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TECTONIC ASPECTS OF THE RIO PARNAÍBA LINEAMENT, DUQUE BACELAR REGION, MARANHÃO STATE, BASED ON THE RECORD OF DINOSAURIA, SPINOSAURINAE

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ABSTRACT – This article shows the tectonic influence of the Parnaíba River Lineament located in the Parnaíba Basin through a paleontological finding of a Cretaceous age close to a Permian sequence. The studied region is in the northeast of the State of Maranhão, near the town of Duque Bacelar, in the vicinity of the lineament. A normal fault in the NNE-SSW direction was responsible for the lowering of the Itapecuru Formation strata (Cretaceous) and the relative upward movement of the Pedra de Fogo Formation (Permian). The unprecedented finding of a Mesozoic (mid-Cretaceous) theropod tooth located topographically at the same level as a Paleozoic unit represents evidence of tectonic activity affecting the stratigraphic successions of the Parnaíba Basin.

Keywords: Parnaíba River Lineament, Pedra de Fogo Formation, Itapecuru Formation, Spinosauridae.

RESUMO – Este artigo objetiva mostrar a influência tectônica do Lineamento do Rio Parnaíba, na Bacia do Parnaíba, através de um achado paleontológico de idade cretácea próximo a uma sequência Permiana. A região estudada encontra-se no nordeste do Estado do Maranhão, próxima ao Município de Duque Bacelar, nas proximidades do lineamento. Uma falha normal na direção NNE-SSW foi responsável pelo rebaixamento dos estratos da Formação Itapecuru (Cretáceo) e pelo movimento relativo ascendente da Formação Pedra de Fogo (Permiano). A descoberta inédita de um dente de terópode mesozoico (meso-Cretáceo) localizado topograficamente no mesmo nível de uma unidade paleozoica representa uma evidência substancial de atividade tectônica afetando aspectos estratigráficos da Bacia do Parnaíba.

Palavras-chave: Lineamento do Rio Parnaíba, Formação Pedra de Fogo, Formação Itapecuru, Spinosauridae.

INTRODUCTION

The northeast portion of the Parnaíba Basin, where the Municipality of Duque Bacelar is located in Maranhão State, is under the domain of an important structural feature, the Parnaíba River Lineament (Figure 1). It is a region of diverse geological history, known for its outstanding record of the Lower Permian and Cretaceous. In the surroundings of Duque Bacelar, the fossil record, until now, only showed Permian taxa, exclusively plants, predominantly woody, belonging to the Pedra de Fogo Formation (Conceição *et al*., 2016). The unprecedented finding of a tooth with indicative characteristics of Theropoda (Dinosauria) north of the municipality, a few kilometers away from the Permian fossiliferous sites, evidenced the need for a more detailed investigation of its origin in the stratigraphic context, seeking an adequate interpretation of the geological events that could be related to the findings.

Dinosaur teeth, mainly theropods, are commonly collected in the Cretaceous strata of the Itapecuru Formation (which crops out extensively in the central, northern, and northeastern regions of Maranhão) and Alcântara Formation, with fossiliferous outcrops concentrated in the northern part of the state (Corrêa Martins, 1997; Carvalho *et al*., 2003; Medeiros & Schultz, 2001, 2002, 2004; Lindoso *et al*., 2012; Medeiros *et al*., 2014, 2019; Lindoso *et al*., 2012; Sousa *et al*., 2015; Letizio *et al*., 2022). Records of the Itapecuru Formation occur near Duque Bacelar, immediately west of the Parnaíba River Valley (CPRM, 2012); however, no fossiliferous occurrences have been reported.

The theropod tooth was casually collected by a resident digging a well to obtain water at a level about five meters deep. The fact that the level at which the tooth was found, in relation to the ground surface, was practically the same as the occurrence of Permian petrified logs sparked the need for explanation explanation that included possible tectonic activity that could justify this atypical alignment.

This study contributes to the knowledge of the tectonic aspects of the northeastern region of the Parnaíba Basin by considering tectonostratigraphic issues.

Geological context of the east portion of the Parnaíba Basin

The State of Maranhão is part of the Structural Province of Parnaíba, as proposed by CPRM (2003), which presents primarily structural, lithostratigraphic, and age distinctive features, taking into account their distribution in the geographic-geological space of the country. The Parnaíba Basin occupies approximately half of this province in its central-south part. The distension related to the separation of South America and Africa was responsible for the origin of this intracratonic basin or Paleozoic syneclisis, implanted on Proterozoic to Cambro-Ordovician rifts. The rifting process related to the different stages of the opening of the Atlantic Ocean began at the Triassic-Jurassic boundary.

