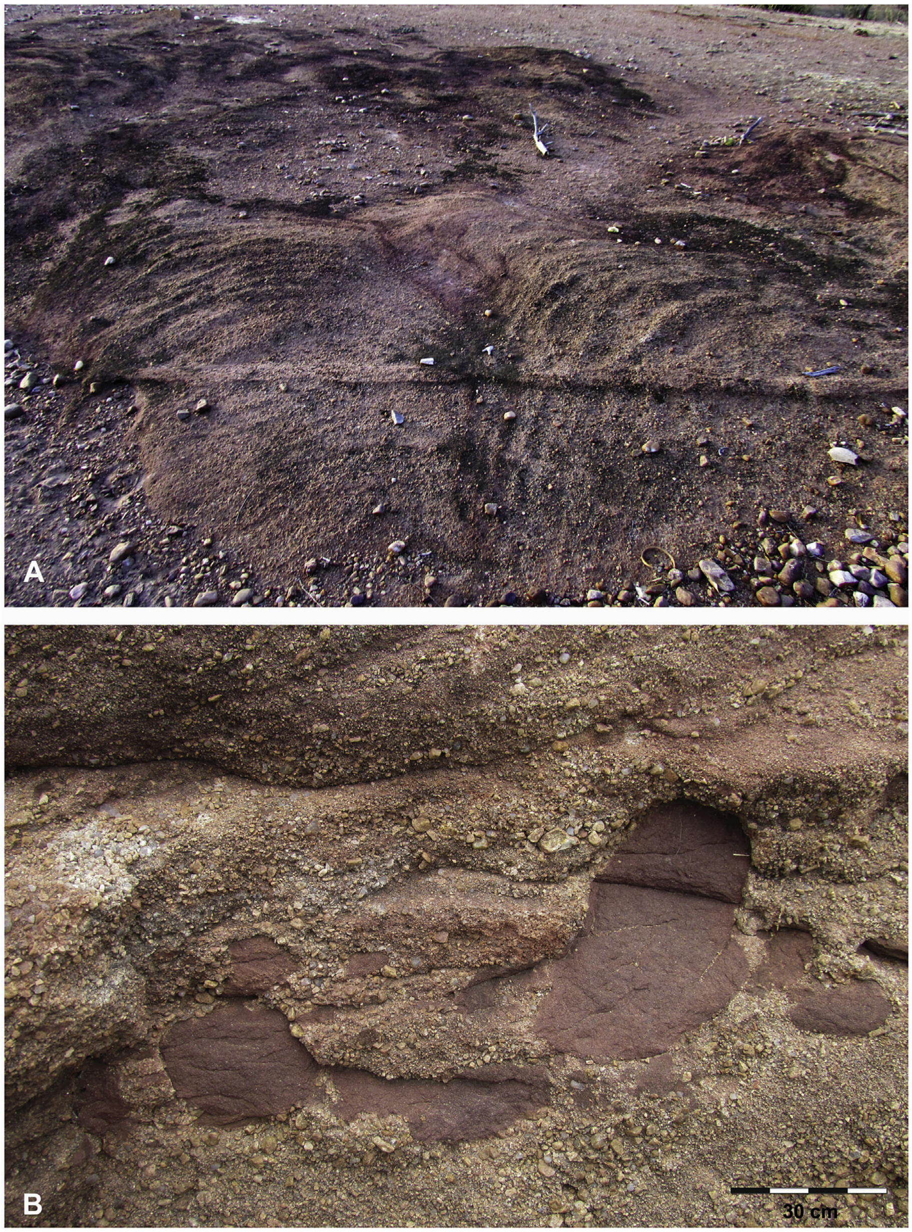

Fig. 3. Outcrop in the Areias Farm exhibiting festoon in plain view (A) and a bed of intraclast conglomerate (B).

subquadrangular in *Triunfosaurus leonardii* gen. et sp. nov. and the prezygapophyses are anteriorly projected, instead of anterodorsally as in the European genus.

