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# Cenomanian vertebrates of the São Luís Basin

## *Vertebrados do Cenomaniano da Bacia de São Luís*

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**ABSTRACT:** The Cretaceous Period is represented in the northern region of Maranhão State by Aptian-Albian deposits cropping out inland and by the Cenomanian succession that is seen along the shoreline in the area of Golfão Maranhense (Large Maranhão Gulf). This region had its sedimentation processes controlled by tectonism related to the evolution of the continental margin. The Alcântara Formation is a sedimentary succession deposited in the northern coast of Maranhão state territory. It yielded a diverse fossil record, including plants and vertebrates. Based on the geologic and paleontologic evidences, the paleoclimate inferred for the studied region was markedly seasonal, with a stormy short season followed by a long dry season, eventually resulting in severe droughts. The fossils collected and studied revealed the biota that lived in northeastern South America in the early Cenomanian including conifers, giant ferns and a diverse community of vertebrates represented by fishes, crocodiles, pterosaurs and dinosaurs.

**KEYWORDS:** Alcântara Formation; São Luís Basin; Cretaceous; Cenomanian.

**RESUMO:** O Período Cretáceo está representado na região norte do estado do Maranhão por depósitos aptianos-albianos que ocorrem no interior e pela sucessão cenomaniana que se observa ao longo da linha de costa, na área do Golfão Maranhense. Esta região teve seus processos de sedimentação controlados pelo tectonismo relacionado à evolução da margem continental. A Formação Alcântara é uma sucessão sedimentar depositada no litoral norte do estado do Maranhão. Ela possui um registro fóssil diversificado, incluindo plantas e vertebrados. Com base em evidências geológicas e paleontológicas, o paleoclima inferido para a região estudada era marcadamente sazonal, com uma curta estação de chuvas tempestuosas seguida por uma longa estiagem, resultando em secas severas. Os fósseis coletados e estudados revelaram a biota que viveu no nordeste da América do Sul no início do Cenomaniano, incluindo coníferas, samambaias gigantes e uma diversificada comunidade de vertebrados representados por peixes, crocodilos, pterossauros e dinossauros.

**PALAVRAS-CHAVE:** Formação Alcântara; Bacia de São Luís; Cretáceo; Cenomaniano.

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## INTRODUCTION

The sedimentary deposits of the Alcântara Formation extend over most of the Golfão Maranhense (meaning large Maranhão gulf) area into the São Luís Basin, northeastern Brazil. Outcrops of this lithostratigraphic unit are usually seen in the São Luís Island and along the continental coast line of São Marcos (west side of the gulf) and São José (east side) bays. Historically, this succession has also been regarded as the Alcântara Member of the Itapecuru Formation, which is predominantly formed by continental deposits extending over most of the northern territory of Maranhão State, markedly along the Itapecuru river valley (Fig. 1). These Cretaceous deposits spans from the late Aptian to the early Late Cretaceous (Mesner & Wooldridge 1964; Campbell 1949; Pedrão et al. 1993a, b; Vivalvi & Carvalho 2002; Carvalho et al. 2003). We consider the studied succession as the Alcântara Formation (*sensu* Cunha 1968), which concordantly overlies the Itapecuru Formation.

The Alcântara Formation has been interpreted as an incised valley filled by sediments deposited under a tide dominated estuarine environment (Rossetti & Truckenbrodt 1997). This Cretaceous formation consists of a 30 to 35m succession of sandstones, limestones, argillites and conglomerates (Mesner & Wooldridge 1964, Klein & Ferreira 1979, Pedrão et al. 1993, Rossetti 1997, 2001; Holz 2003). These deposits revealed a record of the Cenomanian continental vertebrates including fishes, crocodiles, dinosaurs and pterosaurs associated with petrified plant remains. The present paper focus on the vertebrate fossil record of the Alcântara Formation rejoining all data published thus far and interpreting paleoenvironmental and paleoclimate aspects based on the taxa that lived in that region in the mid-Cretaceous.