The rifts that preceded the Paleozoic sedimentation of the Parnaíba Basin crop out on the eastern and southeastern edges (CPRM 2012). Drilling, gravimetry, aeromagnetometry, and electrical and seismic conductivity measurements confirmed its continuity in the subsurface to the interior of the basin. The

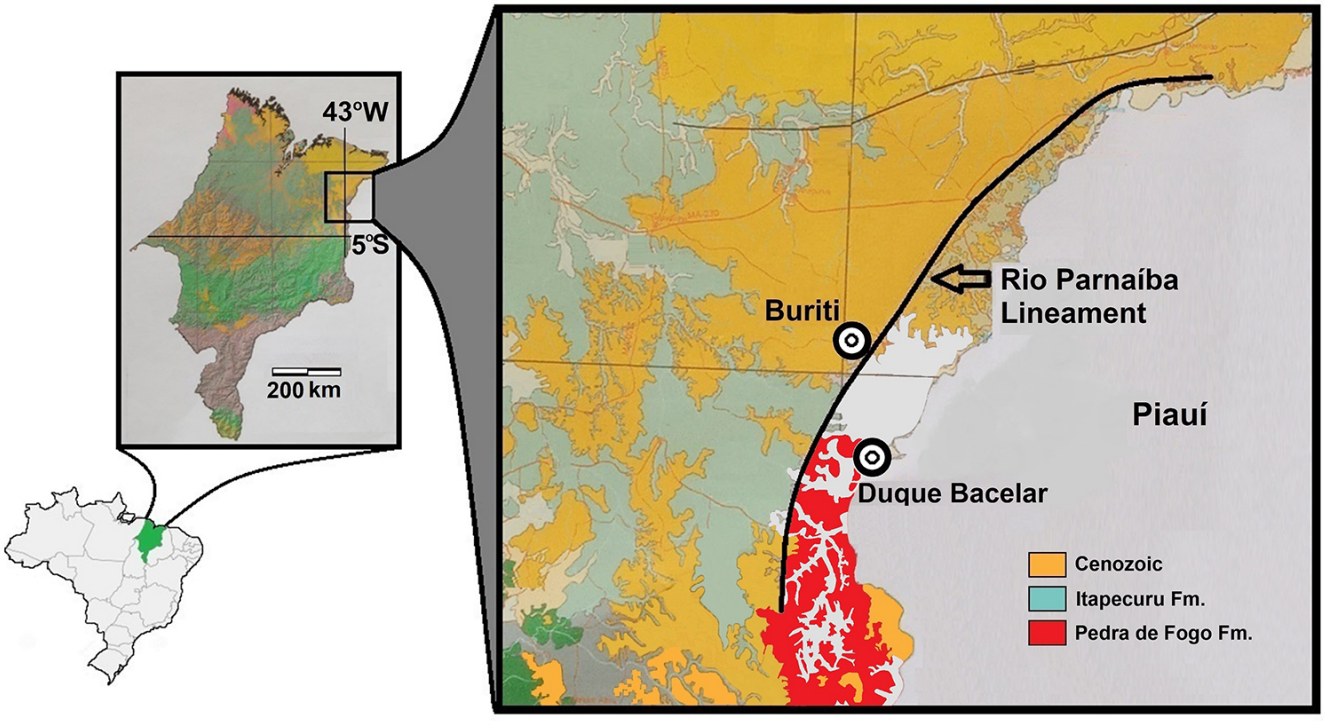

Figure 1. Relief map of Maranhão (on the left), showing the study area (enlarged on the right) of the Parnaíba Basin, highlighting the Parnaíba River Lineament. Modified from CPRM (2012) and including data from Schobbenhaus *et al*. (1981) and Conceição *et al*. (2016).

precursor rifts of the Parnaíba Basin are related to the NE-SW direction lineaments, typical of the Borborema Province, and the NW-SE lineaments of the Parnaíba Province. This reinforces the fundamental role of basement structures in the formation of the Paleozoic cratonic basins of the South American Platform (CPRM, 2012).