The shaft of the ischium of the new species is short and laminar, as is typical in titanosaurs, including some basal forms, like *Andesaurus*. In fact, the proportions of the ischium of *Triunfosaurus leonardii* gen. et sp. nov. and *Andesaurus* are basically similar (Mannion and Calvo, 2011), although that of the former seems to be more laminar. Likewise, the proximal articular surfaces of the anterior chevrons of *Triunfosaurus leonardii* gen. et sp. nov. form two distinct surfaces, as in titanosaurs (Mannion and Calvo, 2011). However, *Triunfosaurus leonardii* gen. et sp. nov. has some characters that are absent in typical titanosaurs. For instance, unlike *Andesaurus* and other titanosaurs, the dorsoventral height of the haemal canal of *Triunfosaurus leonardii* gen. et sp. nov. is less than 50% of the whole chevron (Wilson, 2002).

In order to know the phylogenetic relationships of *Triunfosaurus leonardii*, an analysis was performed using the data matrix of Carballido and Sander (2014), including 71 taxa (counting *Triunfosaurus leonardii*) and 341 characters. The analysis was carried out using TNT (Goloboff et al., 2008). A heuristic tree search was performed consisting in 1000 replicates of Wagner trees (with random addition sequence of taxa) followed by branch swapping (TBR: saving 10 trees per replicate). Fifty six more parsimonious trees of 1003 steps were retrieved (CI: 0.395; RI: 0.718). The Bootstrap and Jacknife support values were calculated and indicated in Fig. 8 (only the Bootstrap and Jacknife support values greater than 50% are shown in Fig. 8). The support for the titanosaurian branches is relatively low, with only a few nodes having Bootstrap and Jacknife values higher than 50% (Fig. 8).

In coincidence with the previous assessment, the phylogenetic analysis recovered *Triunfosaurus leonardii* gen. et sp. nov. as a basal

