FRESHWATER DECAPODA TRACE FOSSILS IN FLOODPLAIN PALEOSOLS OF MARILIA FORMATION IN MINAS GERAIS STATE (SE BRAZIL)

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ABSTRACT – The Marília Formation (Bauru Group, Bauru Basin) is an important record of the Upper Cretaceous in Brazil, and hosts an important fossil content. However, works regarding continental ichnology in this unit are still scarce. In order to improve this knowledge, the present work describes the occurrence of *Camborygma litonomos* in paleosols developed from floodplain deposits of the Marília Formation in the Minas Gerais State. This trace fossil is associated with the activity of freshwater crayfishes, digging the soil looking for protection and to avoid the carapace dryness. Crayfish body fossils have not yet been described in deposits of the Bauru Group, thus, the trace fossil here recorded is the exclusive evidence of this organism, which is of great importance to the knowledge of the invertebrates paleodiversity of the Marília Formation during the Late Cretaceous.

Key words: ichnology, *Camborygma litonomos*, crustaceans, Upper Cretaceous, Bauru Group, paleopedology.

RESUMO – A Formação Marília (Grupo Bauru, Bacia Bauru) é um importante registro do Cretáceo Superior no Brasil e possui um importante conteúdo fossilífero. No entanto, os trabalhos sobre icnologia continental desta unidade ainda são escassos. A fim de ampliar este conhecimento, o presente trabalho descreve a ocorrência de *Camborygma litonomos* em paleossolos desenvolvidos em depósitos de planície de inundação no Estado de Minas Gerais. Estes icnofósseis estão associados à atividade de lagostins de água doce que escavam o solo em busca de proteção e para evitar o ressecamento da carapaça. Até o momento, não foram descritos fósseis destes artrópodes no Grupo Bauru. Assim, o icnofóssil aqui registrado é a evidência exclusiva deste organismo, que é de grande importância para o conhecimento da paleodiversidade de invertebrados da Formação Marília durante o Neocretáceo.

Palavras-chave: icnologia, *Camborygma litonomos*, crustáceos, Neocretáceo, Grupo Bauru, paleopedologia.

INTRODUCTION

The Marília Formation is a sedimentary succession located in the Bauru Basin, an intraplate basin of southeastern Brazil, which records the Upper Cretaceous series. The paleoenvironmental interpretations of this unit were mainly based in their abundant fossil record, which has been the subject of many studies in recent decades, especially based on dinosaurs, crocodiles, fishes, mollusks, and turtles (Bertini *et al.*, 1993; Candeiro *et al.*, 2006, 2008; Carvalho *et al.*, 2007; Marinho *et al.*, 2013; Marsola *et al.*, 2016). However, the studies are still scarce in the case of trace fossils, with just some works referred to the Bauru Basin (Fernandes & Carvalho, 2006; Carvalho *et al.*, 2009; Cardoso *et al.*, 2013; Nascimento *et al.*, 2017a; Mineiro *et al.*, 2017).

Trace fossils are biogenic structures produced by the activity of an organism in the substrate (bioturbation structures, bioerosion and biodeposition), reflecting the behavioral functions (ethology) related to the morphology of the organism that produces it (Bromley, 1990). Furthermore, as the structures are produced in situ, trace fossils are an important paleoenvironmental proxy (Hasiotis, 2007).

Soils are the products of major evolutionary events in the history of life on earth and record changes in

terrestrial ecosystems (Retallack, 2001). One of the tools for understanding the dynamics of terrestrial ecosystems over geological time is the study of the trace fossils associated with the activity of invertebrates in paleosols.

Therefore, the characterization of trace fossils in the paleosols of the Marília Formation can increase the knowledge about the fauna and the paleoecological conditions of this unit. There is little information concerning the invertebrate fauna of the Marília Formation, most of the works documenting the occurrence of mollusks (Mezzalana, 1974; Mezzalana & De Simone, 1999; Dias-Brito *et al.*, 2001).

The trace fossils preserved in paleosols are often the only available evidence to study the diversity of organisms with low potential of preservation, such soil-dwelling organisms (Hasiotis, 2007; Genise, 2017). In order to fill part of this gap, the objective of this work is to record the occurrence of *Camborygma* isp. in the paleosols of the Marília Formation and its contribution to the paleoenvironmental and paleoecological interpretations.

These trace fossils are representative of the *Camborygma* Ichnofacies, typical in paleosols since the Triassic (Genise *et al.*, 2016; Genise, 2017). However, it had not yet been registered in Brazil. In this way, the present work collaborates with the knowledge about the expansion and recurrence of paleosol ichnofacies along the Cretaceous.