A common understanding of syneclyses is that they occur preferentially along highly cataclastic and tectonically unstable zones. Such zones, demarcated by structures formed by shearing, compressive, and stretching forces, indicate areas of crustal fragility and once installed, are easily affected by subsequent tectonic reactivations (Cunha, 1993). The rifts of the northeast and southeast portions have orientation NE-SW (Jaibaras, Oeiras), and some bent towards E (Cococi, São Julião) and agree with the Transbrasiliano Lineament, or Transbrazilian Fault Zone. The Balsas-Imperatriz Graben occurs at a depth of more than 1,500 m, and the sedimentary succession probed reaches approximately 1,000 m in thickness and can reach, based on seismic data, up to 4,000 m (Vasquez *et al*., 2012).

The eastern part of the Parnaíba Basin is cut by extensive NE-SW fault zones related to the Transbrasiliano Lineament, formed during the Brasiliano and reactivated in the Paleozoic. These data were confirmed by the occurrence of normal N-S oblique faults on the eastern edge, where the Rio Parnaíba Lineament has been well recorded. Other reactivated faults in the Transbrasiliano Lineament cut the faults that formed this lineament. The N-S trend was inherited from the structure of the Araguaia Belt (see summary in Vasquez *et al*., 2012).

The Map of Tectonic Domains and Map of Tectonic Associations in the State of Maranhão and the Geological Map of the State of Maranhão highlight the important feature of the Parnaíba River Lineament positioned in the northeast of the state. According to this map, the lineament has an approximate length of 150 km, preferential NE-SW direction, and inflection at the north end to E-W. It passes through Coelho Neto, Duque Bacelar, Buriti, Brejo, Milagres do Maranhão, Santa Quitéria, and São Bernardo.

The Pedra de Fogo Formation (Permian) exhibits successions that include oolitic and pisolitic limestone, cream to white, eventually stromatolitic, interspersed with fine to medium yellowish sandstone, gray shale, siltstone, anhydrite, dolomite, and flint (Plummer, 1946; Vaz *et al*., 2007). Góes & Feijó (1994) interpreted these deposits as being deposited by a shallow marine to coastal environment with sabkha plains under the possible influence of storms.

The Cretaceous Itapecuru Formation (Campbell, 1949) is formed by reddish, medium to coarse sandstones with large cross-bedding and clayey conglomeratic layers and intercalations of claystones and siltstones with a variegated color pattern (see also Lopes, 2019).

The region under analysis in this study, where the tooth was found, is in the northeast of Maranhão and is located in the eastern portion of the Parnaíba Basin (Figure 1).

MATERIAL AND METHODS

Samples of the exposed facies along the well wall were collected and analyzed for their granulometric, textural, and color characteristics. The facies were photographed *in-situ* to create a stratigraphic profile (Figure 2). The tooth, collected in August 2015, came from the village of Santa Helena, between Duque Bacelar and Buriti, in the northeast of Maranhão. It is housed in the Museum of Natural and Environmental History of the Parnaíba Valley (**MUHNAP**), under the registration number MUHNAP-210, in Duque Bacelar. The specimen was analyzed and photographed using a *Leica* EZ4W stereoscopic microscope with an integrated 5.0-megapixel WIFI camera connected to a computer.

RESULTS

As for the lithography of the area where the specimen was collected, it was possible to identify five different lithofacies (Figure 2) by analyzing the sediment samples collected in the well:1) silicified reddish mudstone; 2) fossiliferous (gray + red) mottled siltstone; 3) friable whitish gray siltstone; 4) mottled siltstone; and 5) gray, friable siltstone, containing recent roots.

The tooth was collected from one of the mottled siltstone facies (facies 2 of the profile) at a depth of about five meters. The specimen (Figure 2) is incomplete, 2.7 cm long, missing part of the base of the crown and the entire root; there are some surface cracks. Still, it exhibits several informative morphological characters.

Its shape is long and pointed with a slight lingual inclination. The crown is divided into two faces by the non-serrated carinae. These faces (labial and lingual) have longitudinal ridges, which define longitudinal sub-facets. The cross-section is semi-circular to oval and allows a view of the internal part of the specimen, which is massive, showing that a significant portion of the base of the tooth has been lost since the pulp chamber is absent. Carinae (sharp protuberances) do not have denticulations and show enamel wrinkles along their bases.

DISCUSSION

The two lithostratigraphic units focused on this study were at least 150 million years apart in the stratigraphic column (Figure 3). This fact requires a more detailed understanding of the regional geology of northeastern Maranhão in the context of the Parnaíba Basin to explain its side-by-side alignment.

