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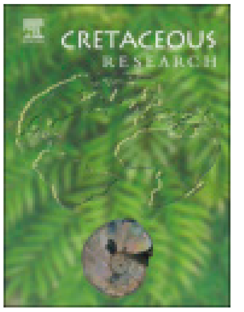

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Vinícius José Maróstica Paio[a*], Isabela Jurigan[a], Rafael Delcourt[b,d], Rafael Souza de Faria[c], Alessandro Batezelli[a], Fresia Ricardi-Branco[a]

[a] *Universidade Estadual de Campinas (UNICAMP), Instituto de Geociências, Departamento de Geologia e Recursos Naturais, Rua Carlos Gomes, 250, 13083-855, Cidade Universitária, Campinas, São Paulo, Brazil.*

[b] *Universidade de São Paulo, Departamento de Biologia, Faculdade de Filosofia, Ciências e Letras de Ribeirão Preto, Laboratório de Paleontologia, Av. Bandeirantes, 3900, 14040-901, Monte Alegre, Ribeirão Preto, São Paulo, Brazil.*

[c] *Pontifícia Universidade Católica de Campinas (PUC-Campinas), Centro de Ciências da Vida, Faculdade de Ciências Biológicas, Av. John Boyd Dunlop, s/n, 13060-904, Jd. Ipaussurama, Campinas, São Paulo, Brazil.*

[d.] *Bayerische Staatssammlung für Paläontologie und Geologie, Richard-Wagner-Straße 10, 80333 München, Deutschland*

[*] *Corresponding author*. Universidade Estadual de Campinas (UNICAMP), Instituto de Geociências, Departamento de Geologia e Recursos Naturais, Rua Carlos Gomes, 250, 13083-855, Cidade Universitária, Campinas, SP, Brazil.

E-mail adresses: dinicio.jmp@gmail.com (V.J.M. Paio), isajurigan@gmail.com (I. Jurigan), rafael.delcourt@gmail.com (R. Delcourt), rafael.faria@puc-campinas.edu.br (R.S. Faria), batezeli@unicamp.br (A. Batezelli), fresia@unicamp.br (F. Ricardi-Branco).

ABSTRACT

The Bauru Group (Campanian–Maastrichtian) has one of the richest fossil records of Cretaceous in South America. All dinosaur fossils from this unit were assigned to Saurischia, most of them poorly preserved. We present the histological and taphonomic analysis of a dinosaur dorsal rib fragment from the Marília Formation in the western state of Minas Gerais. Thin sections were prepared to describe the microstructures of the bone tissue and the fossilization processes involved in preserving the specimen. An elemental analysis was also performed to verify the chemical composition of the fossil and rock matrix. Haversian bone was identified in the rib cortex, and no growth marks or an external fundamental system were found. The rib probably belonged to a saurischian dinosaur because of its plank shape and elliptical cross-section. Hypotheses regarding taphonomic processes were inferred. An extended period of subaerial exposure, followed by high-energy transport, was interpreted due to extensive fractures and signs of abrasion on the outer surface of the bone. Pyrite pseudomorphs (framboids) indicate that the bone was deposited in a reductive environment. After burial, the rapid precipitation of calcite and alkaline stability allowed the preservation of apatite during the recrystallization phase. The manganese hydroxides were deposited on apatite crystals during early diagenesis. We concluded that the fossil rib presented a common taphonomic bias identified among vertebrate fossils of the Bauru Group, which is associated with the exposure of the bones to arid and semiarid climates, their transport into the depositional environments and pedogenetic influence during fossil diagenesis.

Keywords: Osteohistology. Bone Weathering. Fossil diagenesis. Bauru Basin.

1. INTRODUCTION

The Bauru Group is one of the richest sites for paleo-vertebrates from the Cretaceous of South America (Brusatte et al., 2017; Candeiro et al., 2020; Geroto and Bertini, 2014; Langer et al., 2022; Martinelli and Teixeira, 2015). Its dinosaur fossil records are restricted to saurischians, represented by theropods and sauropods, the last of which is exclusively composed of titanosaurs, with 11 recognized species (Faria et al., 2015; Navarro et al., 2022; Silva Junior et al., 2022). For theropods, only three species have been described: the abelisaurids *Thanos simonattoi* Delcourt and Iori, 2020 and *Kurupi itaata* Iori et al., 2021, and the unenlagiine maniraptoran *Ypupiara lopai* Brum et al., 2021b. However, most of the dinosaur fossils in the Bauru Group are isolated or disarticulated bone fragments (Candeiro et al., 2019; Cavalcanti et al., 2021; Delcourt and Langer, 2022; Silva Junior et al., 2017) and numerous theropod teeth (Candeiro et al., 2017; Delcourt et al., 2020; Tavares et al., 2014). Despite the poor preservation of diagnostic characteristics, fossils contain relevant paleoecological information, such as signs of predation (Reis et al., 2023), saprophagous organism activities (Paes Neto et al., 2018), and illnesses and parasite-host relationships (Aureliano et al., 2021b).

Paleohistological studies have contributed to a considerable number of recent discoveries involving the ontogeny, phylogeny, biomechanics, and paleoenvironment of dinosaurs and other extinct organisms (Bailleul et al., 2019; Chinsamy, 2023; Padian, 2013). Based on petrography and histology, paleohistological techniques include preparing, cutting, and mounting fossils on thin sections to analyze microscopic structures preserved inside bones, tendons, eggshells, or other tissues (Lamm, 2007). Paleohistological analyses have been applied to study Brazilian dinosaur records covering several fields of research; for instance, ontogenetic identification (Ghilardi et al., 2016; Sayão et al., 2020; Souza et al., 2020), description of osteohistological structures, and paleopathology (Aureliano et al., 2021b, 2021a; Barbosa et al., 2016; Brum et al., 2021a).

Paleohistological techniques can provide insight into the taphonomy of a fossil. Bone structure and tissues can preserve evidence of pre-burial processes such as decomposing organisms (Kremer et al., 2012; Owocki et al., 2016) and bone exposure (Pfretzschner and Tütken, 2011; Previtera, 2019, 2017). Additionally, minerals deposited within the internal spaces of bones can indicate sub-surface conditions that favored fossil diagenesis and its changes over time (Clarke, 2004). Authigenic minerals provide information about the depositional paleoenvironment, such as oxidation levels and pH, when analyzed for their composition (Wings, 2004). They are also useful for comparing diagenetic processes in different formations (Rogers et al., 2020).

