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A titanosaur (Dinosauria: Sauropoda) osteoderm from the Alcântara Formation (Cenomanian), São Luís Basin, Northeastern Brazil

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Among titanosaurs, osteoderms are morphologically diverse and have been reported from deposits in South America, Africa, Madagascar, Eurasia and Oceania. In Brazil, titanosaur osteoderms are rare and have only been recorded from Bauru Basin sedimentary rocks. Here, we describe a keeled titanosaur osteoderm, which is the first occurrence of an osteoderm specimen in the São Luís Basin, Northeastern Brazil. This osteoderm is characterized by an external bulb, an internal root, and a very rugose cingulum limiting the external and internal surfaces. These characteristics are typical of Titanosauria dermal bones, and this specimen strengthens the idea that the armored sauropods were present during the early Late Cretaceous of Northeastern Brazil, extending their distribution in the northernmost portion of South America.

1. Introduction

Titanosaurs were highly diverse and globally widespread during the Cretaceous (Curry Rogers, 2005), including reports from Antarctica (Cerda et al., 2011). One noteworthy characteristic of some of these animals is the presence of osteoderms (Salgado, 2003). Although dermal spines have been recognized in diplodocids (Czerkas, 1992), titanosaurs are the only known armored sauropods (D'Emic et al., 2009). Almost 90 titanosaur osteoderms from South America, Africa, Madagascar, Eurasia, and Oceania have been recovered thus far, and approximately ten genera have been assigned as osteoderm bearers (D'Emic et al., 2009; Marinho and Candeiro, 2005; Molnar, 2011). Despite the wide geographical distribution of titanosaur osteoderms, these characteristics have been the focus of much phylogenetic debate. The functional aspects of osteoderms are still unknown, but they may be more related to mineral reserves than mechanical defense (Curry Rogers et al., 2011; D'Emic et al., 2009; Marinho, 2007).

Titanosaur osteoderms are rare in Brazil and have only been recorded from the Late Cretaceous in the Bauru Basin (Marinho and Candeiro, 2005; Marinho and Iori, 2011). Five specimens have been identified thus far: three small isolated osteoderms from Peirópolis, municipality of Uberaba, Minas Gerais State (Marília Formation, Maastrichtian) (Azevedo and Kellner, 1998; Marinho and Candeiro, 2005); one large isolated osteoderm from Ibirá, São Paulo State (Adamantina Formation, Late Cretaceous) (Marinho and Iori, 2011); and one osteoderm associated with *Maxakalisaurus topai* from Prata, Minas Gerais State (Adamantina Formation, Late Cretaceous) (Kellner et al., 2006).

The Laje do Coringa bone bed (São Luís Basin) crops out at the north and northwestern coast of Maranhão State, Brazil, at Cajual Island (Fig. 1A). This site records a Cenomanian paleocommunity composed of several dinosaur, pterosaur, crocodilian, turtle, fish and plant taxa (Corrêa-Martins, 1997; Elias et al., 2007; Lindoso et al., 2011, 2012; Medeiros et al., 2007; Medeiros and Schultz, 2001, 2002). Sauropod remains are less common than theropod remains, which are mostly represented by isolated teeth and vertebrae (see Medeiros et al., 2007).

Although the Laje do Coringa dinosaur record is abundant and diverse, Medeiros et al. (2007) observed that most of the taxonomic attributions of these fossils were based on very fragmentary