It is important to analyze some episodes in the evolution of the basin to discuss the occurrence of stratigraphic alignment between temporally distinct units, in this case, a Paleozoic unit from the Permian (Pedra de Fogo Formation) and a Mesozoic unit from the Cretaceous (Itapecuru Formation).

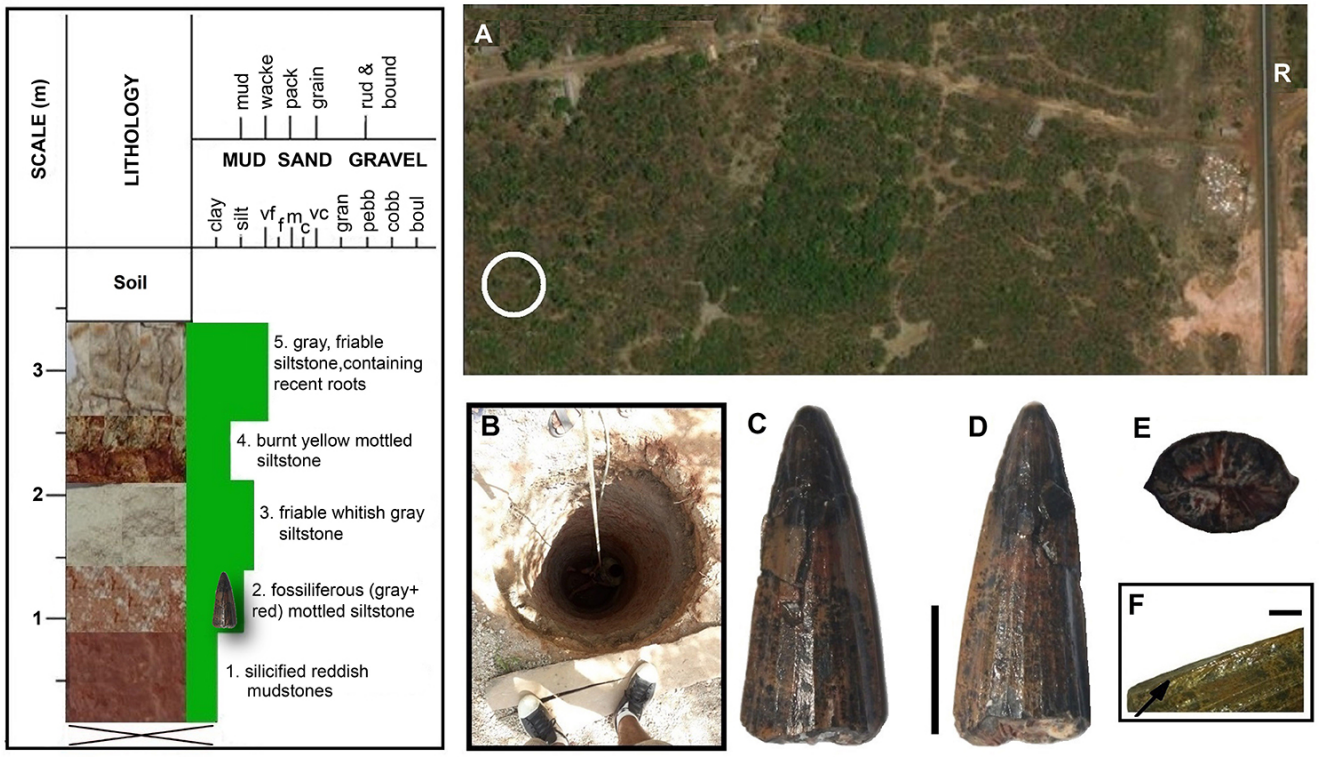

Figure 2. Satellite photo (**A**) showing the collecting area – Santa Helena village, less than 500 m from the Duque Bacelar – Buriti road (R); the white circle indicates the area where the well was excavated (40º 06'27"S; 42º 95' 85"W). Details of the well excavation to obtain water **(B).** In the rectangle on the left, the profile of the succession recorded inside the well, mounted with photos taken of facies collected *in situ* (the tooth is not on the same scale). Collected tooth on its labial (**C**) and lingual (**D**) surfaces; in the cross-section (**E**), we can see the absence of the pulp chamber and the two carinae (opposite sharp protuberances). In the magnified image (**F**), details of the non-serrated carina (arrow) can be seen, with enamel wrinkles along its base. Satellite photo from Google Earth. Scale bars: C–E = 10 mm; F = 2 mm.