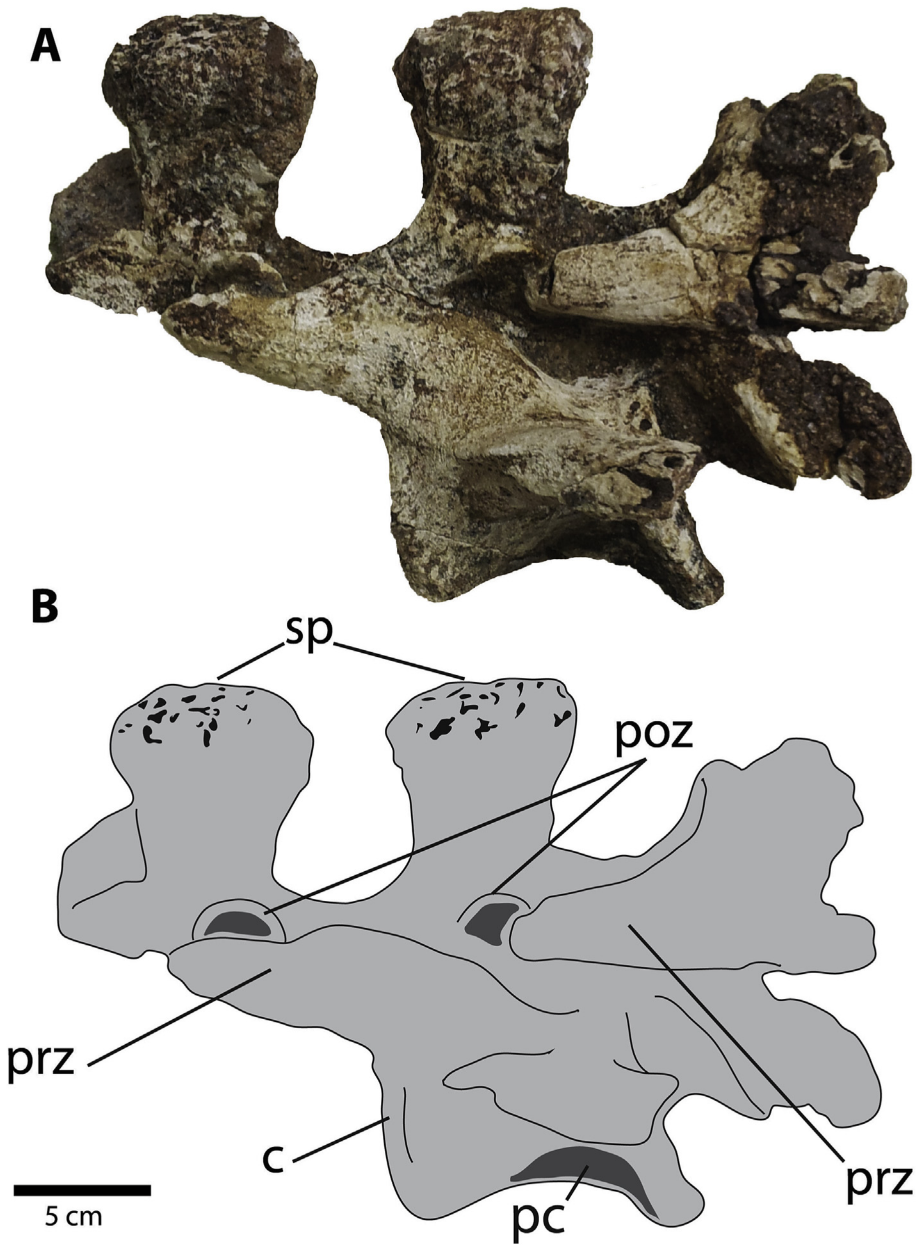

Fig. 4. Holotype of *Triunfosaurus leonardii* gen. et sp. nov. Caudal vertebra (UFRJ-DG 498- K-R) in dorsolateral view. Photo (A) and schematic drawing of these caudal vertebra (B).

titanosaur, forming a politomy with *Malawisaurus dixeyi*, *Epachthosaurus sciuttoi*, *Argentinosaurus huinculensis*, *Malarguesaurus florenciae* and more derived forms. The characters that allow to include the new species into the Titanosauria (defined as the clade containing the most recent common ancestor of *Andesaurus delgadoi* and *Saltasaurus loricatus* and all of his descendants, Wilson and Upchurch, 2003) are absence of hyposphene ridge in the anterior caudal vertebrae (not observed in the holotype specimen) (c202), and anterior caudal centra slightly procoelous (not observed in the holotype specimen) (c192). In turn, *Triunfosaurus leonardii* shares with titanosaurs more derived than *Mendozasaurus neguyelap* middle and posterior dorsal vertebrae with accessory spinodiapophyseal lamina (not observed in the holotype specimen) (c164), middle caudal vertebrae with vertical neural spines (c212), and anterior-posterior caudal vertebrae with vertical neural spines (c215).

Enforcing *Triunfosaurus leonardii* outside Titanosauria resulted in 58 trees of 1005 steps, that is, two additional steps. This clearly indicates that the hypothesis that *Triunfosaurus leonardii* as a titanosaur is weakly supported, which is coherent with the low support values obtained.

As observed by Dunhill et al. (2016) the connectivity of all major landmasses persisted until the Berriasian-Barremian. This was a critical moment to the understanding of the later macrobiogeographical patterns of the terrestrial faunas. The basal titanosaur *Triunfosaurus leonardii* gen. et sp. nov. comes from this geological context, in which the progressive posterior continental isolation resulted in increased origination rates in some dinosaurian lineages (Dunhill et al., 2016). Recently, models involving divergence times based on “morphological clock” have suggested