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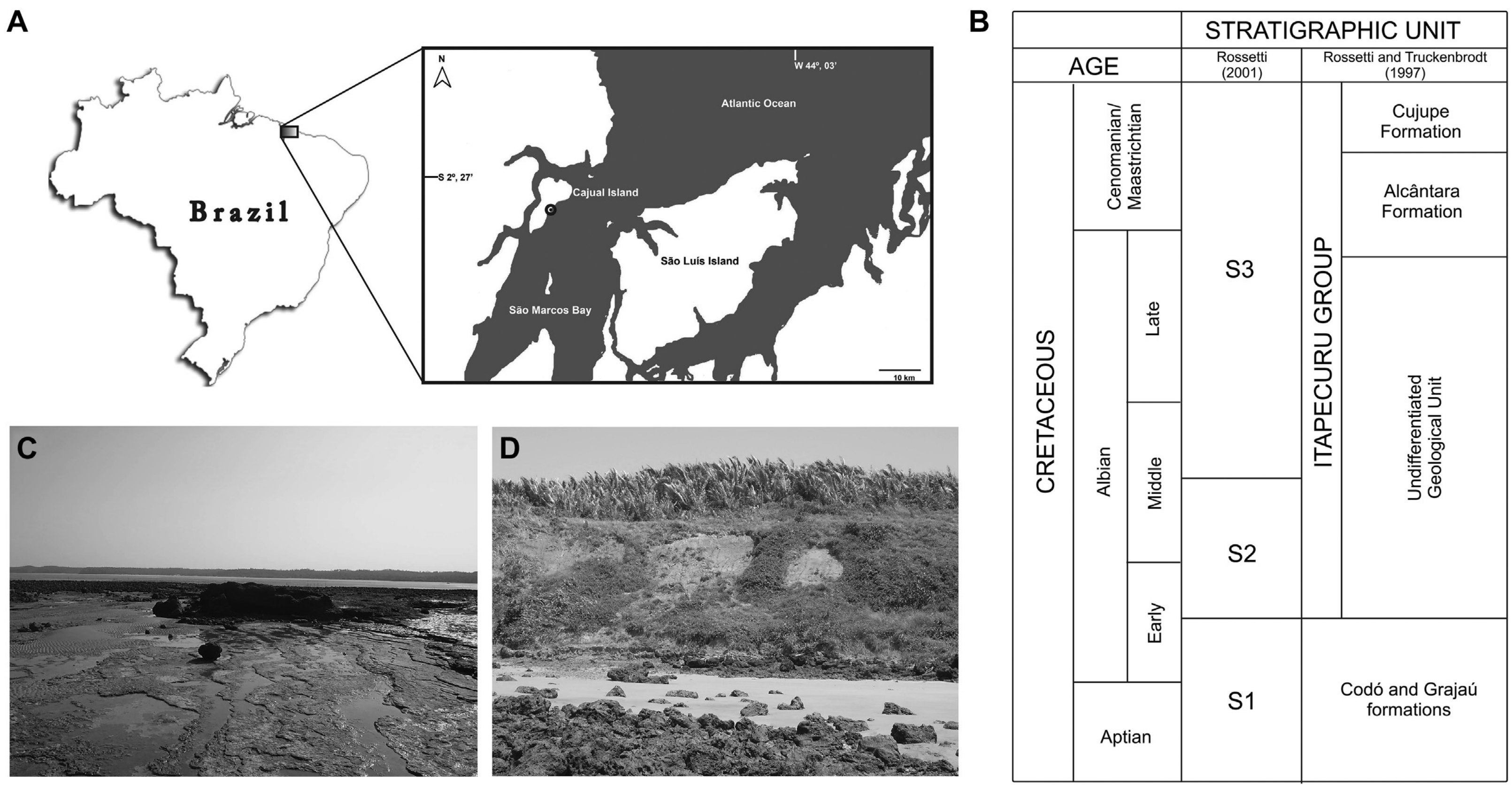

Fig. 1. Location of Cajual Island, Northeastern Brazil. The black point indicates the area where the material was collected (A); Geological setting of osteoderm UFMA 1.10.1958 and stratigraphy of the São Luís Basin sequence (modified from Rossetti, 2001) (B); Laje do Coringa bone bed, the main paleontological site of Cajual Island (C); Encantado Beach, site where the osteoderm UFMA 1.10.1958 was collected.

material and hence inadequate for a better understanding of the true Late Cretaceous dinosaur diversity (e.g., Titanosauria) in Northeastern Brazil. Here, we describe the first titanosaur osteoderm from Cajual Island (Alcântara Formation, São Luís Basin, Cenomanian), Maranhão State. This record sheds new light on the understanding of the titanosaur diversity in Brazil and extends the distribution of these armored sauropods to the northernmost region of South America.