However, taphonomic studies of vertebrate fossils from the Bauru Group (Upper Cretaceous) are rare and have only been applied to a few tetrapod groups such as crocodylomorphs (Araújo Júnior and Marinho, 2013; Vasconcellos and Carvalho, 2006) and testudines (Bertini et al., 2006). Studies comparing the modes of preservation of different taxa are even rarer (Azevedo et al., 2013; Bandeira et al., 2018). Regarding fossil diagenetic patterns, Garcia et al. (2005) proposed a general model for bone microstructure preservation in the Uberaba, Adamantina, and Marília formations. In recent years, only three studies on the fossil diagenesis of bones in the Bauru Group have been published. The research of Marchetti et al. (2019) examined specimens of the crocodylomorph *Montealtosuchus arrudacamposi* Carvalho et al., 2007, from the Adamantina Formation. Pinto et al. (2020) conducted a geochemical analysis of turtle bone fragments collected from the outcrops of the Presidente Prudente Formation, which is equivalent to part of the Adamantina Formation (Fernandes and Coimbra, 2000), in Pirapozinho, São Paulo, Brazil. Both studies concluded that bone preservation was facilitated by the recrystallization of apatite during early diagenesis, a process that may have been promoted by groundwater saturated with carbonates and fluorine (Marchetti et al., 2019; Pinto et al., 2020). In a histological study of titanosaur vertebrae from the Marília Formation, Aureliano et al. (2020) suggested that diagenetic scenarios played an essential role in preserving bone tissue (pneumosteum).

This study aimed to improve our understanding of the paleoenvironment of the Bauru Group (Upper Cretaceous) and the fossil diagenesis of its dinosaur bones through the histotaphonomic characterization of the fossil rib fragment CP2/200A-B from the Marília Formation. The specimen was found in the western part of Minas Gerais, known as the Triângulo Mineiro region, and was interpreted as belonging to an indeterminate saurischian dinosaur.

1.1. **Geological Context**

The Bauru Basin consists of an intracratonic depression that sustained the deposition of an inland continental sedimentary sequence after separating the South American Plate from the Gondwana continent (Fernandes and Coimbra, 2000; Menegazzo et al., 2016). This basin covers an area of approximately 379,000 km², is located almost exclusively in Brazil, and occupies the western region of São Paulo and Minas Gerais states, Southern Goiás, Eastern Mato Grosso do Sul, and the Northwest of Paraná state (Fernandes and Coimbra, 2000; Menegazzo et al., 2016). The Bauru Basin is Aptian–Maastrichtian and is composed of sandstones and sandy mudstone deposits at the bottom and sandstones and conglomerates at the top (Batezelli, 2017). The Bauru Basin is subdivided into Caiuá and Bauru groups (Fernandes and Coimbra, 2000). The Bauru Group (Campanian–Maastrichtian) is represented by the Araçatuba, Adamantina, Uberaba, and Marília formations (Batezelli, 2017; Batezelli and Ladeira, 2016; Castro et al., 2018), as well as the Serra da Galga Formation, proposed based on recent studies carried out on the former Serra da Galga Member of the Marília Formation (Soares et al., 2021).

The fossil fragment (CP2/200A-B) was collected from an outcrop of the Marília Formation located at kilometer 159 of the BR 364 highway (Figure 1) between Campina Verde and Gurinhatã, in Minas Gerais, Brazil. The stratigraphic unit is characterized by sandstones, conglomerates, and paleosols cemented by calcium carbonate and silica, which comprise the fluvial facies (Batezelli, 2017). Batezelli et al. (2019) analyzed outcrops of the Bauru Group in the Triângulo Mineiro region and identified them as part of the facies association called Campina Verde paleosol sequence (Figure 1). According to the authors, the deposits that were formed in an environment composed of ephemeral rivers, eolian dunes, and paleosols correspond to the medial portion of the distributive and progradational fluvial system of the northeastern region of the Bauru Group. The prospective stratum of the fossil is characterized as a Ck (Figure 1) horizon paleosol (inceptisol/entisol) developed under the influence of a semiarid climate Batezelli et al. (2019).

2. MATERIALS AND METHODS

The fossil rib fragment is housed in the Scientific Collection of Vertebrate Paleontology (CP2) at the Instituto de Geociências (IG), Universidade Estadual de Campinas (UNICAMP), under the collection number CP2/200A-B. The specimen measured approximately 50 mm in proximodistal length, 60 mm in anteroposterior width, and 27 mm in mediolateral height in cross-section prior to sectioning (Figure 2). Partial erosion exposed a portion of the medullary spongiosa on one of the dorsal rib surfaces (Figure 2).

2.1. Petrographic and Elemental Analyses

The rib fragment was cross-sectioned, and two petrographic thin sections were produced according to standard paleohistological techniques (Chinsamy and Raath, 1992; Lamm, 2013). For a more detailed analysis of the rock matrix, the petrographic slides were polished to a thickness of 30 µm (Marchetti, 2017).

The samples were analyzed at the Laboratory of Paleohydrogeology at UNICAMP using a Carl Zeiss Scope A1 ZEISS petrographic microscope under normal and cross-polarized light using a gypsum compensator. A ZEISS AxioCam camera captured images, and the microscope software Zenlite from ZEISS Microscopy was used to visualize and treat the images. The thin section received carbon coverage, and elemental analysis was performed using an LEO 430i model Scanning Electron Microscope (SEM) equipped with an energy dispersive detector (EDS) manufactured by Oxford Instruments. The SEM was operated at 67 eV in vacuum mode at the Laboratory of Mineral Quantification at the Instituto de Geociências at UNICAMP.

2.2. Paleohistological Analysis

Histological descriptions of the sections were performed according to the standard nomenclature of microstructures and classifications of bone tissues, as grouped by de Buffrénil and Quilhac (2021). Considering the fossil bone to be a fragment of a dorsal rib, our interpretation of the ontogenetic stage of the specimen was based on current models and hypotheses regarding the growth and development of this type of bone in sauropod dinosaurs (Brum et al., 2022; Gallina, 2012; Waskow and Sander, 2014). In addition, three histological parameters for ontogenetic analysis developed by Mitchell and Sander (2014) were used: (i) the apposition front (AF), which represents the deposition of primary bone tissue on the periosteal surface; (ii) the Haversian substitution front (HSF), which indicates the deposition of secondary osteons; and (iii) the resorption front (RF), which characterizes the resorption of bone tissue and expansion of the medullary cavity.

3. RESULTS

3.1. Taxonomy

Based on its flattened shape, the fossil was first compared with published data on other rib specimens found in the Marília Formation and correlated geological units of the Bauru Group (e.g. Baiano and Cerda, 2023; Bertini et al., 2001; Coria et al., 2013; O'Connor, 2007; Santucci and Arruda-Campos, 2011; Silva Junior et al., 2022; Silva Junior et al., 2019). For example, the sauropod rib specimens reported by Bertini et al. (2001) were similar in size to those studied in the present study. In the appendix of the publication, the authors describe up to 44 rib fragments assigned to Titanosauria that were found in an outcrop of the Marília Formation (Echaporã Member) in Monte Alto, São Paulo. The specimens are stored in the collection of the Museu de Paleontologia 'Professor Antônio Celso de Arruda-Campos' (MPMA) located in Monte Alto. Among these fossils, four ribs (MPMA-04) were 932 mm long and 55.5 mm average wide. Six other rib fragments (MPMA-06) listed in this article were 48 and 80 mm wide. By comparing the measurements with the CP2/200A-B specimen, the width corresponded to the average size observed in previous studies.