GEOLOGICAL SETTING

The Bauru Basin is an Upper Cretaceous continental basin originated by flexural process during the Alto Paranaíba Uplift event in the Southeastern Brazil (Fernandes, 1998; Batezelli, 2015). It is one of the most documented sedimentary basins in Brazil, with available data including more than 500 outcrops descriptions (350 outcrops described by Fernandes, 1998 and 150 outcrops described in Batezelli, 2003).

The substrate of the basin is partly formed by the Caiuá Group sandstones (Lower Cretaceous) and the Serra Geral Formation basalts (São Bento Group, Lower Cretaceous), rearranged as an elongated NE-SW-trending depression, the sedimentation controlled by uplifts in the northern and northeastern portion. The basin records continental sedimentation (Bauru Group) with maximum thicknesses of about 300 m, constituted by mudstones and very fine sandstones at the base (Araçatuba Formation), grading to fine- to medium-grained sandstones in the intermediate

portion (Adamantina and Uberaba formations), and fine- to coarse-grained, also conglomeratic, sandstones at the top (Marília Formation) (Figure 1).

The trace fossils described in this work occur in the paleosols of the Marília Formation from the Upper Cretaceous (Maastrichtian) located in western Minas Gerais State (MG), southeastern Brazil (Figure 2), and were described in detail by Batezelli (2015) and Nascimento *et al.* (2017b). The Marília Formation in the study area consists predominantly of sandstones and matrix-supported conglomerates, subordinated sandy-clay deposits, and CaCO₃ rich paleosols (calcretes).

Based on the integration of paleontological data (Gobbo-Rodrigues, 2001; Dias-Brito *et al.*, 2001; Santucci & Bertini, 2001; Martinelli *et al.*, 2011; Fragozo *et al.*, 2013), stratigraphic information (Batezelli, 2015), as well as correlations with tectonic and magmatic events (Amaral *et al.*, 1967; Hasui & Cordani, 1968; Sonoki & Garda, 1988; Machado Junior, 1992) that occurred in the northern and northeastern portions of the Bauru Basin, a Maastrichtian age is admitted for the Marília Formation.

Figure 1. Chronostratigraphic chart of the Cretaceous sequence in Bauru Basin (Batezelli, 2015).

Figure 2. Map of localization of study area of the Bauru Basin.

The outcrops of the Marília Formation are densely bioturbated and cemented, resulting in the almost total obliteration of many sedimentary structures. However, it is possible to distinguish two different facies associations: fluvial deposits, and floodplain deposits composed of sandy-conglomeratic and clay deposits, respectively.

The paleosols occur interspersed with sandstones and conglomerates consisting of clasts of quartz, carbonate and bioclasts. The depositional architectures of the Marília Formation are associated to river channels, lenticular sandbars and floodplain elements (e.g. Miall, 1996), constituting amalgamated channel complexes, interspersed with paleosols (Batezelli, 2015; Nascimento *et al.*, 2017b).

The semi-arid climate of the Marília Formation is attested by the large amount of calcretes that are common in environments with annual rainfall between 400 and 600 mm (Goudie, 1983), and by clay minerals from the group of illite and palygorskite/sepiolite (Suguio & Barcellos, 1983; Goldberg & Garcia, 2000), as well as paleoprecipitation proxies (Pereira *et al.*, 2015).

MATERIAL AND METHODS

The sedimentological analysis was based on the analysis of four outcrops where the paleosols were described according to the recommendations of Miall (1996) for the facies and their associations, using photographic mosaics to identify and interpret the external architecture and geometry of the deposits. The lithostratigraphic sections range from 5 to 15 m in height and are located near of Campina Verde, MG (19° 40.065'S, 49° 60.405'W) (Figure 2). They were studied in detail by Batezelli (2015) and Nascimento *et al.* (2017b).

Paleosols were described as recommended by the Soil Survey Manual (Soil Survey Staff, 1999), and Retallack (2001), who emphasizes the identification of horizons,

color, presence of nodules, as well as bioturbation standards (rhizolith and burrows). The micromorphological descriptions were performed with the help of a petrographic microscope following the methodology of Stoops *et al.* (2010).