## GEOLOGIC SETTING

The evolution of the coastal zone of northern Brazil was controlled by thermo-tectonic processes of passive margins (Gilchrist & Summerfield 1994). Sedimentary dynamics and landform features are directly related to the structural and sedimentary development of the tectonically affected coastal basins (Souza Filho 2000). The São Luís Basin is an E-W oriented graben bounded by normal faults located in the central portion of the Gurupi Graben System. It includes a structural high and grabens confined by WNW-ESE and NW-SE oriented normal faults and NE-SW strike-slip faults (Soares Jr. et al. 2011). The normal faults can reach vertical extension up to 2,000 m (Mesner & Wooldridge 1964).

Presumably, the area has a geomorphological evolution dating back to the Early Cretaceous. It is evidenced by intense faulting in the sedimentary rock successions related to the tectonic activity of the strike-slip and normal faults (Aranha et al. 1990, Costa et al. 1996, Souza Filho 2000, Soares Jr. et al. 2011). The faulted blocks of the northern portion of the basin (Asmus & Guazelli 1981) mark the transition to the Santana Island platform. In the southernmost portion of the São Marcos bay large lineaments passing through the Crabs Island and Itapeua Beach locally evidences a tectonic control of the Cretaceous sedimentation (Figure 1). This tectonism is related to the opening of the Equatorial Atlantic Ocean (Aranha et al. 1990, Costa et al. 1996, Souza Filho 2000, Soares Jr. et al. 2011).

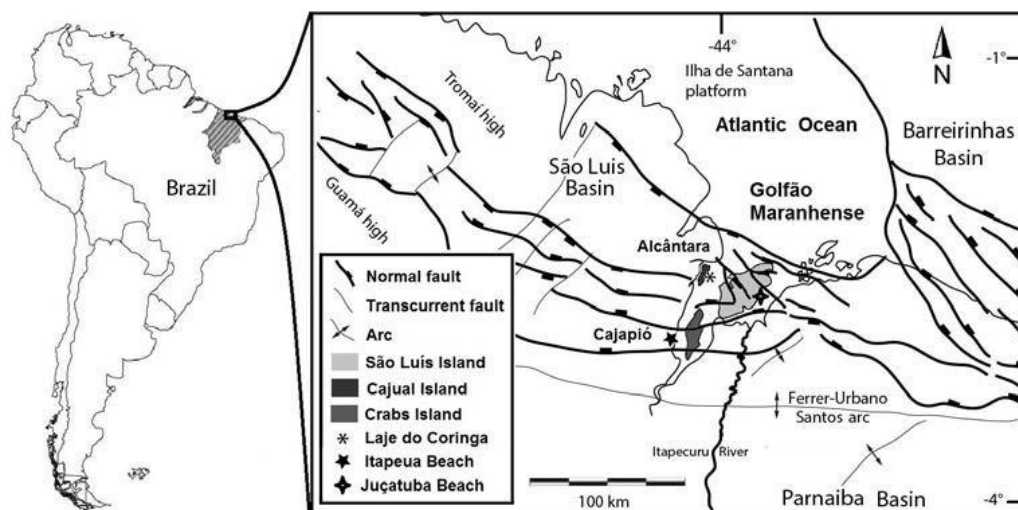


Figure 1: Map of northern Maranhão state including Golfão Maranhense and the localities Alcântara, Cajual Island, São Luís Island, Cajapió and the Itapecuru river valley. The tectonic compartmentation showing faults, structural highs and tectonic arc between the basins is based on Veiga Jr. & Oliveira (2000).

Structural subdivision of the northern and central portion of the Maranhão State, supported by geophysical data, is defined by two distinct sedimentary, tectonic and geochronological domains: 1) Parnaíba Basin, in the south and 2) Mesozoic basins along the continental margin. The structural high Ferrer-Urbano Santos (Fig. 1) separate these domains. They represented important Early Cretaceous dividers and strongly influenced the evolution of the basins along the coastal margin (Veiga Jr. & Oliveira 2000). The establishment of these structural highs is closely associated with the mid-Mesozoic rifting process and originated the Mesozoic São Luís and Barreirinhas basins.