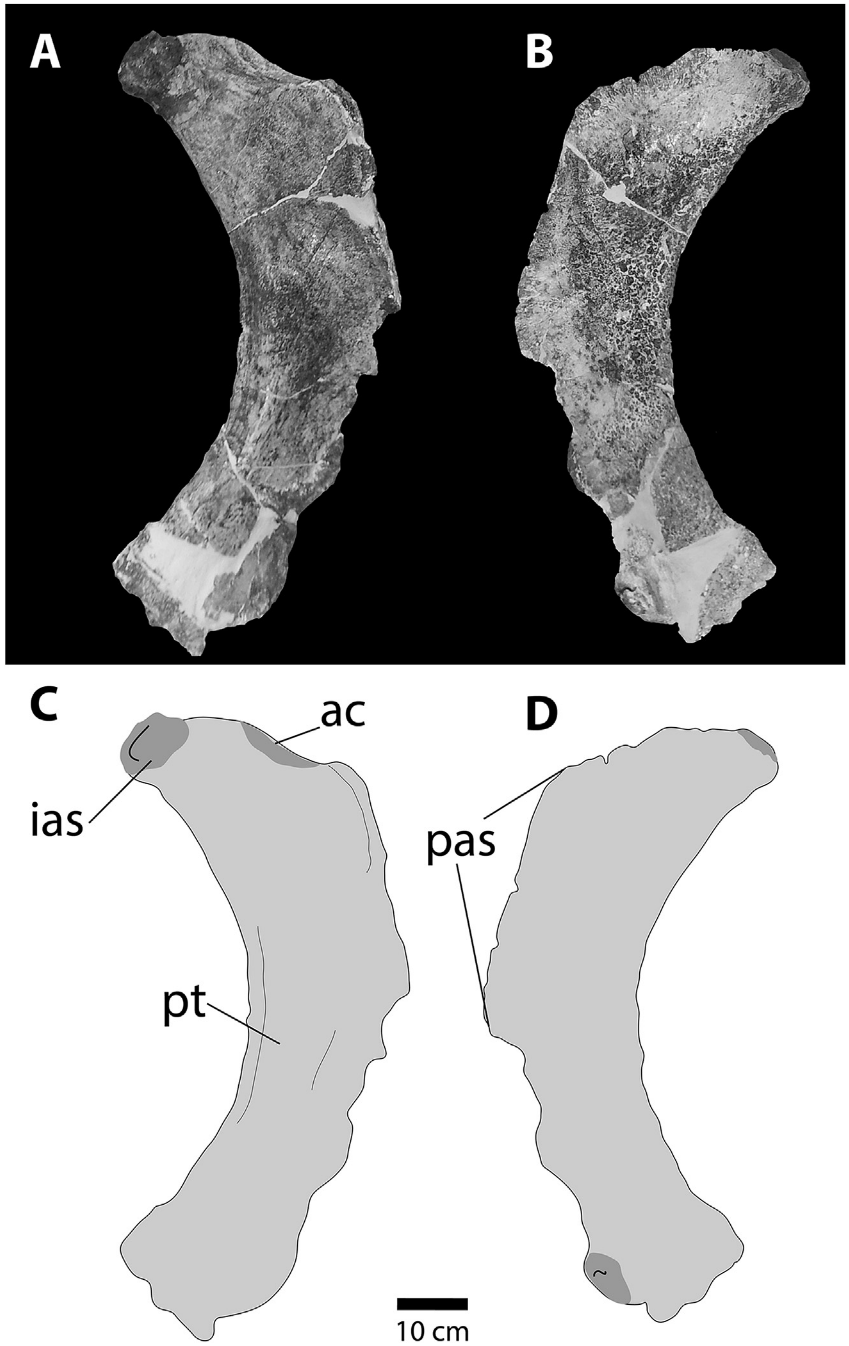

Fig. 5. Holotype of *Triunfosaurus leonardii* gen. et sp. nov. Right ischium (UFRJ-DG 498-a-R) in lateral (A) and medial (B) views.

a Gondwanan origination in South America for Titanosauria during the Early Cretaceous (approximately 135 Ma; Hauterivian) (Gorscak and O'Connor, 2016). Considering *Triunfosaurus leonardii* gen. et sp. nov. as one of the oldest basal titanosaur ever recorded, its occurrence in the Triunfo Basin supports this hypothesis.

In biogeographical terms, *Triunfosaurus leonardii* gen. et sp. nov. Supports the model presented by Gorscak and O'Connor (2016) for titanosaurian origin. Another alternative to this newer paleobiogeographic hypothesis, based on trackways records from the Middle Jurassic of Europe (Santos et al., 1994), is to consider a dispersive route from the European continent around the Jurassic-Cretaceous boundary, then through northern South America/Africa during the Early Cretaceous and later reaching a nearly global distribution during the Late Cretaceous. Therefore, the palebiogeographical possibilities are certainly more complex. The discovery of an Aptian-Albian titanosaur in Italy by Dal Sasso et al. (2016) suggests, through phyletic relationships, an Afro-Eurasian route for the ancestors of the Italian titanosaur.