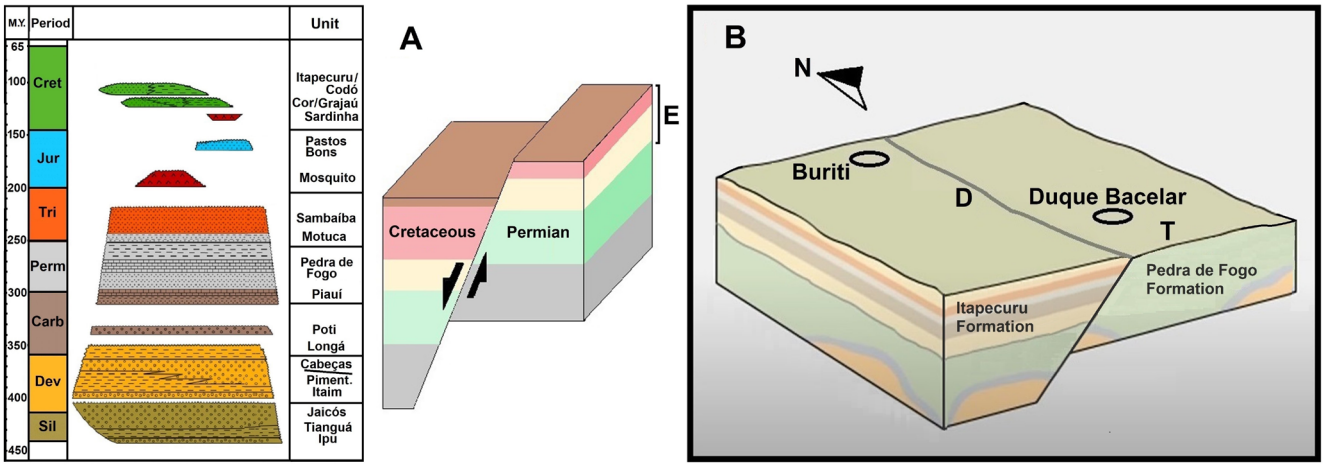

Figure 3. A, stratigraphic column of the Parnaíba Basin modified from Klöcking *et al*. (2018) and Vaz *et al*. (2007) showing the relative positions of Pedra de Fogo and Itapecuru formations. **B,** proposed geological situation along the Rio Parnaíba Lineament: normal fault with lowering of the left block (west portion), resulting in the side-by-side alignment **(B)** of the fossiliferous expositions of the Permian (Pedra de Fogo Formation) and Cretaceous (Itapecuru Formation) units. **Abbreviations: E**, corresponds to the layers that were later eroded; **D**, location of the Spinosaurinae tooth; **T**, area where are located the fossilized trunks of the Pedra de Fogo Formation described by Conceição *et al*. (2016).

It is important to note that studies in the Parnaíba Basin show that from the Late Carboniferous onwards, arches and structural ridges were established in response to uplifts on its southern and eastern edges. These structural highs interfered with the depositional axis of the Silurian and Middle Devonian–Early Carboniferous sequences, forcing migration from the depositional region to the center of the basin. There were transgressions and regressions, erosive unconformities, and sedimentation gaps in the Paleozoic sequences of the basin, all of which were related to uplift. However, the evolution of the Parnaíba Basin was controlled by an ENE-WSW extensional axis, with the installation of WNW-ESE and NNE-SSW direction rifts in the Jurassic (Klein *et al*., 2012). The literature points out that both these structures and large N-S, NW-SE, and NE-SW bend and inverse and transcurrent faults have been mapped on the surface and subsurface in the Parnaíba Basin (see summary in CPRM, 2012). The tectonics that generated these structures seem to have affected all the Phanerozoic sedimentary sequences in the context of syneclysis. It is possible that these compressive and transcurrent structures resulted from the Late Cretaceous tectonics that affected the coastal basins and that they reached more inland portions of the Parnaíba Basin. However, the relationship with the Cenozoic tectonic events cannot be ruled out (Vasquez *et al*., 2012).