The ichnological description was based in Hasiotis (2002), and its characterization considered main ichnotaxobases, as proposed by Bromley (1990), such as general form, type of wall structure, type of branching, and nature of the fill. The description included the elaboration of sketches, drafts, and photographs for the documentation and the dimensional characterization of trace fossils. The morphological description sought to emphasize the distribution, size, geometry, frequency, and orientation concerning sedimentary facies, paleosols and other ichnological assemblages, as well as the superficial morphological characteristics, such as cementation and filling of the chambers.

RESULTS

The analysis of the deposits of the Marília Formation resulted in six sedimentary facies (Table 1), which were grouped into three facies associations, related to the following depositional paleoenvironments: fluvial deposits and floodplain fines.

The parent material of paleosols of the Marília Formation in the studied area comprises red to pinkish sand from the Lenticular Sandbars Facies Association (facies St and Sm), conglomeratic deposits from the Amalgamated Channels Facies Association (facies Gmm and Gt), and fines deposits from the Floodplain Facies Association (facies St, Fm and Fl) (Table 1). The exposition is 15 m high, have metric thicknesses and a lateral exposure up to 100 m (Figures 3A–B).

The Lenticular Sandbars Facies Association comprises poorly sorted medium to coarse sandstones with subangular grains, besides angular clasts of 0.4 to 3.0 cm in diameter

Table 1. Synthesis of the general characteristics of the deposits described in study area.

Facies	Facies Associations	Architectural elements	Characteristics
St, Sm, Gmm and Gt	Amalgamated channels, lenticular sandbars	CH (channel), SB (sand bedform)	Lenticular bodies of sandstones and conglomerates with concave base marked by intraformational conglomerate with fining upward. These deposits occur eroding floodplain deposits and paleosols.
St, Fm and Fl	Floodplain, overbank fines	FF (Floodplain fines)	Massive mudstones and sandstones (overbank) with oxidation features (rhizohalos), intensely bioturbated and pedogenized.

Figure 3. General aspects of some architectonic elements and facies of the Marilia Formation in the studied area. **A–B**, despite of pedogenetic process, the architectural elements are still visible. Note that the floodplain elements (**FF**) are truncated by channel deposits and sandy bars (**SB**). **C**, facies Gmm composed large mudstone clasts. **D**, vertebrate fossil in conglomeratic deposits (Facies Gmm). **E–F**, floodplain facies association eroded by channel deposits. Arrow heads in F indicates where *Camborygma litonomos* is preserved. Scale bars: A = 2,5 m; B = 1,2 m; E = 60 m; F = 30 m.

scattered along the profile. The conglomerates of the Amalgamated Channels Facies Association have fragments of reworked quartz, flint, calcretes, and CaCO_3 nodules that range from 1 to 10 cm in diameter in a fining upward sequence (Figure 3C).

Sedimentary structures are present in St facies, but poorly preserved, they consist of small to medium-sized laminations and cross-beddings that are rich in carbonate nodules and bioclasts (vertebrate bones) (Figure 3D). The basal contacts (Gmm and Gt facies) of these deposits are conglomeratic and erosive, predominantly horizontal to sub-horizontal.

The Floodplain Fines Association is composed of dark red and brown claystones (facies Fl and Fm), predominantly consisting of clay (Figures 3C–D), with variations in the sand content (facies St). The Fl and Fm facies are bioturbated and pedogenized in some exposures. Laterally they occur as metric lenticular layers, representing the most distal portions of the floodplains.

The facies association composes the architectural elements, which are indicative of a fluvial environment that comprise lenticular sandbars (SB) and poorly confined, multi-story, amalgamated channels (CH) and clayey-sandy deposits (FF) associated to deposition in distal floodplains. The mudstones with redoximorphic and bioturbation associated with pedogenesis obliterates the contact surfaces between the different deposits. There is no evidence of preservation of organic matter in these deposits.

Studied paleosols

The paleosols where *Camborygma* occur are composed of stacked C horizons (Figure 4A) with evidence of oxidation and reduction processes, such as rhizohalos (Figure 4B). The main distinguishing feature of this pedotype is the argillaceous parent material (Figures 4C–D) with pinkish white (2.5YR8/2) and weak red (7.5R5/3) colors. The micromorphological analysis shows a groundmass composed of argillic and sand material; the matrix is mostly inherited from the source material (Figure 4E). The quartz grains are immersed in this fine matrix, composing a loose arrangement of the grains, which results in a relative distribution, ranging from eunalic to chitonic.

The coatings are associated with alteration of primary minerals, resulting in a crystallitic to granostriated b-fabric (Figure 4F).