The fossil morphology presented in this study places it in a more inclusive group. Wilson (2002) proposed the anterior dorsal ribs with a plank-like shape, whose anteroposterior width was three times larger than their mediolateral length, as a synapomorphy of Titanosauriformes. Fossil rib CP2/200A-B had approximate measurements of 60 and 27 mm for these parameters. The morphology of the fragment is like that described for the dorsal rib shafts of *Overosaurus paradasorum* (Coria et al., 2013) of the Anacleto Formation (Campanian) in Argentina (Garrido, 2010). *O. paradasorum* has an elliptical or lateromedially flattened shape, in cross-section, of the distal shaft of both the third and fourth pairs of anterior ribs, and the posterior dorsal ribs. The maximum anteroposterior width determined for *O. paradasorum* dorsal ribs is also like CP2/200A-B with sizes ranging from 70 mm (third rib pair), 65 mm (first right rib), and 55 mm (fourth rib pair) (Coria et al., 2013).

Compatibility with a large South American theropod dinosaur was determined by comparing the ribs identified and described in the literature. Abelisaur dorsal ribs commonly have an anterior intercostal ridge (Filippi et al., 2018; Méndez et al., 2022; O'Connor, 2007), but this structure was absent in the CP2/200A-B fossil. The distal shafts of the second and third dorsal ribs of *Majungasaurus crenatissimus* (Depéret, 1896) (see O'Connor, 2007) and the distal sections of the dorsal ribs of *Aucasaurus garridoi* Coria et al., 2002 (see Baiano and Cerda, 2023) exhibited a mediolaterally flattened shape in the cross-section, which is like the titanosaur specimens mentioned earlier here. These features are conflicting and insufficient to assign the bone fragment CP2/200A-B to abelisaurs or titanosaurs with conviction. Megaraptors, another group of carnivorous dinosaurs, have posterior and anterior intercostal ridges, as well as intercostal grooves on their dorsal rib shafts (Aranciaga Rolando et al., 2022; Lamanna et al., 2020; Porfiri et al., 2014). Neither of these features was identified in the fossil CP2/200A-B. Therefore, the hypothesis that the specimen belonged to a megaraptorid theropod was rejected.

3.2. **Histological analysis**

Regarding the composition of bone tissues in both thin sections, we identified a 6-mm-thick dense Haversian bone throughout the length of the rib cortex (Figures 3 and 4). Secondary osteons presented overlaps, indicating one or more generations of bone remodeling (Figures 3C and 4B). A large area of cancellous bone up to 10 mm thick was observed in the medullary region, with trabeculae and erosion cavities derived from bone reabsorption (Figures 3E and

4C). The same secondary osteonal structures were observed in the cortex on both sides of the rib. Lines of arrested growth (LAGs) are absent.

On the outer surface of the cortex in the periosteal region, the osteons were severely damaged, part of them with half of their structures eroded (Figures 3C and 4B). No external fundamental system (EFS) or associated lamellar tissue is preserved in this region of the compact bone. The endosteal region was poorly preserved, and several parts of the lamellar tissue were replaced by calcite. We also identified deep and wide fractures extending into the medullary cavity of the rib (Figure 3B and 3E), sometimes filled with a rock matrix or calcitic cement, forming veins. However, the mineralogical composition of the bone tissue was preserved, with a predominance of apatite [$Ca_5(PO_4)_3$] in all areas, as predicted in the EDS analysis (see Supplementary Material).

Some considerations were made regarding the possible stages of ontogenetic development of the specimen. According to recent proposals for the development of bone tissue in sauropod ribs, advanced HSF and RF limited to the perimedullary region suggest an adult or senescent individual (Brum et al., 2022). However, no confident statement about the ontogeny can be made because of the absence of an EFS and the unknown position of the fragment in the length of the rib (see Discussion section). EFS represents the deceleration of bone deposition (AF).

3.3. **Petrographic analysis**

A calcitic matrix and cement characterized thin sections of the rib fragment (CP2/200A-B) in the medullary region and the outer surface of the bone as veins (Figures 3C, 3E and 4C). The internal spaces are mainly filled with spathic calcite (~0.35 µm). On the surface of the rib trabeculae, a recrystallized calcite phase was identified under polarized light, with a slight fringe at the edges of the structures along their entire perimeters (Figures 3E and 5D). In addition, we observed deposits of opaque minerals inside the Haversian canals and osteocyte cavities. According to EDS analysis, the minerals correspond to iron oxides, which have a framboidal habit (see Supplementary Material) and constitute pyrite pseudomorphs. In addition, deposits of opaque minerals in a dendritic pattern were observed, percolating out of the vascular canal and covering the lamellae of secondary osteons (Figure 3D), consistent with manganese oxides.

The sample was associated with calcitic cement sandstone, with poorly selected grains ranging from coarse sand (0.70 mm) to very fine sand (0.10 mm), although it was predominant in the fine sand fraction (0.19 mm). The larger grains (medium and coarse sand fractions) exhibited variable roundness ranging from sub-rounded to well-rounded. Smaller grains exhibited more angular shapes ranging from angular to subangular. The mineral grains are predominantly composed of quartz, plagioclase feldspar, and alkali feldspar (microcline and orthoclase) (Figure 5C and 5D). Under cross-polarized light, grains of monocrystalline quartz with straight and undulating extinction and polycrystalline quartz were observed (Figure 5A). Most polycrystalline or undulating extinction quartz grains occurred in the coarse and medium sand fractions, with little contribution from straight extinction quartz. However, the monocrystalline grains of straight extinction are limpid and concentrated mainly in finer particles. Overall, the minerals exhibited fractures and slightly corroded edges associated with calcite replacement (Figure 5B and 5D).

The two thin sections exhibited a few unique structures. On petrographic slide 234 (CP2/200A), a few unidentified grains of a brownish color and peloidal texture were found. However, on slide 235 (CP2/200B), a small number of grains configured a residual texture filled with calcite laths, which may have been associated with volcanic lithic fragments (Figure 5E and 5F).

4. DISCUSSION

4.1. Taxonomy and ontogeny

The similarities in size between fossil CP2/200A-B and other titanosaur specimens described from the same geological unit (Bertini et al., 2001) along with the plank-like morphology of the rib (Wilson, 2002) and its elliptical shape in cross-section (Coria et al., 2013), suggest that the specimen may belong to the Titanosauria group. However, there are exceptions to dorsal rib morphology in some titanosaur species, including those found in the Bauru Group. For example, the recognized specimens of *Uberabatitan ribeiroi* Salgado and Carvalho, 2008 (see Silva Junior et al., 2019), whose dorsal ribs present the medial part of the shaft slightly concave, and the holotype of *Arrudatitan maximus* (Santucci and Arruda-Campos, 2011) (Silva Junior et al., 2022), which has mid-thorax ribs with well-developed anterior and posterior ridges in the proximal shaft, acquiring a "D" shape in cross-section. Even the *Overosaurus* ribs used for comparison in this study present laminar projections on the posterior face of the proximal shaft of the second and third anterior dorsal ribs, which are considered diagnostic characteristics of the species (Coria et al., 2013).