The age of the Pedra de Fogo Formation has been defined as Cisuralian – Early Permian or Guadalupian – Middle Permian (see summarization and discussion in Cisneros *et al*., 2012; Conceição *et al*., 2016). Thus, a fossil tooth exhibiting features of a predatory animal found close to a typical petrified logs site of this lithostratigraphic unit should be primarily investigated because it could have pertained to a Permian tetrapod. Considering the size of the collected tooth there are some Permian groups that must be considered when investigating this possibility.

The largest Permian vertebrate recorded in the Parnaíba Basin is *Prionosuchus plummeri* Price, 1948, which is the largest Temnospondyli ever found in Permian rocks of South America. However, Temnospondyli had pleurodont teeth with an inner labyrinthine pattern of labyrinthodont folds (see summarizations and images in Santos & Carvalho, 2004; Silva & Dias, 2009). The tooth collected in the water well does not match this pattern.

Another medium-sized tetrapod group that was common in the Early Permian was the Sphenacodontidae synapsids, which had large and robust teeth, and some showed typical predatory traits. Sphenacodontians typically had bulbous tooth type, with a thickened region below the tip, folded internal architecture, blade-like and posteriorly recurved, more convex medially due to a longitudinal sulcus (or groove) near the distal cutting edge; their carinae could have large denticles (Boonstra, 1962; Paton, 1974; Brink & Reisz, 2014; Brink *et al*., 2015; Spindler, 2016). Some variation is documented, considering differences in the premaxillary, canineform, and postcanineform teeth, and amongst distinct taxa, with reported types being conical and not recurved, unserrated or having denticles-like enamel flutes (*e.g*., Paton, 1974; Eberth, 1985; Spielmann *et al*., 2010; Brink & Reisz, 2014). The widely documented types are quite different from the teeth described here, as can be easily verified by comparison with the high-quality images in Brink *et al*. (2015).

If the Pedra de Fogo Formation proves to be more recent than the Cisuralian, as proposed by some authors (see discussion in Conceição *et al*., 2016), we should investigate the possibility of finding a tooth of a medium-sized predator (or herbivore with predator-like teeth). This is representative of Dinocephalia (Therapsida), a group that ruled mid-Permian times (Guadalupian) and has been recorded in Brazil (Langer, 2000; Ribeiro & Abdala, 2011; Cisneros *et al*., 2012; Olroyd & Sidor, 2017). Most dinocephalian lineages are heterodonts, and actually one of their diagnostic features is the dentition. Incisors have a long, curved, claw-like piercing tip called talon, usually including convex and flat faces in the same tooth. The basal part of the crown includes a ledge, named heel, that may have a crushing or cutting surface. Maxillary canines usually have a large conical crown that curves moderately to strongly backward, may be flattened from side to side, and may or may not have denticulation in the cutting edge; lower jaw canines are shorter and show a blunter aspect. Postcanines are frequently spatulate, coarsely striated or serrated, sometimes presenting talon and heel (Boonstra, 1962, 1963; Rubidge, 1991, Rubidge & Van Den Heever, 1997). Even in herbivores, canines are usually long and robust (Boonstra, 1962, 1963, 1969). The good-quality images seen in Langer (2000), Ribeiro & Abdala (2011), Kruger (2014), and Sidor *et al*. (2014) illustrate the general shape, surface texture, and cross-section of the dinocephalian incisors, canines, and postcanines. In either descriptions or images, whether drawings or photos, no similarity in details can be recognized between dinocephalian teeth and the specimen described here.

The characters of the studied specimen typify it as belonging to the Spinosaurinae (Dinosauria, Theropoda). Their dental features are the general straight and conical shape, the presence of ridges and longitudinal sub-facets on the labial and lingual surfaces, and, particularly, the smooth (not serrated) carinae associated with enamel wrinkles at their bases. This set of characters is present in *Spinosaurus* Stromer, 1915, the type genus of the family Spinosauridae, a member of the subfamily Spinosaurinae (Sereno *et al*., 1998).

Spinosaurid teeth are quite similar to those of crocodiles, and this is considered significant evidence that this predator would have piscivory as its main primary feeding strategy (Charig & Milner, 1997; Holtz, 1998; Rayfield *et al*., 2007; Hone *et al*., 2010). Adaptations for a semiaquatic lifestyle in *Spinosaurus aegyptiacus* and the common occurrence of spinosaurid teeth in sediments deposited in wetlands reinforce this interpretation (Buffetaut & Ouaja, 2002; Ibrahim *et al*., 2014; Isasmendi *et al*., 2022).