2. Geological setting and lithostratigraphy

The osteoderm described here came from the São Luís Basin, Northeastern Brazil, which corresponds to Upper Cretaceous sediments deposited during the opening of the South Atlantic Ocean (Góes and Rossetti, 2001; Rossetti, 2001). The sedimentary rocks of the São Luís Basin are informally divided into three depositional sequences *sensu* Rossetti (2001): S1, S2, and S3 (Fig. 1B). The S1 sequence was accumulated during the late Aptian to early Albian and includes 450 m of sandstones, shales, and limestones deposited in lacustrine, fluviodeltaic, and shallow marine environments, composing the Grajaú and Codó formations. The S2 sequence is constituted of 500 m of sandstones and pelitic deposits formed during the early to mid-Albian in shallow marine and fluviodeltaic environments and represented by the Itapecuru Formation (Campbell et al., 1949) or Undifferentiated Unity (see Rossetti and Truckenbrodt, 1997). The S3 sequence developed from the mid-Albian to Late Cretaceous. This sequence comprises 600–800 m of sandstone and pelitic deposits referred as to the Alcântara and Cujupe formations (Paz and Rossetti, 2001; Rossetti and Truckenbrodt, 1997). Palynological studies indicate a hot and arid climate for this Albian–Cenomanian sequence (Pedrão et al., 1993).

The Alcântara and Cujupe formations represent the uppermost lithostratigraphic unity of the Cretaceous sequence of the São Luís Basin (Rossetti, 1998; Rossetti and Truckenbrodt, 1997) and record important continental vertebrate fauna of the early Late Cretaceous. The formations exhibit 30–35 m of sandstones, limestones, claystones, and conglomerates that were accumulated in estuarine and tidal environments under the influence of storms (Holz, 2003; Klein and Ferreira, 1979; Mesner and Wooldridge, 1964; Pedrão et al., 1993; Rossetti, 1997, 2001).

3. Systematic paleontology

Saurischia Seeley, 1888
Sauropodomorpha Huene, 1932
Sauropoda Marsh, 1878
Titanosauria Bonaparte and Coria, 1993
(Fig. 2)

4. Material and methods

The titanosaur osteoderm here studied is housed at the Universidade Federal do Maranhão collection as UFMA 1.10.1958. The description follows the terminology proposed by D'Emic et al. (2009) for the classification of titanosaur osteoderms.

5. Locality and horizon

The specimen was found some 2.2 km south from the Laje do Coringa bone bed (Fig. 1C), the main paleontological site of Cajual Island. The specimen comes from Encantado Beach, also on Cajual Island, Maranhão State (Fig. 1D).

6. Description

UFMA 1.10.1958 is a well-preserved osteoderm with moderate signs of abrasion due to pre- or post-burial transport. The osteoderm is 13.0 cm long, 8.0 cm wide, and 10.5 cm high. The osteoderm is almost bilaterally symmetric, and its marginal border