A mediolaterally flattened shape may be identified in the ribs of other taxa, such as the distal shaft of the anterior dorsal ribs of the abelisaurid *Majungasaurus* (O'Connor, 2007). Degradation of one of the fragment's faces during telodiagenesis precludes the identification of an anterior intercostal ridge, which is also present in abelisaurid theropods (Aranciaga Rolando et al., 2021; Filippi et al., 2018; Méndez et al., 2022; O'Connor, 2007). Histological comparison of the dorsal ribs was insufficient for decisive taxonomic classification because of similarities in bone tissue and microstructure, such as the thickness ratio of the medullary cavity and cortex, and advanced remodeling, which were found in both the dorsal ribs of *Aucasaurus garridoi* (Baiano and Cerda, 2023) and titanosaur species of the Bauru Group (Brum et al., 2022; Windholz et al., 2023). Thus, owing to the high fragmentation of fossil CP2/200A-B and the absence of clear diagnostic characters attributed to abelisaurs, as exemplified above, we identified it as an indeterminate saurischian dinosaur from the Marilia Formation.

To assess the ontogenetic stage of the organism, some characteristics of the studied sample were unable to be identified precisely, such as the absence of recognizable LAGs, growth rings, and EFS. The absence of the latter histological structure may be related to extensively damaged secondary osteons present on the surface of the cortex (Figures 3C and 4B), as discussed in the next section. Based on the current interpretations of rib bone development (Brum et al., 2022), we could only classify the organism as adult or senescent. However, the sampling location of the bone may have influenced the interpretation of the results. According to Waskow and Sander (2014), the posteromedial side of the proximal end of the rib shaft is the area with optimal growth record. The proximodistal growth direction of bone justifies this characteristic during ontogeny, with resorption and secondary deposition induced by mechanical stress. It promotes intra-elemental histovariability with significant bone remodeling in more distal regions, reducing the number of recognizable growth rings at these sites (Gallina, 2012; Waskow and Sander, 2014). Since it is a fragment and its position in the rib length is possibly distal, remodeling may not represent an adult organism but a tissue adaptation to mechanical pressure applied at the distal and lateral ends of the bone.

4.2. **Taphonomy**

Based on the petrographic and histological characteristics of sample CP2/200A-B, we inferred the taphonomic processes recorded during its preservation. The presence of damage to the secondary osteons on the outer surface of the rib suggests that the bone was worn away during transport (Figures 3C and 4B). This feature is attested by the calcitic cement in the rib medullary cavity, veins, and rock matrix as well as the presence of grains inside the larger cracks (Figure 3B and 3E). The occurrence of these fractures may be associated with the weathering of bones exposed to the ground surface under semiarid conditions (Behrensmeyer, 1978). Subaerial exposure for months or years before burial is a typical taphonomic pattern in vertebrate fossils of the Bauru Group because a considerable amount of material has been fragmented or isolated (Azevedo et al., 2013; Bandeira et al., 2018, 2016; Brum et al., 2021b; Delcourt and Iori, 2020). A reductive phase in the early diagenesis of the rib is indicated by iron oxides as pyrite pseudomorphs (framboids) near the Haversian canal surfaces (see Supplementary Material). Pyrite formation and precipitation typically occur in reductive environments. Iron input is derived from the decomposition of organic substances, and sulfide availability is controlled by collagen hydrolysis and diffusion from external sources (Pfretzschner, 2001). Thus, the leaching of organic components increases the porosity of the bone structure, allowing recrystallization (Pfretzschner, 2001). This process ended in the early diagenesis phase, leaving the fossil barely permeable and resistant to diagenetic changes (Cazalbou et al., 2004). At this stage, the deposition of manganese hydroxides on apatite crystals (Figure 3D) may have occurred through groundwater activity (Pfretzschner, 2004; Pfretzschner and Tütken, 2011).

The characteristics identified in the rock matrix allowed us to reconstruct the palaeodepositional environment in which the final burial of the rib occurred. Framework grains of diverse sizes, degrees of roundness, and different quartz populations indicate that the paleoenvironment received sedimentary intake from distinct sources. This petrographic feature may be related to the development of the Bauru Basin during the Upper Cretaceous, which underwent a second phase of uplift in its eastern region due to alkaline intrusions from the mantle (Batezelli, 2017; Batezelli et al., 2005; Mattos and Batezelli, 2020). Because most of these grains have more angular shapes, it is suggested that their sources were closer to the deposition site.

We propose that the deposition of the dorsal rib was rapid in a high-energy system owing to the poor selection of grains from the rock framework, both internally and externally, to the fossil bone. This refers to the palaeodepositional system of the Marília Formation, which is characterized as alluvial and dominated by progradational braided rivers with a high sediment supply driven by constant avulsions and abandonment of distributive channels (Batezelli, 2017). The loose packing of Bauru Basin rocks is due to calcrete formation by pedogenetic and phreatic processes under semiarid and arid environmental conditions (Batezelli et al., 2005; da Silva et al., 2019; Fernandes, 2010). Comparing the microstructure with the facies profiles from the Campina Verde site (Batezelli et al., 2019), we inferred that the rib (CP2/200A-B) was deposited in an ephemeral or intermittent channel bed with high sediment input and was later abandoned, providing the initial fast cementation of the stratum by phreatic processes over a long period of stability. During late diagenesis, an oxidation stage was noted that was associated with the deposition of opaque minerals on the outer surface of the bone, which were probably formed by the action of rainwater (Batezelli et al., 2005). The inferred taphonomic sequence for specimen CP2/200A-B is summarized in Figure 6.

Our findings support the hypothesis that the rapid recrystallization of apatite during early diagenesis allows the preservation of bone structure, as suggested by other studies on fossil bones from the Bauru Group (Marchetti et al., 2019; Pinto et al., 2020). However, differences were observed in the petrographic patterns proposed by Garcia et al. (2005). The presence of crystalline calcite fringes on the bone surface is a feature observed in fossils from the Adamantina and Uberaba Formations and is also present in this specimen from the Marília Formation. To verify the proposed patterns, we recommend conducting additional petrographic comparisons between specimens from the Bauru Group formations.