Góes & Rossetti (2001) considered the São Luís Basin as contiguous to the continental Grajaú Basin, defining both areas as the São Luís-Grajaú Basin. These authors assumed that the barrier separating these two depressions was not effective as a basin divider. They also included the Aptian-Albian strata that crops out along the Itapecuru river valley and the upper succession, including the Cenomanian levels of the Alcântara region in the so called Itapecuru Group (Góes & Rossetti 2001, Rossetti 2001), assuming the Cenomanian strata as the Alcântara Formation (*sensu* Cunha 1968). Nonetheless, traditionally the São Luís Basin has been considered as a small coastal independent basin and the so called Grajaú Basin is assumed as the northern portion of the Parnaíba Basin (see Klein & Ferreira 1979; Vicalvi & Carvalho 2002; Carvalho 1995, 2001; Carvalho *et al.* 2003, Pessoa & Borghi 2005, Pedrão *et al.* 2003 a, b).

## MATERIAL AND METHODS

In the region of Alcântara most of the collected specimens were removed directly from the host rock using traditional excavating tools. A remarkable concentration of skeletal elements was recorded in the Laje do Coringa fossiliferous site (Fig. 2a). Small specimens were collected by sieving the sediment. The only set of associated skeletal elements belonging to a large animal (a diplodocoid sauropod) was discovered at Itapeua Beach (Fig. 2b), Cajapió city, lying on an area of about 30m<sup>2</sup> in a mudstone on the intertidal zone, and was exposed by the action of the waves. Bones that required more than two hours to be exhumed were involved with steel wire, flexible aluminum film and synthetic polyurethane foam to stand one or more tide cycles until they got ready to be safely removed into plaster involucres. After the removal, the materials were transported to the laboratory to be clean, prepared and studied.

Specimens were studied by using pachymeters, binocular magnifiers, petrographic microscope and scanning electron microscope. The morphological and anatomical analysis were made by comparison with

specimens of fossil collections in Brazil (Departamento Nacional de Produção Mineral, Universidade Federal do Rio de Janeiro), Argentina (Universidad Nacional del Comahue; Fundación Miguel Lillo), Portugal (Centro Português de Geo-História e Pré-História) and USA (American Museum of Natural History), and also by comparison with published data concerning taxonomic features considered as diagnostic.