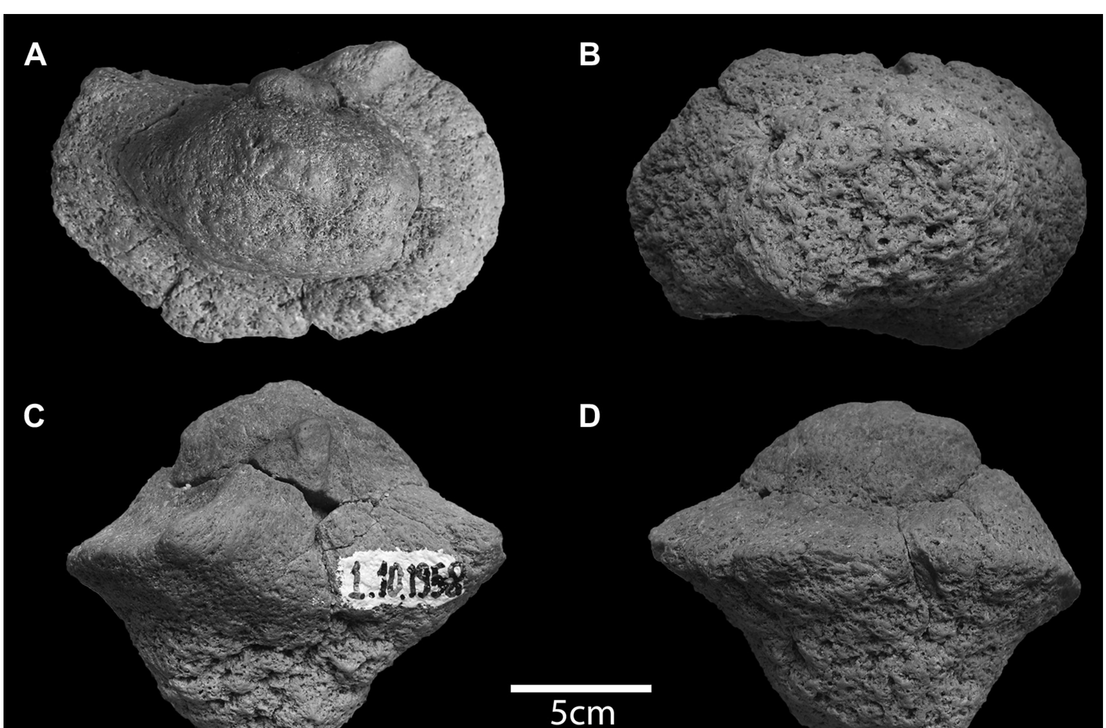

Fig. 2. Titanosaur osteoderm UFMA 1.10.1958 in dorsal (A), ventral (B), and lateral (C, D) views.

exhibits a robust and well-developed cingulum. It presents an external bulb, which is anteroposteriorly elongated, and an internal root with a flat base in lateral view. In both the external and internal views, UFMA 1.10.1958 is subcircular in shape, with its general elliptical shape only modified by a depressed area that gives it a concave shape when observed in external view. We exclude the possibility that this concavity is due to breakage during transport because neither sharp edges nor different bony textures were observed in this portion of the osteoderm. The external and internal surfaces present different textures. The former is smoother, and the latter is coarser. The base of the external bulb is almost entirely delimited by cracks, and its external surface is slightly irregular with some sparse and small rounded perforations and foramina that are larger towards the cingulum (Fig. 3A). At its mid portion, these perforations and foramina are 0.5 mm in diameter and reach up to 3 mm in diameter at the cingulum. The internal surface is rugose, especially at the root, with pits that vary from rounded to irregular in shape (Fig. 3B). In the internal view, the characteristic interwoven patterns observed in many amniote osteoderms (D'Emic et al., 2009), as well as the associate foramina, are not evident in UFMA 1.10.1958. Moreover, no signs of lateral articulations are observed in this osteoderm. Following the classification proposed by D'Emic et al. (2009) we classify this dermal bone as a keeled osteoderm.

7. Discussion

Osteoderms occur in many extant vertebrate lineages and are common in the fossil record, in many cases being the only direct evidence of the integument in extinct animals (Hill, 2005; Romer, 1956). These mineralized structural organs occur embedded in the dermis and display considerable morphological, tissue, and compositional variation (Vickaryous and Sire, 2009). In dinosaurs, osteoderms appeared independently in three lineages: Thyreophora, Neoceratosauria, and Titanosauria (D'Emic et al., 2009). One of the most representative characteristics of Thyreophora is the presence of a dermic cuirass. All members of this suborder have osteoderms (Coombs, 1978). Within Neoceratosauria, only *Ceratosaurus nasicornis* and possibly *Carnotaurus sastrei* are osteoderm bearers (Bonaparte et al., 1990; Gilmore, 1920; Madsen and Welles, 2000). Titanosaurs are the only known sauropods that have confirmed to have osteoderms (D'Emic et al., 2009) and have been reported from South America, Africa, Madagascar, Eurasia, and Oceania (Azevedo and Kellner, 1998; Bonaparte and Powell, 1980; Curry Rogers et al., 2011; D'Emic et al., 2009; Depéret, 1896; Dodson et al., 1998; Piveteau, 1926; Heredia and Saldado, 1999; Huene, 1929; Huene and Matley, 1933; Le Loeuff et al., 1994; Marinho and Candeiro, 2005; Marinho and Iori, 2011; Molnar, 2011; Powell, 1980; Salgado, 2003; Sanz and Buscalioni, 1987).