4.3. **Regional and interregional contexts**

Specimen CP2/200A-B provides an example of bone preservation associated with calcrete pedogenesis in a semi-arid climate (Batezelli et al., 2019; da Silva et al., 2019). It can be used for comparison with other fossil bones found in similar depositional environments around the world. Evidence of bone weathering by surface exposure is present in sauropod fossils from the Hasandong Formation (Paik et al., 2001), Lower Cretaceous of the Korean Peninsula, and in sauropod and theropod fossils from the Neuquén Basin (Previtera, 2019, 2017), Upper Cretaceous of Argentinian Patagonia. These lithostratigraphic units probably indicate arid to semi-arid paleoclimates (Paik et al., 2001; Previtera, 2017), further supporting the correlation between climate and pre-burial weathering. In addition, pseudomorphic framboids composed of iron oxides have been discovered in dinosaur bones from the Two Medicine and Judith River formations of the Upper Cretaceous of North America (Rogers et al., 2020), suggesting that pyrite precipitation occurred in a reducing environment during initial diagenesis.

It is important to note that the preservation of vertebrate fossils, such as bones, eggs, and coprolites, associated with pedogenesis is common in Cretaceous records (e.g. Fiorillo et al., 2016; López-Martínez et al., 2000; Paik et al., 2001; Therrien et al., 2009). Soils are the largest terrestrial environment, and their characteristics, such as pH and redox index, are important for the preservation of organic remains and the formation of fossils (Retallack, 2019). For example, calcareous soils are alkaline enough to prevent the dissolution of bones and shells (Retallack, 2019, 1988), favoring the preservation of the fossil rib discussed in this paper. The study of paleosols that contain fossil assemblages is relevant to vertebrate paleontology because it provides essential information for paleoecological reconstruction and can reveal possible preservation biases (Retallack, 1988; Therrien et al., 2009).

5. **CONCLUSIONS**

The analyses on the rib fragment (CP2/200A-B) highlighted the presence of compact bone completely remodeled in the cortex and cancellous bone occupying the entire medullary region.

Regarding taxonomic classification, the morphology of the fossil rib and similarities in size suggest its classification as an indeterminate saurischian dinosaur.

The taphonomic processes associated with the fossil rib can be summarized as follows: (i) a long period of subaerial exposure of the bone, followed by high-energy transport; (ii) deposition of the specimen in a reductive environment with alkaline stability, recrystallization of apatite, and rapid precipitation of calcite in early diagenesis, reducing fossil porosity; and (iii) manganese hydroxides deposited on the apatite crystals by groundwater.

Finally, the study concluded that the CP2/200A-B specimen presented a taphonomic bias identified among vertebrate fossils of the Bauru Group, which has been reported in previous studies. Isolated fragments and the loss of bone structure, even at the histological level, are recurrent signs in dinosaur specimens. These characteristics may be associated with the extensive exposure of bones to arid and semiarid climates, their transport into depositional environments and diagenesis associated with the development of soils.

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FIGURE CAPTIONS

Figure 1. Location of the outcrop in Brazil where the fossil studied was collected. A, extension of the Bauru Basin in the Brazilian territory and position of the outcrop in the Triângulo Mineiro region (stratigraphy based on Batezelli, 2017). B, and C, sampling site and the rib fragment position in the outcrop stratigraphic column (modified from on Batezelli, 2019). B, view of outcrop next to BR 364 highway. B. layer in which the fossil was found (petrographic hammer for size reference = 30cm).

Figure 2. Pictures of the rib fragment before (left side) and after (right side) cutting. A, and B, transverse view of the rib (CP2/200A), highlighting the eroded lateral region of the bone (arrow) and the rock matrix layer (arrow). C, and D, longitudinal view of the rib (CP2/200B), highlighting the eroded region (arrow) and a fine layer of rock (arrow) still covering to the fossil. Section CP2/200A is represented on the slide 234 and CP2/200B on the slide 235. Scale bars = 20mm.

Figure 3. Petrography of the rib fragment of the sample CP2/200A (slide 234). A, panoramic view of transverse section, the arrow show point to the fine layer of residual rock on the side of the bone, natural light. B, secondary osteon at the edge of the cortex, with extensive fracture present on the right under natural light. C, Damaged second-generation osteon, arrow showing overlap, polarized light with gypsum compensator. D, osteon in natural light with the presence of dendrites in its lamellae, indicates by arrow. E, bone remodeling region with a large erosion cavity (white arrow), vein (black arrow) and replacement process of

bone tissue by calcite, natural light. Scale bar= 10mm in A; 500µm in B, C, E; 250µm in D. C = calcite (sparite and micrite)

Figure 4. Petrography of the rib fragment of the sample CP2/200B (slide 235). A, panoramic view of transverse section, the arrow show point to the fine layer of residual rock on the side of the bone, natural light. B, damaged secondary osteon observed under polarized light with gypsum compensator. C, medullary region, with the presence of trabeculae and erosion cavities, pointed by arrows, polarized light with gypsum compensator. Scale bar= 10mm in A; 500µm in B, C. Legend: C = calcite (sparite and micrite).

Figure 5. Microscopy of observed mineral grains and diagenetic structures. A, rounded polycrystalline quartz with slightly eroded edges (center), close to an isolated secondary osteon (upper right), both surrounded by calcitic matrix and cement, polarized light. B, quartz grain with features, indicates by arrow, polarized light. C, rounded plagioclase feldspar grain (arrow), with eroded edges, polarized light. D, subangular microcline feldspar grain (arrow), with eroded edges, close to the bone trabeculae under the process of initial tissue replacement by calcite ("shading" effect), shows by arrow, polarized light. E, rounded grain of volcanic-like texture (center) with partial replacement, polarized light. F, grain peloidal texture (center) with spatic calcite overlay (arrow), natural light. Scale bar= 500µm in A, B, C, D, E, F. Legend: C = calcite (sparite and micrite), T= trabeculae, Os = secondary osteon.

Figure 6. Diagram of the sequence of taphonomic processes inferred for the fossil rib fragment CP2/200A-B. I, exposure of the bone on the ground surface, associated with pre-burial weathering and abrasion. II, deposition of the specimen in a reducing environment, inducing the precipitation of framboidal pyrite on the inner spaces of the bone. III, deposition of manganese oxides on apatite crystals due to groundwater action, followed by calcite cementation related to pedogenesis. IV, deposition of opaque minerals on the bone's surface, associated with leaching by rainwater action.