Early Cretaceous titanosaurs are rare in South America. The best known Early Cretaceous titanosaur is *Tapuiasaurus*, which comes from the Aptian of Minas Gerais (Brazil) (Zaher et al., 2011). *Triunfosaurus leonardii* gen. et sp. nov. comes from Berriasian-early

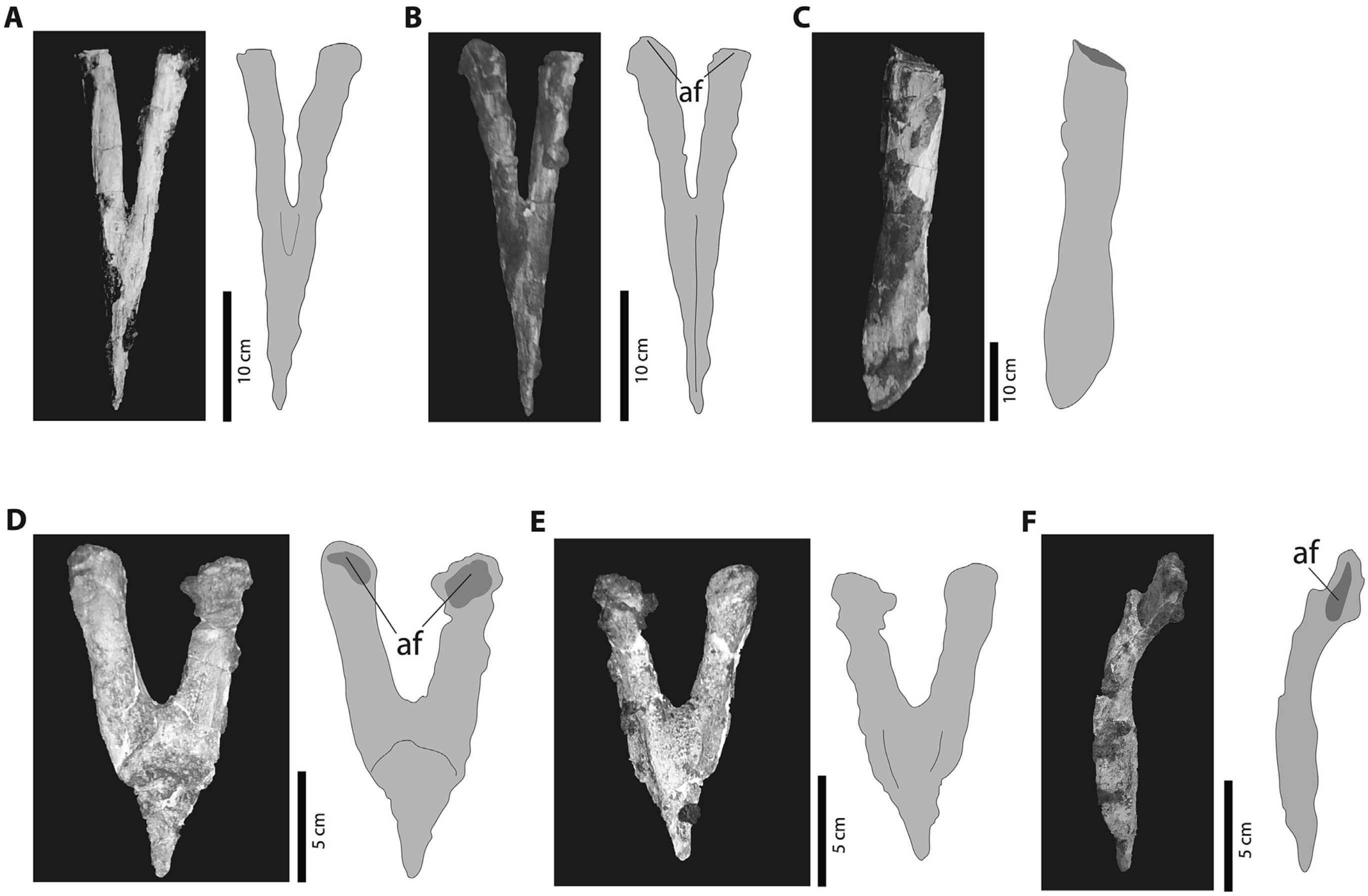

Fig. 6. Holotype of *Triunfosaurus leonardii* gen. et sp. nov. Anterior haemal arch (UFRJ-DG 498-b-R) in anterior (A), posterior (B) and lateral views. Mid haemal arch (UFRJ-DG 498-d-R) in anterior (D), posterior (E) and lateral (F) views.