## RESULTS AND DISCUSSION

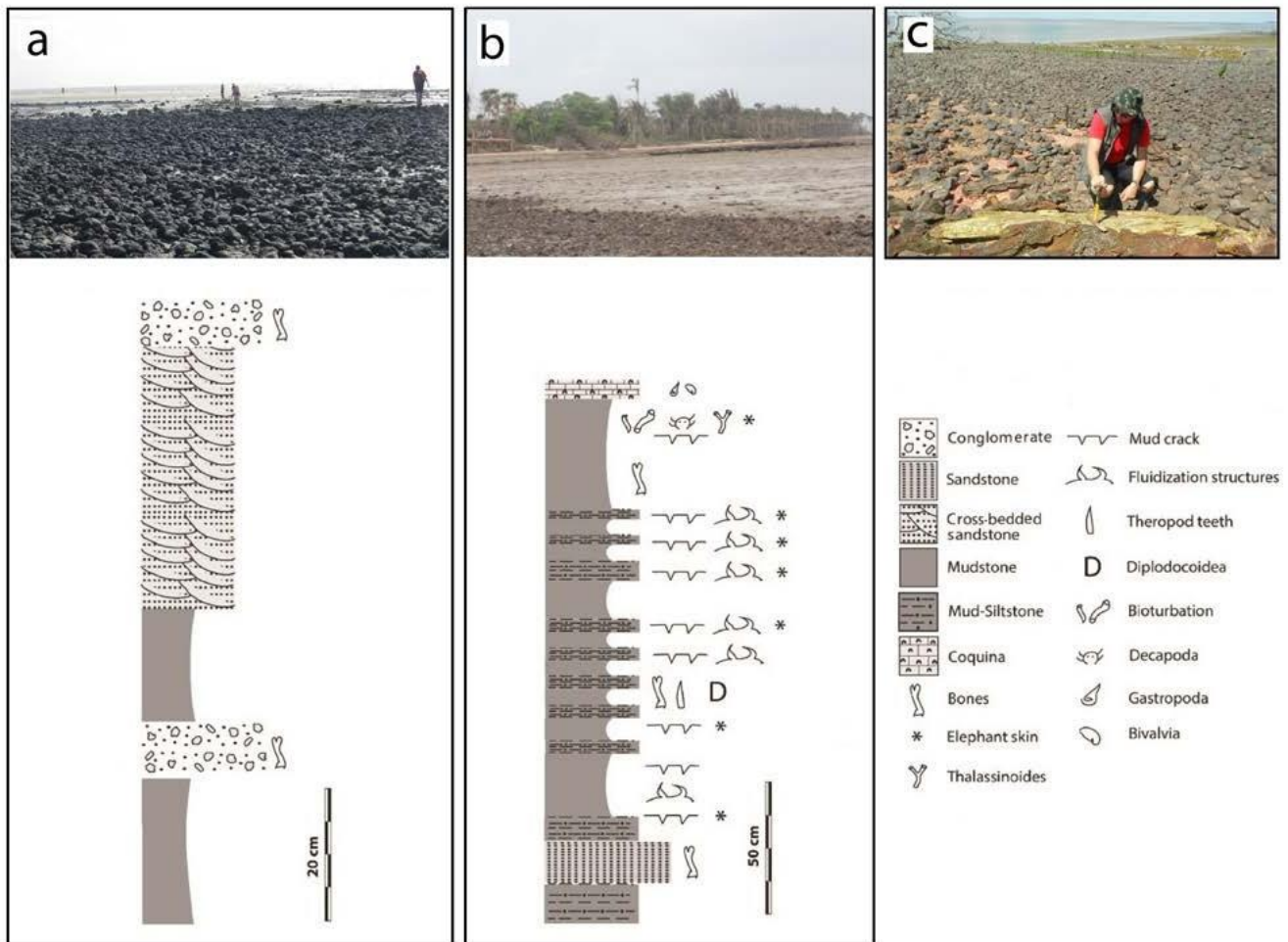
Cretaceous fossils are usually found exposed on the tidal plains of the northern Maranhão State, in Alcântara, Cajapió, São Luís and surrounding areas. These strata are considered as belonging to the Alcântara Formation (Cenomanian). Fossil remains are found in the sandstones, mudstone and conglomerates and seismic cracking are seen on several exposed levels. NW-SE normal faults and NE-SW strike slip faults are clearly distinguished in the mudstone and greenish clayey silt level at Itapeua Beach (see Fig. 1).

Along the coastal bluffs and flagstones of the Golfo Maranhense several fossiliferous sites have provided a record of the continental biota that lived in the mid-Cretaceous of northeastern South America.

Thus far only conifer logs have been collected in São José bay, mainly at Juçatuba Beach (Figs. 1 and 2c), but a diverse paleocommunity of vertebrates has been recorded in the strata of São Marcos bay, including mainly bones, teeth, scales, spines and coprolites associated to conifer logs and fern stalks (Fig. 3) along with an expressive dinosaur tracksite (Carvalho & Gonçalves 1994, Carvalho 1995, 2001; Corrêa-Martins 1997, Medeiros & Schultz 2002, Medeiros *et al.* 2014a, b; Lindoso *et al.* 2012, 2013; Sousa *et al.* 2015).

The vertebrate fossils collected in the Alcântara Formation (early Cenomanian) are: skull bones of the coelachantiform fish *Mawsonia gigas* (Carvalho 2002, Medeiros *et al.* 2011), teeth of the theropod dinosaur *Carcharodontosaurus* and bones and teeth of spinosaurids (Vilas Bôas *et al.* 1999; Medeiros & Schultz 2002; Medeiros 2006, Medeiros *et al.* 2014a); dental plates of dipnoi fishes, mainly *Ceratodus brasiliensis* and *Arganodus tiguidiensis* (= *Asiatoceratodus tiguidiensis*; see Dutra & Malabarba 2001); vertebrae of titanosaurids and diplodocoids (Medeiros & Schultz 2002, Castro *et al.* 2007, Medeiros *et al.* 2014a); and material referred to the crocodylid *Candidodon itapecuruense* (Carvalho 1994, Santos *et al.* 2011).