ARTICLE HIGHLIGHTS

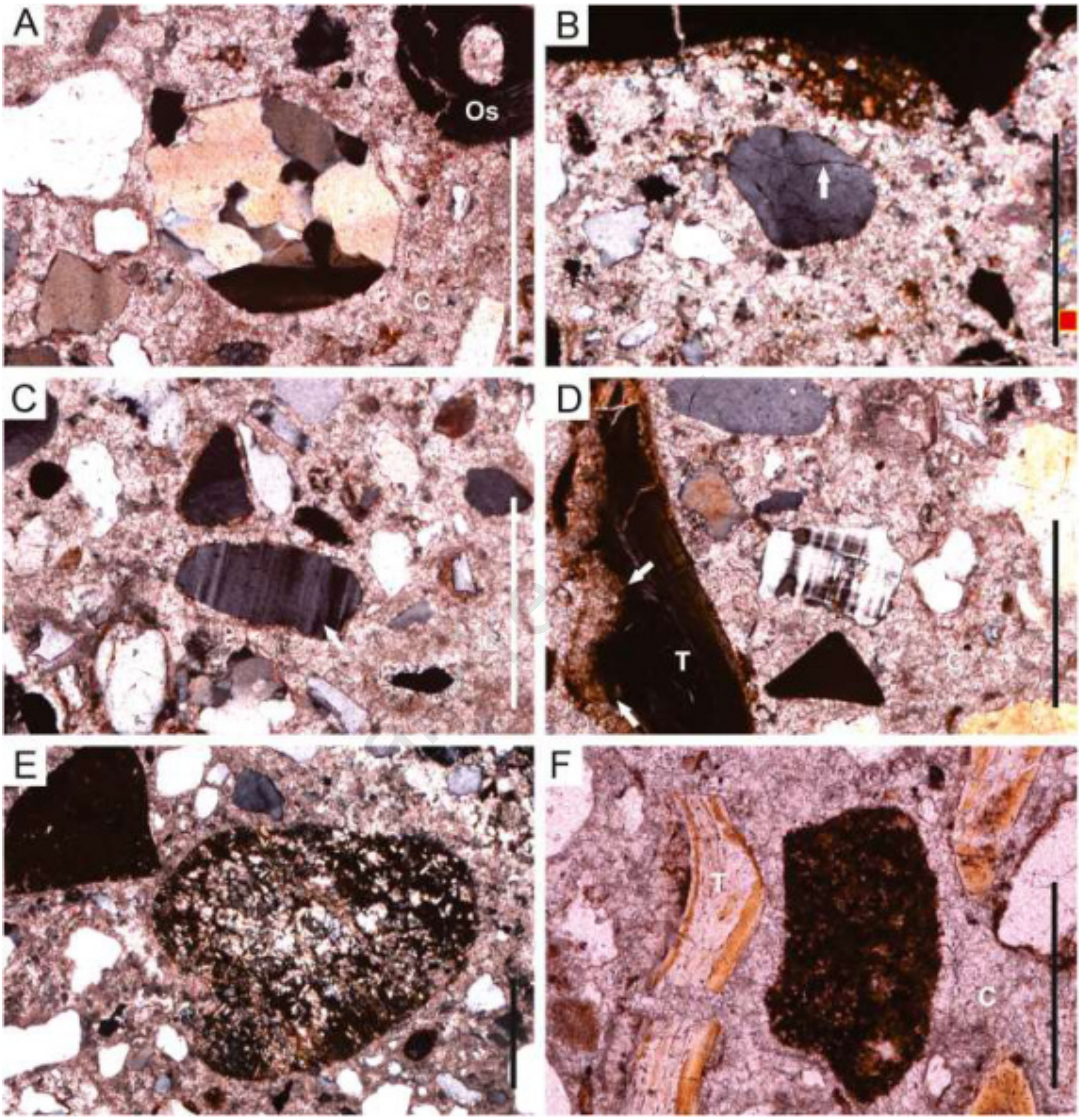
TAPHONOMY AND PALEOHISTOLOGY OF A DINOSAUR RIB FROM MARÍLIA FORMATION, BAURU GROUP, IN THE STATE OF MINAS GERAIS, BRAZIL

- Loss of histological structures due to transport and bone weathering
- Fossil preservation associated with bone exposure and burial on semiarid climate
- Hypothesis support a taphonomic bias in dinosaur fossils from the Bauru Group

