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The paleoecological and paleoenvironmental importance of root traces: Plant distribution and topographic significance of root patterns in Upper Cretaceous paleosols

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ABSTRACT

Rhizoliths are organosedimentary structures produced by plants and are an important proxy for paleoenvironmental reconstructions because the differences in the morphology of rhizoliths and their rooting depths can be used to interpret soil humidity regimes, overall biomass at the soil surface, and the behavior of the water table. With the objective of advancing knowledge on rhizoliths, a study was performed on the macromorphological and micromorphological characterizations of the rhizoliths preserved in the thirty-one paleosols of the Marília Formation in Minas Gerais, southeastern Brazil. Based on the topological and architectural attributes of rhizoliths, and on their possible functional adaptations, such as mycorrhizal associations, three different types of rhizoliths are described in this study and represent at least three different plants: rhizohaloes, root casts and rhizocretions. Well-developed paleosols with nodular horizons contain the higher density of long root casts, indicating a seasonally dry environment, because the root casts present two meters in length. These adaptations are associated with an exploitation of a lowered water table during most times of the year. The higher density of rhizoliths indicates an area with agglomerated arboreous arbustive vegetation cover. Paleosols with chalky horizons also show a high density of root casts, indicating a landscape with high plant density that is adapted to drained soils, but with a seasonally elevated water table or the influence of ephemeral flows, given the proximity to the flow channels. The poorly drained paleosols with redoximorphic features show the lowest density of rhizoliths, thus indicating an incipient vegetation in response to near-surface water table and waterlogged soils in a distal floodplain. The rhizogenic laminar horizons have developed near fluvial channels with frequent sedimentary input, resulting in a sequence of laminar horizons composed of rhizocretions that are separated by sandy deposits or poorly developed pedogenic horizons. The micromorphological analysis on the rhizogenic laminar calcretes showed biogenic features, such as alveolar septal structures, calcified filaments, microcodium, calcified cells and pisoliths. Despite the scarce paleobotanical findings in the Marília Formation, the results obtained indicate an ecosystem that was composed of plants varying from herbaceous to arboreous, with an environment similar to modern semiarid shrublands.

1. Introduction

Rhizoliths are organosedimentary structures produced by plants that record their activities in a substrate, reflecting the ancient patterns of vegetation cover, as well as the interactions with soil and microorganisms during the lifetime of the plants (Sarjeant, 1975; Klappa, 1980). Therefore, rhizoliths are very important for the identification of paleosols and the interpretation of paleoenvironments, including the humidity, drainage, and topographic characteristics (Retallack, 2001; Kraus and Hasiotis, 2006).

As pointed out by Sarjeant (1975), rhizoliths are not body fossils; they are trace fossils that do not preserve the morphological structures of plants. Nevertheless, it is possible to make some qualitative and quantitative inferences about the densities and sizes of paleovegetation from rhizoliths (Pfefferkorn and Fuchs, 1991; Rinehart et al., 2015). In response to the interactions among roots, pedogenetic and diagenetic environments and the precipitation of carbonate or iron, rhizoliths can be preserved in different styles and morphologies. Rhizoliths are also

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one of the development factors of soils, especially regarding pedogenetic calcretes (Wright et al., 1988, 1995; Alonso-Zarza et al., 1998, Alonso-Zarza, 2018).

The pedogenetic calcretes in the Marília Formation, belonging to the Bauru Basin in southern Brazil, provide insight into the role of rooting patterns based on root trace fossils. The Marília Formation has only one occurrence of the gymnosperm fossil *Dadoxylon* sp. (Mezzalira, 1981), and this scarcity of plant fossils is still a subject of debate and is an important gap in the paleoecological knowledge of the Late Cretaceous in Brazil. Therefore, the analysis of rhizoliths is very important for the Marília Formation, but also for any geological unit with scarcity of macrofossils and paleobotanical information.

Most studies about rhizoliths have focused on macro- and microstructure and its classification according to their mode of occurrence (molds, filled molds or casts) (Klappa, 1980; Ekdale et al., 1984). However, the functional role of rhizoliths in paleosols, rooting styles and patterns and their influence on paleosol development have not received the same attention.