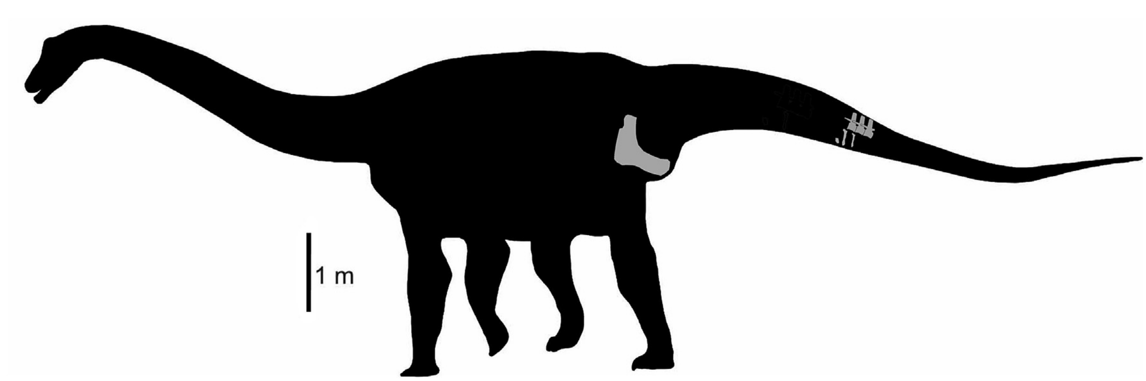

Fig. 7. Diagramatic reconstruction of *Triunfosaurus leonardii* gen. et sp. nov., indicating the preserved osteological elements (in gray).

Hauterivian, which extends back the Brazilian titanosaur record in approximately 20 Ma. *Tapuiasaurus* is an indisputable advanced titanosaurian, based on the possession of several characters (Zaher et al., 2011). Other basal titanosaur material is recorded in the Sousa Basin (Berriasian-lower Barremian) by Ghilardi et al. (2016) and others much younger, such as those reported by Medeiros and Schultz (2002) and Medeiros et al. (2014) from the São Luís Basin (Cenomanian).

Finally, the Northeast Brazilian Interior Basins stand out by their prominent vertebrate ichnofauna (see Carvalho, 2000; Leonardi and Carvalho, 2002). Around 395 dinosaur tracks have been identified in these basins, including 74 sauropod tracks. Leonardi and Carvalho (2002) suggested, based both on the age of the fossil-bearing unit and morphology of the tracks, Dicraeosauridae, Rebbachisauridae and basal titanosaurs as the possible trackmakers for the sauropod tracks. Considering that the size of some sauropods footprints are compatible with that of *Triunfosaurus leonardii* gen. et sp. nov., we include this new species among the possible trackmakers of the Northeast Brazilian Interior Basins (Fig. 9).