Spinosaurids are recorded in Africa, Europe, South America and Asia (Buffetaut & Ouaja, 2002; Buffetaut *et al*., 2008; Hone *et al*., 2010; Alonso & Canudo, 2015). In Africa, as in South America, Spinosaurinae have been recorded in strata spanning the end of the Early Cretaceous

to the beginning of the Late Cretaceous (Stromer, 1915; Sereno *et al*., 1998; Buffetaut & Ouaja, 2002; Kellner *et al*., 2011; Medeiros, 2006; Medeiros & Schultz, 2001; Ibrahim *et al*., 2014).

Since the first report of Spinosaurine isolated teeth in this region (Medeiros & Schultz, 2001), it became one of the most commonly found fossil items in the various fieldworks we performed in the last decades; hundreds of them have been collected. It is common in Cretaceous sediments of northern Maranhão (Medeiros, 2006; Medeiros *et al*., 2014) and elsewhere worldwide (Sánchez-Hernández *et al*., 2007; Alonso & Canudo, 2015; Heckeberg & Rauhut, 2020; Isasmendi *et al*., 2022). The surprise was to find one of them just side by side with a petrified forest dated as Permian. As this dinosaur group lived during the Cretaceous, the possibility that the stratigraphic level to which it belongs is the Pedra de Fogo Formation is ruled out. The fossil tooth was considered to belong to the Itapecuru Formation, which is widely distributed in north central and northeastern Maranhão, reaching the outskirts of the Parnaiba Valley, near Duque Bacelar town (CPRM, 2012).

In addition to the fossil evidence, the sediments exposed in the well are typically found in the Itapecuru Formation (see Lopes, 2019). This fossil from the vicinity of the Rio Parnaíba Lineament, which intercepts both Cretaceous and Permian stratigraphic units, allows us to deduce that the region was affected by a geological event capable of causing a side-by-side alignment of layers of different geological ages (strata of the Pedra de Fogo Formation with those of the Itapecuru Formation; Figure 3).

Thus, it is assumed that the Spinosaurinae tooth, belonging to this second unit (Cretaceous), is aligned with a Permian unit (Pedra de Fogo Formation). Regionally, the studied area is intersected by extensive fault zones in the NE-SW direction in the context of the Rio Parnaíba Lineament, originating a structural high with preferential N-S orientation, with normal oblique components (CPRM, 2012). The right (east) block of this fault exposes the sequences of the Balsas Group, particularly the Piauí and Pedra de Fogo formations. The left block (west) exposes the Cretaceous strata of the Itapecuru Formation. It is important to note that the focus of the present study is on the local relationship between the fossiliferous strata of the Itapecuru and Pedra de Fogo formations.

As an evolutionary model to explain the alignment of the outcrops, it is proposed that the kinematics involved were responsible for the relative uplifting of the block on the right (rise of the foot wall / floor) and lowering of the block on the left (lowering of the hanging wall / upper limit) due to the normal fault movement with oblique component (Figure 3), already identified by Costa & Hasui (1997) and reported by CPRM (2012). The relative motion of these blocks on opposite sides of the fault would justify the alignment of a unit with just over 100 Ma. to another with more than 275 Ma. (Pedrão *et al*., 1993 a, b; Ferreira *et al*., 2016, 2020; Conceição *et al*., 2016). The surface of the eastern block of the fault was later eroded since the region does not show great topographical differences but subtle alterations in the elevations in the relief.

Additional fieldwork is recommended to search for elements along the fault line (slickensides), which can be observed, documented, or collected, to present more robust data of this displacement already revealed by fossiliferous evidence.

CONCLUSIONS

The finding of surface strata of the Itapecuru Formation, including a dinosaur tooth, aligned with outcrops of the Pedra de Fogo Formation, evidence vertical displacement between blocks of these two lithostratigraphic units in that region. It can be inferred that the tectonic activity inherent to the Rio Parnaíba Lineament in the NE-SW direction affected the area of Duque Bacelar, Maranhão State. The tectonic events caused an upward relative motion of Permian fossiliferous strata (Pedra de Fogo) in relation to the Cretaceous layers of the Itapecuru Formation; layers that could have been superimposed on these two lithostratigraphic units in the region were later eroded, resulting in fossils of these different ages occurring side by side on the surface in the vicinity of Duque Bacelar town.

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