These taxa have also been collected in the Itapecuru river valley (Fig. 1). The occurrence from the late Aptian (Itapecuru Formation) to the early Cenomanian (Alcântara Formation) suggests that the same vertebrate fauna lived in northeastern South America for more than thirteen million years, possibly evolving only at the level of species in some cases (see Medeiros *et al.* 2014a).



**Figure 2:** Main fossiliferous sites of Golphão Maranhense with stratigraphic sections shown to the most prolific ones. **a** – Laje do Coringa, a flagstone at Cajual Island, Alcântara; **b** – Itapeua Beach tidal plain, Cajapió. The upper strata, including the level with Decapoda, seems to pertain to the Pirabas Formation (Miocene); **c** – A log of conifer at Juçatuba Beach, São José bay.

In the deposits of the Cajual Island, mainly at the Laje do Coringa site, there was a taphonomic concentration of reworked material (Holz 2003) and the numbers of isolated fossils are astonishing. Thousands of theropod and pterosaurs teeth, hundreds of isolated vertebral centra and other impressive numbers of fish's teeth and scales concentrated in an area of just about 4 hectares (Corrêa-Martins 1997, Medeiros & Schultz 2002, Medeiros *et al.* 2014a). Most of the material is disarticulated and severely abraded, but many specimens are identifiable. On the other hand, the Itapeua deposit includes a partial skeleton of a large herbivorous dinosaur (a diplodocoid), including bones of the rib cage, pelvic girdle and tail. Thus, the taphonomic history of Itapeua is completely different from that of the Laje do Coringa site. The diplodocoid carcass must have been shortly transported by a current, experiencing disarticulation. Nonetheless, many vertebrae and other bones remained close together trapped and

preserved in a muddy stratum. Many of them underwent deterioration but retained diagnostic characters. A detailed approach on anatomy and taxonomy of this material is to be presented in an upcoming article (Lindoso *et al.* submitted).

Titanosauria (Figs 3A e 3D) is one of the sauropods present in the Alcântara Formation assemblage, but Diplodocoidea isolated vertebrae (Fig. 3B) are far more numerous. It seems that the diplodocoids were dominant amongst the sauropods in the beginning of the Cenomanian in northeastern South America. The only two partially preserved skeletons of Cretaceous sauropods found thus far are of Diplodocoid - *Amazonsaurus maranhensis*, in the Itapeuru river valley (Itapeuru Formation), and the specimen of Itapeua Beach, at Cajapió (Carvalho *et al.* 2003, Medeiros *et al.* 2015). In contrast, sauropod teeth (Fig. 3E) are very rare in the same deposits where vertebrae were collected, what is interpreted as a taphonomic bias.