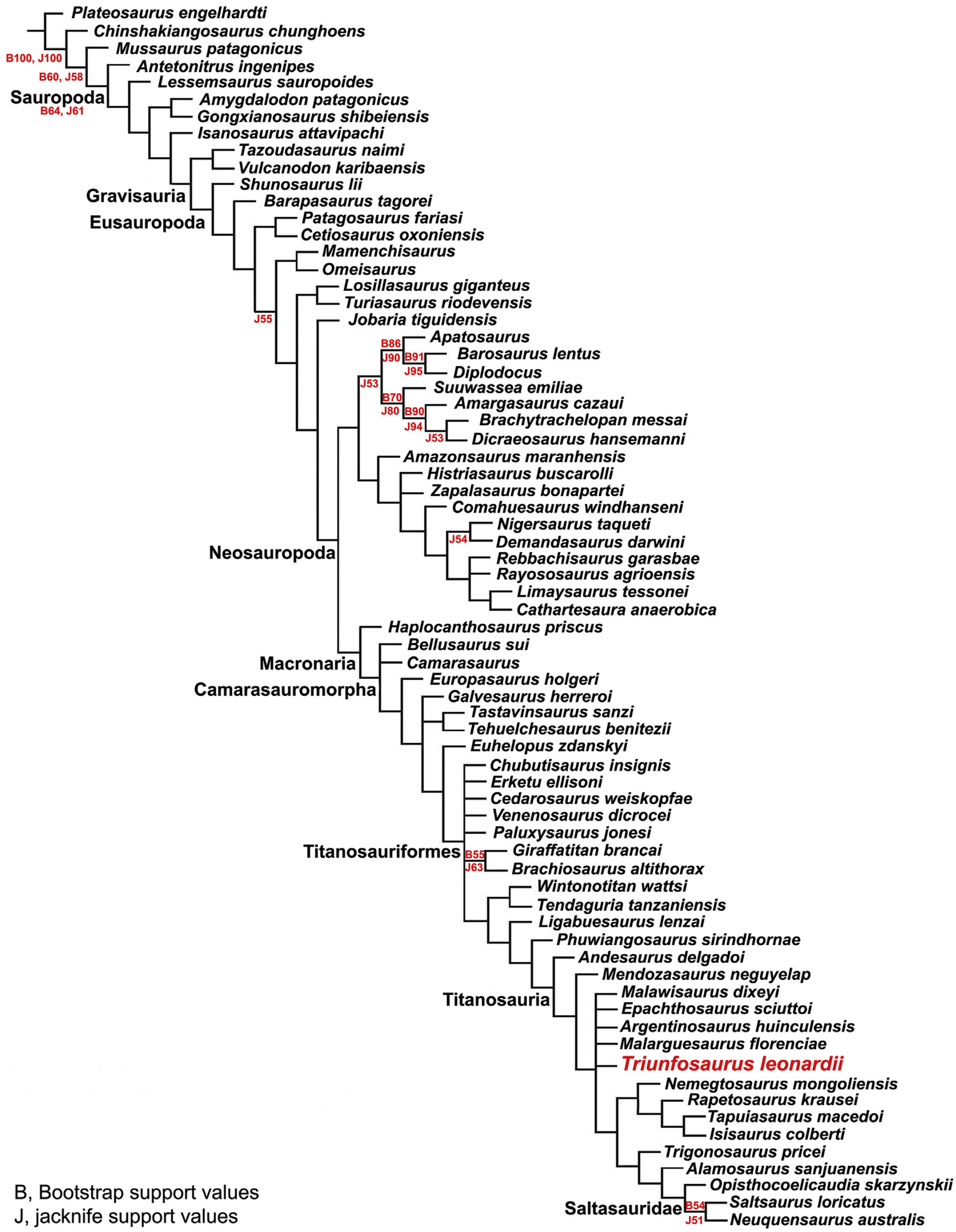

Fig. 8. Cladogram after the analysis carried out using TNT. A heuristic tree search was performed consisting in 1000 replicates of Wagner trees. Fifty six more parsimonious trees of 1003 steps were retrieved (CI: 0.395; RI: 0.718).

5. Conclusion

The new sauropod from the Triunfo Basin opens new perspectives into the understanding of the paleobiogeographical distribution of the titanosaur sauropods throughout South America during the first steps of their evolution. The species described herein is one of the oldest described titanosaur ever recorded in that landmass. This reinforces the hypothesis of a Gondwanan origin in South America for Titanosauria during the Early Cretaceous.

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Fig. 9. Artistic reconstruction of *Triunfosaurus leonardii* gen. et sp. nov (art by Pepi).

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Glossary

ac: acetabulum
af: articular facets
c: centrum
ias: iliac articular surface
pas: pubic articular surface
pc: pleurocoel
poz: postzygapophysis
prz: prezygapophysis
sp: sagital processes
pt: protuberance