SYSTEMATIC ICHNOLOGY

Camborygma (Hasiotis & Mitchell, 1993)

Camborygma litonomos (Hasiotis & Mitchell, 1993)
(Figures 5A–F)

Description. simple, cylindrical, vertical to subvertical burrows. The burrows are lined with a thin material and filled with medium and poorly sorted sand indicating passive filling. The surface morphology of the burrow display scratch and stretch marks. The trajectory is helical or winding, with

up to 50 cm in length and 10 cm in diameter. Generally, the burrows maintain the diameter throughout of their length, but may display constrictions or nodules throughout the structure, which presents sub-spherical to spherical chambers in your base.

Remarks. Due to their architecture, surficial morphology, burrows predominantly quasi-vertical, absence of branches and basal chamber, these structures are attributed to *Camborygma litonomos* Hasiotis & Mitchell, 1993 (see also Hasiotis & Honey, 2000). This trace fossil represents the activity of freshwater crayfishes (Decapoda: Cambaridae). The morphology and stratigraphic position of *C. litonomos* indicates that the trace maker digged the areas near to channels or flooded environments, looking for protection to be able to reproduce using their appendages to dig and manipulate sediment, as well to avoid carapace dryness in semiaquatic environments, that are exposed to subaerial conditions during part of the year (Hobs, 1981; Hasiotis & Mitchell, 1993; Walls, 2009; Genise, 2017).

RHIZOLITHS

Rhizohalos

Characteristics of Fe depletion in predominantly vertical shape, yellow and grey tones, with horizontal lateral ramifications. The diameter ranges from 2 to 5 mm and the length ranges from 10 to 15 cm (see Figures 6A–B). The ramifications do not have a preferential orientation, and they are distributed close to the surface with dichotomic pattern.

PALEOENVIRONMENTAL INTERPRETATION

The characteristics of the facies association described above are compatible with a fluvial channel-influenced depositional setting. The facies described (Table 1) indicates the migration of channels belts and aggradation over the floodplains, resulting in the amalgamation of lenticular sandy bars (Miall, 1996; Gibling, 2006). These features are typical of environments associated with variable or ephemeral flow regimes (Fielding *et al.*, 2011). The contact between the deposits are always marked by an erosive surface associated with multi storey sandstones, interpreted as fluvial channels migrating to distal portions of the fluvial plain directly under floodplain deposits and paleosols (Kraus & Wells, 1999).

In the case of the biogenic structures of the Marilia Formation, these cylindrical structures have similarities with lungfish burrows. However, such structures tend to be shorter, and do not have branches (Hembree *et al.*, 2004). Despite the record of lungfish fossils in the Marilia Formation (Alves *et al.*, 2013), the characteristics of the *Camborygma* described in the present study display knobby textures on their surface, scratch and stretch marks. These characteristics are not found in trace fossils produced by lungfishes. Due to this, the most probable trace maker for *C. litonomos* is the freshwater crayfish (Decapoda), common in fluvial plains (Hasiotis & Mitchell, 1993). According to these authors, the method used by crayfishes to make the burrows is the same through time (Triassic to present); the organism uses

Figure 4. General aspects of floodplain paleosols. **A**, the **C** horizon truncated by sandbar deposits and altered by pedogenesis (**Ck** horizon). **B**, paleosols with rhizohalos; note the Fe depletion in the paleorhizosphere (arrow heads). **C**, massive aspect of paleosols without bioturbation. **D**, paleosol bioturbated by *Camborygma litonomos* (arrow head). **E**, micromorphological aspects of paleosols. The arrow indicates clayey matrix, which involves the grains. **F**, granostriated b-fabric of paleosols. The arrow heads indicate the orientation of the clays on the side of the grains; note that the grains also tend to be oriented. Scale bars: A = 1 m; B–D = 15 cm; E–F = 0,3 mm.

Figure 5. Examples of *Camborygma litonomos*. **A**, arrows indicate the protuberances associated with the appendages of crayfish during excavation. **B**, arrows indicate the scratch marks on the inside of shafts. **C**, picture showing the basal chamber (**Ch**) at the bottom (**Sh**, shaft). **D**, *C. litonomos* occurring associated with undetermined burrow. Arrow heads show the nodules throughout the structure. **E–F**, the arrow indicates the difference between the lining and infilling material.