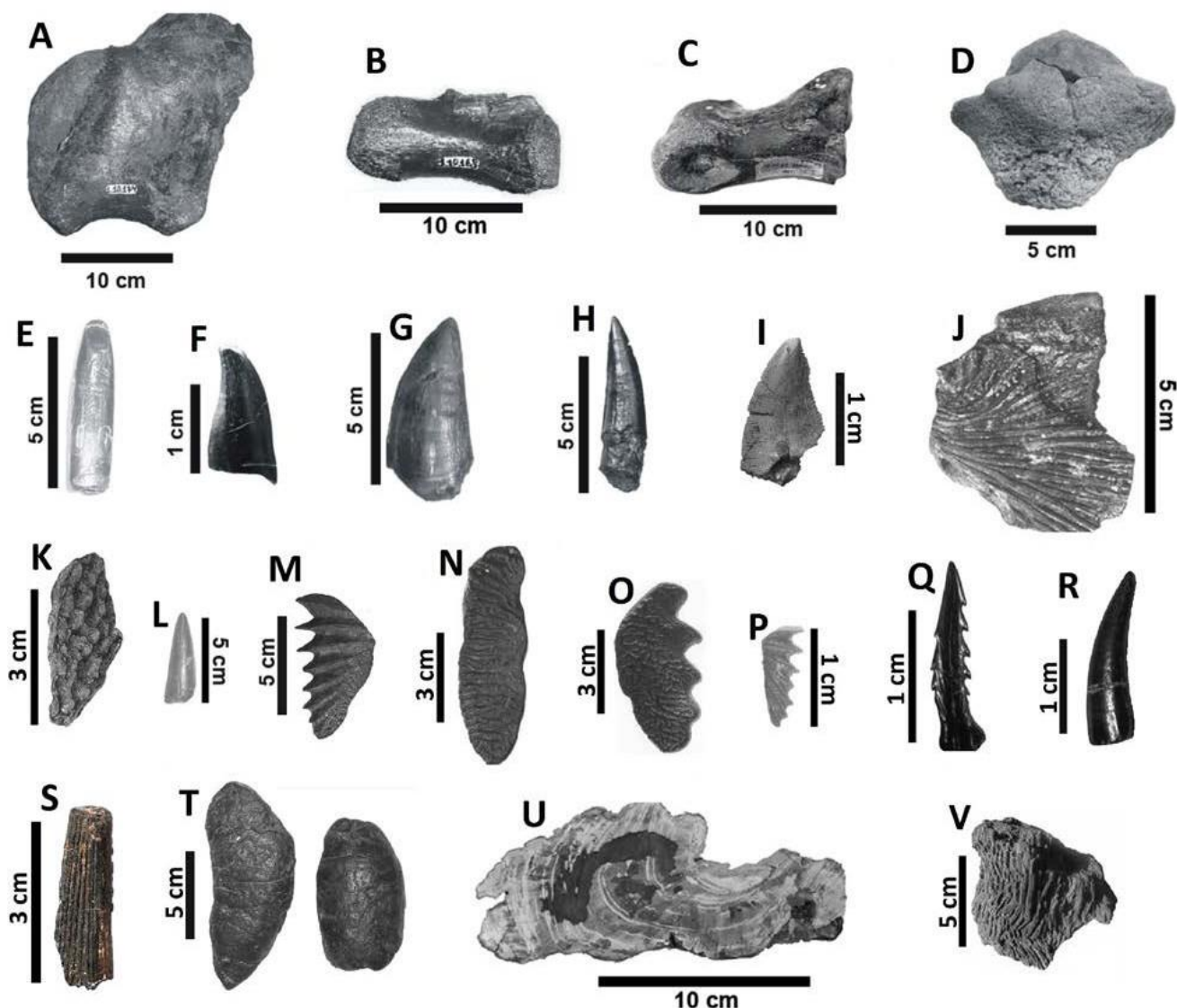


Figure 3: Fossils from the Alcântara Formation: A – UFMA 1.10.174 - caudal vertebra of a titanosaurid sauropod; B – UFMA 1.10.168 - caudal vertebra of a diplodocoid sauropod; C – UFMA 1.10.016 - phalanx of a theropod dinosaur; D – UFMA 1.10.1958 - osteoderm of a titanosaur; E – UFMA 1.20.473 - sauropod tooth; F – UFMA 1.20.554 - small theropod tooth related to *Masiakasaurus*; G – UFMA 1.20.029 - tooth of *Carcharodontosaurus* sp.; H – UFMA 1.20.069 - tooth of Spinosauridae; I – UFMA 1.20.584 - tooth of an unidentified small to medium sized theropod; J – UFMA 1.40.032 - cranial fragment of *Mawsonia gigas*; K – CPHNAMA VT 1486 - osteoderm of a crocodile; L – UFMA 1.30.032 - tooth of crocodile. Dipnoi dental plates: M – UFMA 1.40.088 - *Ceratodus brasiliensis*; N – UFMA 1.40.086 - *Equinoxiodus alcantarensis*; O – UFMA 1.40.085 - *Equinoxiodus schultzei*; P – UFMA 1.40.454 - *Arganodus tiguidiensis*. Q – CPHNAMA VT 1085 - rostral tooth of *Atlanticopristis equatorialis*; R – UFMA 1.30.038 - tooth of ornithocheiroid; S – UFMA 1.40.528 - *Tribodus limaе* dorsal spine; T – UFMA 3.10.139 - coprolites of undetermined reptiles; U – UFMA 2.10.123 - log of conifer in cross section; V – UFMA 2.10.104 - stalk fragment of *Paradoxopteris sanctiluigi* (full descriptions in: Vilas Bôas, 1999; Mussa *et al.* 2000; Castro *et al.* 2004; Elias *et al.* 2007; Pereira & Medeiros 2008; Araújo *et al.* 2011, Toledo *et al.* 2011, Souto & Medeiros 2012, Lindoso *et al.* 2012, 2013; Medeiros *et al.* 2014a, Sousa *et al.* 2015). UFMA: Universidade Federal do Maranhão; CPHNAMA: Centro de Pesquisa de História Natural e Arqueologia do Maranhão.

Identifiable theropod bones are less commonly found in the deposits of the Alcântara Formation when compared to the collected sauropod vertebrae. Nonetheless, some specimens are undoubtedly recognized as pertained to large predatory animal, as some big phalanxes (e.g. Fig. 3C). On the other hand, large theropod teeth are amongst the most common items found in the Laje do Coringa site, at

Cajual Island. Based on hundreds of isolated teeth collected we can confidently affirm that there were large predatory dinosaurs of two distinct theropod groups living in the early Cenomanian in the northeastern Brazilian territory: *Carcharodontosaurus* (Carcharodontosauridae, Fig. 3G) and spinosaurids (Fig. 3H). The possibility of more than one morphological species of Spinosauridae was