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: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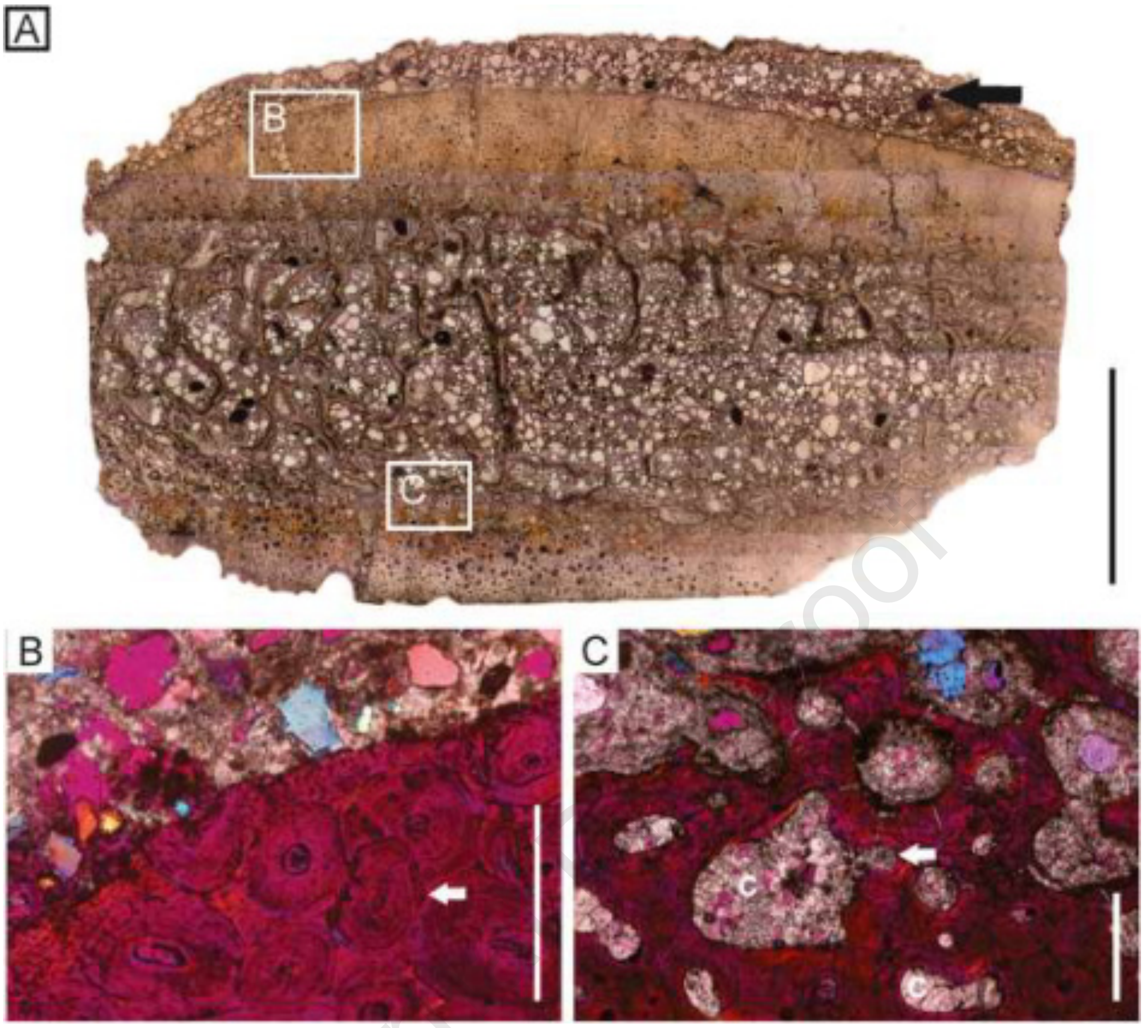
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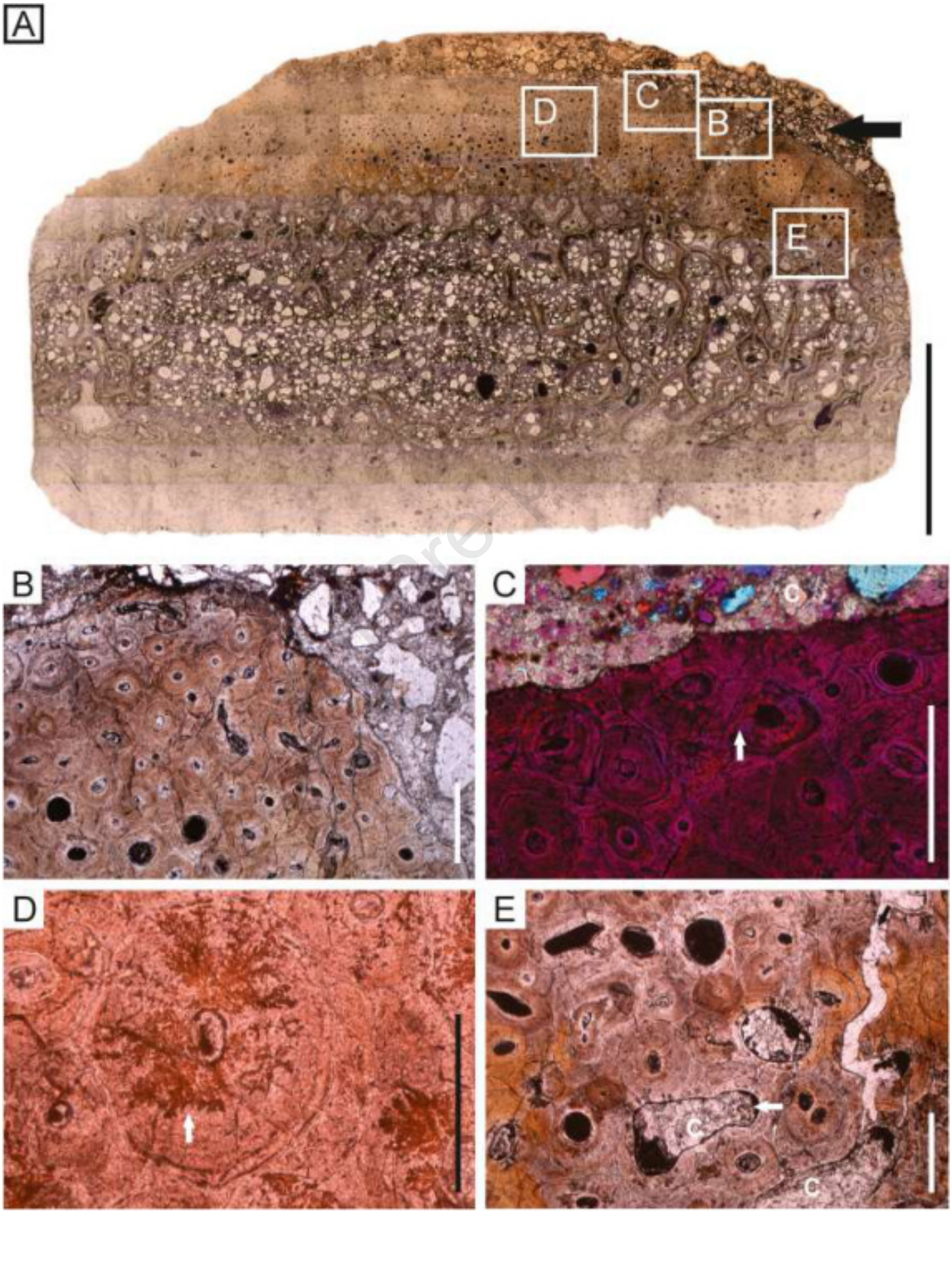
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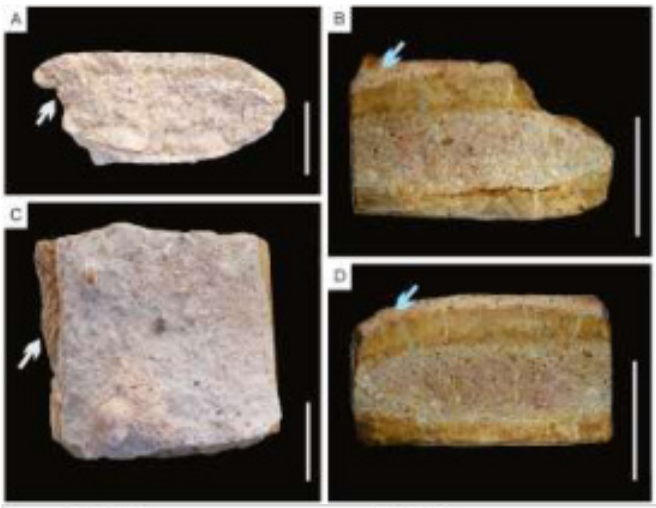
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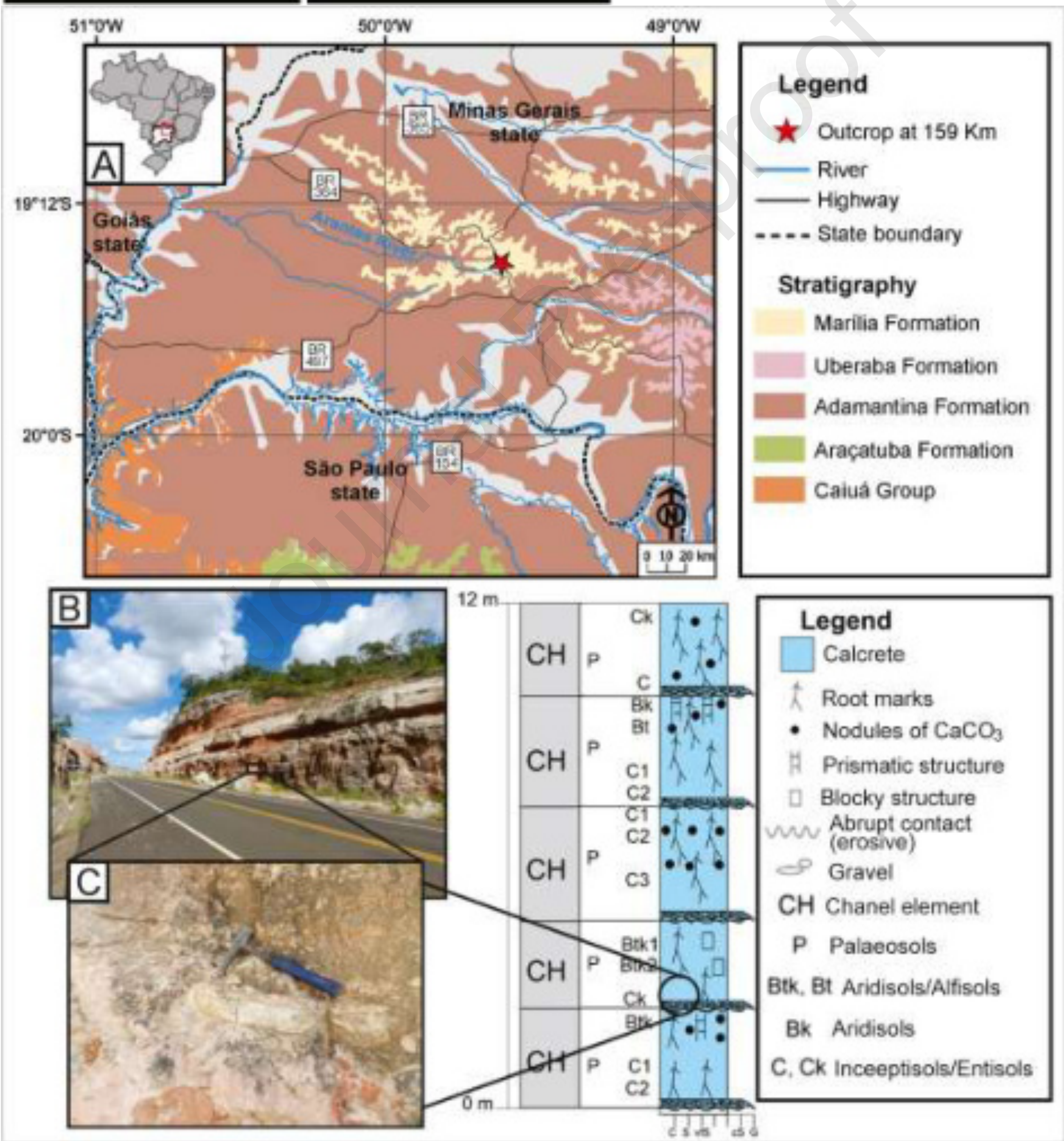
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Outcrop at 159 Km
River
Highway
State boundary
Stratigraphy
Marília Formation
Uberaba Formation