UFMA 1.10.1958 is here classified as a titanosaurian osteoderm due to the presence of the following features: (1) irregular perforations and foramina at the external surface, (2) rugose internal surface with interwoven bone pattern and foramina, and (3) presence of a bulb and root separated by a cingulum. In addition, UFMA 1.10.1958 fits into the keeled morphotype grouping proposed by D'Emic et al. (2009, pg. 172, Fig. 5M, see also Salgado, 2003, pg. 448, Figs. 5A and C) for classification of titanosaur osteoderms because the osteoderm has a robust keel with a flat base, a cingulum delimiting the external and internal surfaces, and a similar concavity in the cingulum. UFMA 1.10.1958 differs from this keeled osteoderm by having a more convex bulb on the external surface. To date, keeled osteoderms have been found in Argentina and Madagascar, and some of them have been attributed to *Neuquensaurus*, *Saltasaurus*, and *Aeolosaurus* (Dodson et al., 1998; Powell, 1980; Salgado, 2003; Salgado and Coria, 1993; Salgado et al., 2005).

Thyreophoran dermal plates are dorsally keeled and plane or slightly concave ventrally (Coombs, 1978). In ankylosaurus, the dermal plates compose an extensive cuirass composed by oval keeled plates, defined as a continuous mosaic of small plain ossicles (Coombs, 1978). Neoceratosaurian osteoderms are amorphous and exhibit a very rugose texture with perforations, as observed in *Ceratosaurus nasicornis* osteoderms (Gilmore, 1920; Madsen and Welles, 2000). Skin impressions with some rugose, keeled conical protuberances, varying from 4 to 5 cm in diameter, were described by Bonaparte et al. (1990) for *Carnotaurus sastrei*. Crocodyliform osteoderms are scarce at Laje do Coringa and are different from UFMA 1.10.1958 by being dorsoventrally compressed with subcircular and oval punctuations at the external surface and also for their smaller size. Thus, UFMA 1.10.1958 does not display any similarity with the osteoderms found in Thyreophora, Neoceratosauria, or crocodyliforms.

At Laje do Coringa, titanosaurs are commonly represented by caudal vertebrae and teeth. Amphiplatyan caudal vertebrae have been attributed to basal titanosaurs (Medeiros and Schultz, 2001) and a fragmentary vertebral centrum was assigned by Medeiros (2002) to Saltasaurinae. More recent studies, however, do not support this latter assignment to Saltasaurinae (Medeiros et al., 2007). Sauropod teeth are abundant at Laje do Coringa, and some of these are related to *Malawisaurus dixeyi* (Freire et al., 2007), an armored Early Cretaceous titanosaur from Africa (Gomani, 2005; Jacobs et al., 1993). The presence of diplodocids in these deposits is attested by the occurrence of caudal vertebrae related to *Limaysaurus tessonei* (Medeiros and Schultz, 2004).

Concerning the aforementioned titanosaurian taxons, *Malawisaurus* and Saltasaurinae are known as osteoderm bearers (Bonaparte and Powell, 1980; Gomani, 2005; Jacobs et al., 1993; Powell, 1980, 2003; Salgado, 2003; Salgado et al., 2005). In the description of *Malawisaurus*, Jacobs et al. (1993) noticed the