evidenced by distinct pattern of teeth found in the Cajual Island (Medeiros 2006). One species has been named *Oxalaia quilombensis*, based on some cranial features (Kellner *et al.* 2011). Small theropod teeth have also been collected. An interesting *Masiakasaurus*-like morphotype (Fig. 3F) established a link in-between the Cenomanian Brazilian fauna and that of the Maastrichtian of Madagascar. The species of Abelisauroida (Noasauridae) recorded in the Alcântara Formation is bigger and much older than the malagasy one (Lindoso *et al.* 2012).

Since most of the tetrapod fossil items found in the Laje do Coringa site are continental, transported by fluvial currents, buried, reworked and definitively deposited in an estuarine context (see Holz 2003) associated to fresh water fish remains, we should expect a more expressive occurrence of material related to crocodiles. Nonetheless, crocodile fossils are very rare in the Laje do Coringa site and still rarer in other sites of the Alcântara Formation; just a few osteoderms and teeth (Figure 3K, L) have already been collected. This fact is an interesting and still obscure question and seems to be related to any taphonomic effect.

*Mawsonia gigas* (Mawsoniidae), a freshwater Coelacanthiform fish, is represented by fragments of its huge cranial bones (Fig. 3J). The specimens collected from the Alcântara Formation are amongst the biggest ever recorded. Some skull bones suggest that the largest specimens could reach more than 4 meters in length (Medeiros *et al.* 2011, Medeiros *et al.* 2014a).

One of the most remarkable records amongst the vertebrates is that of lungfishes. Several Dipnoi species have been identified or created to accommodate the variety of tooth plates found at Laje do Coringa site (Figs. 3M, N, O e P). *Ceratodus africanus*, *Arganodus tiguidiensis* (= *Asiatoceratodus tiguidiensis*), *Equinoxiodus alcantarensis* and *E. schultzei* are commonly collected (Castro *et al.*, 2004, Toledo *et al.*, 2011, Medeiros *et al.* 2014a, Sousa *et al.* 2015, see also Dutra & Malabarba 2001). On one hand, *Mawsonia gigas*, as well as large semionotids scales collected in the same sites, indicate that a large river flowed into the north coast of Maranhão state territory. On the other hand, the presence of several species of lungfishes indicates that the environmental conditions were very suitable to this group adapted to long dry seasons. To reconcile these conflicting evidences, we interpreted the climate of the region as having a well defined seasonality, with a short stormy season followed by frequent prolonged droughts (Medeiros *et al.* 2014 a, b, Sousa *et al.* 2015).