Adamantina Formation
Araçatuba Formation
Caiuá Group
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C
12 m
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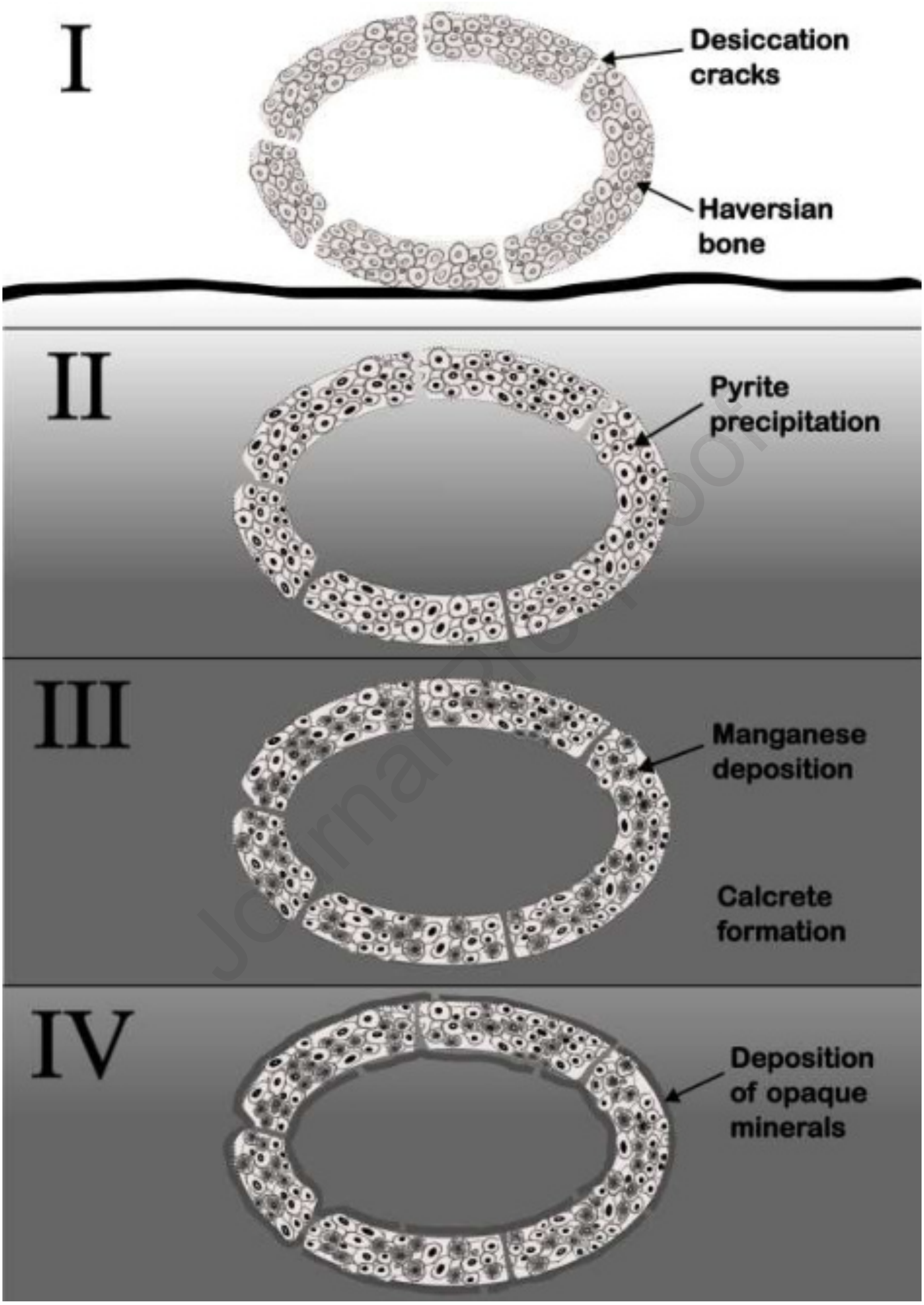
C3
Btk1
Btk2
Btk
Legend
Calcrete
Root marks
Nodules of $CaCO_3$
Prismatic structure
Blocky structure
Abrupt contact (erosive)
Gravel
CH Chanel element
P Palaeosols
Btk, Bt Aridisols/Alfisols
Bk Aridisols
C, Ck Inceptisols/Entisols


I
Desiccation cracks
Haversian bone
II
Pyrite precipitation
III
Manganese deposition
Calcrete formation
IV
Deposition of opaque minerals