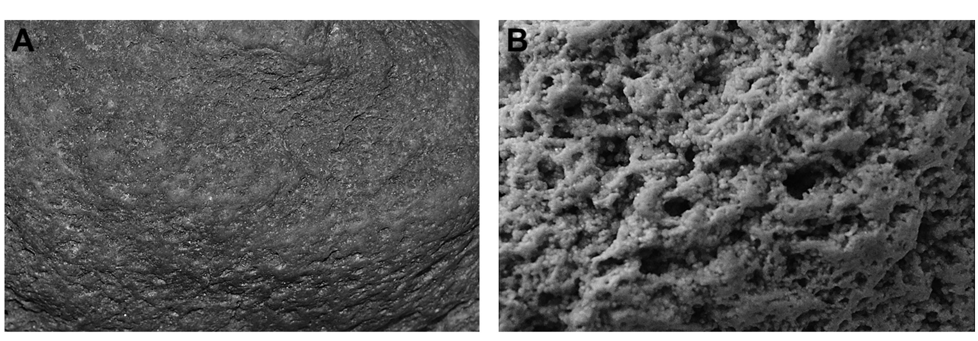

Fig. 3. Details of osteoderm UFMA 1.10.1958 showing the external (A) and internal (B) surface. Scale bar represents 1 cm.

presence of pseudomorphs of calcite associated to the fossils and considered them osteoderms. Gomani (2005) described large dermal scutes associated to the skeleton of *Malawisaurus*. The osteoderms in *Malawisaurus* are ellipsoid, with a plain internal surface and a concave external surface. This morphology is strikingly different from that observed in UFMA 1.10.1958. Two different dermal bones components are observed in *Saltasaurus*: oval plates with external conical surface and tiny subspherical ossicles arranged as a mosaic (Bonaparte and Powell, 1980; Powell, 1980, 2003). The dermal plates assigned to *Saltasaurus* are ellipsoid and keeled osteoderms. Salgado et al. (2005) described two keeled osteoderms associated to *Neuquensaurus*, the larger one exhibits a typical shallow concavity at the external surface and a longitudinal keel at the internal surface, which is different from the smaller osteoderm. UFMA 1.10.1958 is distinct from any osteoderm attributed to *Saltasaurus* and *Neuquensaurus* by having a root at the internal surface and not a longitudinal keel.

Two small osteoderms assigned to titanosaurs were described from the Marília Formation (Bauru Basin, Maastrichtian) at Peirópolis, municipality of Uberaba, Minas Gerais State (Azevedo and Kellner, 1998; Marinho and Candeiro, 2005). These osteoderms were characterized by a rugose external surface, internal interwoven pattern, absence of a cingulum and presence of an internal ridge. UFMA 1.10.1958 differs from these osteoderms by clearly having a cingulum and by the absence of an internal longitudinal ridge. An osteoderm associated to the skeleton of *Maxakalisaurus topai* was described by Kellner et al. (2006), from Prata, Minas Gerais State (Bauru Basin, Adamantina Formation). In external view, this osteoderm is elliptical and has a strongly convex external surface, with an elevated midline, and a less convex internal surface. Although UFMA 1.10.1958 also presents convex internal and external surfaces, the osteoderm of *Maxakalisaurus* does not present a cingulum or a well-delimited root and bulb structures as the Laje do Coringa material does.

Recently, a large ellipsoid osteoderm was described by Marinho and Iori (2011) from the municipality of Ibirá, São Paulo State (Bauru Basin, Adamantina Formation). This osteoderm exhibits a well-delimited external bulb and a plain internal surface in lateral view. This osteoderm differs from UFMA 1.10.1958 by having a proportionally smaller bulb located at one of the extremities of the bone and by having a plain internal surface.

The bulb and root limited by a cingulum are rare in titanosaur osteoderms, being much more common a ridges or keels in the internal or external surfaces or in both. In internal view, the interwoven pattern and foramina are not very evident in UFMA 1.10.1958. This feature quality might be related to the quality of preservation, as it is a common characteristic that is present in amniote osteoderms (Hill, 2005; Romer, 1956). We assume here that this pattern was occulted by the intense permineralization, substitution, and transport underwent by UFMA 1.10.1958; therefore, this specimen is here referred to as Titanosauria indet.

8. Conclusions

The presence of UFMA 1.10.1958 in deposits of the Alcântara Formation corroborates the hypothesis that armored titanosaurs inhabited the northernmost portion of South America during the early Late Cretaceous. However, new well-preserved and articulated specimens will provide a better understanding of the real diversity of these armored sauropods in Brazil.

Finally, considering that the Alcântara Formation is regarded as Cenomanian in age, this osteoderm, together with those ones reported for *Malawisaurus*, is one of the oldest occurrences of this type of dermal bone known to date.

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