Two Sclerorhynchidae rays were recorded in the Cajual Island deposits. They were identified by their pre-

served rostral teeth: *Onchopristis numidus* (rare) and *Atlanticopristis equatorialis* (Fig. 3Q; Pereira & Medeiros 2008) that is much more numerous. Hybodontiform fresh water sharks are represented by *Tribodus limae*, whose dorsal spines (Fig. 3S) were found (Medeiros *et al.* 2014a).

One of the most common fossils found in the Laje do Coringa site is the characteristic teeth of Ornithocheiroidea pterosaurs (Fig. 3R; Elias 2006, Elias *et al.* 2007). More than a thousand have been collected in the locality, indicating animals that could have wingspan of more than 3 meters. This impressive number may indicate that the estuary would be used as feeding and/ or nesting area (Lindoso *et al.* 2011). Other taxa that are part of the Cenomanian paleobiota are an undetermined species of turtle referred to *Pelomedusoides* collected in the region of Alcântara (Moraes-Santos *et al.* 2001), the small sized crocodiles *Coringasuchus anisodontis* and *Candidodon itapecuruense* (Kellner *et al.* 2009; Santos *et al.* 2011), the snake *Seismophis septentrionalis* (Hsiou *et al.* 2014), and an undetermined Unelangiinae theropod (Letízio *et al.* 2017). There is also the teeth of a small to medium sized theropod that have morphological characters similar to velociraptorine dromaeosaurids (Vilas Bôas 1999; Elias 2006), but is still to be definitively identified (Fig. 3I). Some small serrated teeth collected at Baronesa Beach, Alcântara, exhibiting similar morphology have recently been attributed to an abelisaurid (Sales *et al.* 2018).

Coprolites of different morphologies are very common in the Laje do Coringa site (Fig. 3T). Some of them have been analyzed revealing successive mineralization processes that culminated with goethite and limonite impregnation. The inner content indicated different taxa with distinct diets: herbivorous and carnivorous tetrapod and carnivorous fishes, probably chondrichthyes. The different morphologies of the hundreds of coprolites collected are consistent with the variety of fossil taxa known from this locality and confirm the presence of diverse trophic levels in this region during the Cenomanian (Souto & Medeiros 2012).

The humid zone of the large estuary was covered by conifers (Figs. 2C e 3U), dominantly Araucariaceae (Araújo *et al.* 2011; Medeiros *et al.* 2014a, b) and the giant fern *Paradoxopteris sanctiluigi* (Fig. 3V), a South American species (Mussa *et al.* 2000) that thrived along the margins of the coastal streams. Most of the vertebrate fauna was probably concentrated into the vegetated perimeter (Medeiros *et al.* 2014a, b) surrounding what is today the area of the Golfão Maranhense (Fig.1), since the landscape around the estuary were semi-arid to arid (Pedrão *et al.* 1993a).



The fish and tetrapoda remains were transported by fluvial currents before being reworked and definitively buried on the Early Cenomanian shoreline (Holz 2003). As the fossiliferous sites including vertebrates are located in the São Marcos bay, it may indicate that the river discharge could be concentrated in the western side of the studied area. Thus far, no vertebrate remains have been found in São José bay.

Thus, the Alcântara Formation has been very informative on the vertebrate fauna that lived in northeastern South America along the transition from Early to Late Cretaceous. The taphonomic processes concentrated thousands of bones, teeth, scales, logs and other kinds of fossils in the coastal deposits of this stratigraphic unit, now opening a unique window that reveals the biota that thrived in the northeastern South America during the mid-Cretaceous.

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