Figure 6. A–B, Rhizohalos present in studied paleosols.

its appendages for digging and manipulating sediments and soils, a well documented process for modern crayfishes (Walls, 2009). The flooded soils developed in floodplains presents the semi-aquatic environmental conditions necessary for the occurrence of crayfishes, such as oscillation of the water table and subaerially exposition (Hasiotis & Mitchell, 1993; Hasiotis & Honey, 2000). The morphology of their burrows is usually elongated and circular or cylindrical, with dimensions varying from a few centimeters to metric, depending on the distance from the water source (Martin, 2013; Miller *et al.*,

2014). Therefore, the modern freshwater crayfish burrow display the same morphology of their fossil content.

Crayfishes have hydrophilic behavior and they are dependent of freshwater sources (Buckup, 2003). Thus, the same is expected in the case of *Camborygma litonomos* trace maker. There are previous records of this ichnogenus in poorly drained paleosols with sandy-clay source material and high water table (Hasiotis & Mitchell, 1993; Smith *et al.*, 2008; Figure 7). In this way, many authors have pointed out *Camborygma* as structures commonly associated to paleosols

Figure 7. Paleoenvironmental scenario of Marília Formation in the study area.

developed on floodplains or wetlands settings (Betadou *et al.*, 2009; Genise *et al.*, 2016).

The trace fossils are reflecting a behavior in response of the drainage conditions of the substrate, as it reaches its maximum depth to intercept the water table (Smith *et al.*, 2008). *Camborygma litonomos* requires a constant presence of the water table (Hasiotis & Mitchell, 1993). In this way, this ichnotaxon indicates the oscillation of the water table in the paleotopography of the distal plains. According to the length of the burrows, the water table remained high for most of the time ranging from 40 to 50 cm, *i.e.*, the same length of the burrows. Modern crayfish digs the substrate looking for shelter, protection of predators and carapace dryness (Wells, 2009). This mechanism is a primitive survival behavior to intercept the water table as an exit to face the climatic seasonality, ephemerality of the fluvial channels, and the fluctuations of the water table (Walls, 2009), in this case in semi-arid conditions prevailing during the formation of the deposits of the Marília Formation (Goldberg & Garcia, 2000; Pereira *et al.*, 2015).

The soil was poorly drained and regularly exposed to subaerial conditions, indicated by the presence of redoximorphic features, such rhizohalos (Kraus & Hasiotis, 2006) and shrink-swell features, like the microfabric granostriated (Figure 3F), in response to repetitive cycles of saturation and dryness (Lindbo *et al.*, 2010). There is no evidence of preservation of organic matter in these deposits, indicating a relatively oxidative environment associated with the sub aerial exposure of these materials, at least seasonally (Retallack, 2001).

The occurrence of rhizohalos suggest that the deposits were exposed to the advancement of pedogenesis, which

allowed the colonization by plants (Kraus & Hasiotis, 2006), probably the format of the rhizohalos was conditioned by the high water table, as indicated by their adventitious shape. This indicates relatively low sedimentation rates too, which enabled the development of soil and colonization of plains by plants (Kraus, 1999).

Camborygma is the typical representative trace fossil of the *Camborygma* Ichnofacies. The occurrence of this ichnofacies represents local swamps or wetlands (with a herbaceous communities) paleoenvironments (Genise *et al.*, 2016; Genise, 2017). In addition, the ichnofacies reflects the transition period after the Permian extinction, where the continental invertebrate ichnofaunas disappear, and sequentially, these assemblages became dominated by earthworms and crayfishes, which characterize the paleoenvironmental scenario of the paleosols during the Cretaceous. Therefore the trace fossils described in Marília, as well the trace fossil associations documented in Upper Jurassic and Lower Cretaceous paleosols in Patagonia dominated by crayfish trace fossils (Bedatou *et al.*, 2008), are representatives of *Camborygma* Ichnofacies in South America.

CONCLUSIONS

The trace fossils described in this paper (*Camborygma litonomos*) record the activity of freshwater crayfishes, in the sedimentary successions of the Upper Cretaceous Bauru Group. *C. litonomos* is restricted to paleosols, which in this case were developed in the floodplain settings of a river system in a semi-arid environment.

In the Marília Formation deposits, these burrows represent the strategy of the crayfishes to survive in an environment with

drought periods throughout the year. The main conditioning factors to the tracemaker distribution were the presence of water, the food sources, and the paleosol clayey texture with the water table near the surface, indicated by the presence of rhizohalos and redoximorphic features. Crayfish body fossils have not yet been found in Marília Formation. Therefore, the presence of *C. litonomos* expands the knowledge about the macroinvertebrate fauna and the continental ichnofacies associated with floodplain settings of the Marília Formation on the Bauru Group.

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