Considering that rhizoliths are not body fossils, how can their interpretative potential be optimized? What can rhizoliths reveal about the ancient vegetation cover? To understand this potential, it is important that in semi-arid environments due to fluctuations in the water table, pedogenesis and erosive dynamics make the plant remains exposed to subarea conditions, resulting in low rates of preservation of plant macrofossils (Gastaldo and Demko, 2011), so in these cases the rhizoliths may be the only information regarding the vegetation cover.

The vegetation cover is influenced by the soil characteristics and the architecture of roots with regards to the shape of the root system and its position and distribution in the soil, which reflects the distribution of water and nutrients and their functional adaptations (cluster roots, sand binds and mycorrhizal associations). This work presents an analysis methodology with an architectural and functional bias of the rhizoliths, aiming to increase its potential for paleoenvironmental and paleoecological reconstitutions using the paleosols of the Marília Formation, in the Southeast of Brazil, as a case study. This approach uses methodology and terms used to describe modern root systems, extracting from rhizoliths the maximum information regarding their ecological function and abiotic relationships with soils based on the knowledge of modern roots.

The topology and geometry of roots are functional components in the architecture of a root system (Fitter, 1987; Pregitzer et al., 2002) and can be adapted for rhizolith analysis.

Therefore, combining detailed macro- and micromorphological analyses of rhizoliths and paleosols, the objectives of this study are as follows: (1) to characterize the topology of the rhizoliths; (2) to identify the functional adaptations of the root systems, through their structures and architectures; and (3) to highlight the role of vegetation cover in the development of paleosols.

Thus, to advance the paleoenvironmental interpretation of rhizoliths, we propose an analysis based on their topological and architectural attributes as well as on their possible functional adaptations.

2. Materials and methods

2.1. Study area

The study area is in the western part of Minas Gerais State, in southeastern Brazil (Fig. 1), between the cities of Campina Verde – MG and Prata – MG, containing outcrops of deposits and paleosols belonging to the Marília Formation, which is the top unit of Bauru Basin. This region has been studied in detail by Batezelli (2015), Batezelli and Ladeira (2016), Nascimento et al. (2017a, 2017b, 2017c) and Batezelli et al. (2018).

The Bauru Basin provides an important record of the continental Cretaceous of South America, being located in the southeast and southwest parts of Brazil and occupying approximately 330,000 km^2. This intracratonic basin developed in the Superior Cretaceous in response to a flexural deformation that was associated with magmatic activity related to the Trindade Plume (Gibson et al., 1995) and the Alto Paranaíba Uplift (SAP) in southeast Brazil (Fig. 1) (2015; Batezelli et al., 2018). Its sedimentary record includes the Bauru Group, which presents a maximum thickness of 300 m and has deposits composed of mudstone and very fine sandstone at the base (Araçatuba Formation), grading of fine- to medium-grained sandstone in the intermediate portion (Adamantina and Uberaba formations) and fine- to coarse-grained, also conglomeratic, sandstone at the top (Marília Formation).

The Marília Formation is the youngest unit of the Bauru Basin and, according to paleontological research (Gobbo-Rodrigues, 2001; Dias-Brito et al., 2001; Santucci and Bertini, 2001; Martinelli et al., 2011; Fragoso et al., 2013), its deposits date from the Maastrichtian age. Its sedimentary record is composed of paleosols that occur interspersed with sandstones and conglomerates that consist of quartz and carbonate clasts and bioclasts. The depositional architectures of the Marília Formation are associated with river channels, lenticular sandbars and floodplain elements that constitute amalgamated channel complexes interspersed with paleosols (Batezelli, 2015) (Fig. 1B).

The semiarid 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 clay minerals from the group of illites and palygorskite/sepiolite (Suguio and Barcelos, 1983; Goldberg and Garcia, 2000; Nascimento et al., 2017a; Silva et al., 2018), as well as by paleoprecipitation (mean annual precipitation - MAP) index derived of the degree of chemical weathering (CIA-K) of Bt paleosol horizons according Sheldon and Tabor (2009), showed average values of 420 and 500 mm/year for the study area (Pereira et al., 2015; Silva et al., 2018).

2.2. Field methods

The sedimentological analysis was based on the analysis of four outcrops that 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.

Paleosols were described in the field, following the recommendations of the Soil Survey Staff (1999), regarding the identification and limits of horizons, color, abundance and color of nodules, in addition to the redoximorphic features and bioturbation patterns (rhizoliths and burrows), such as size and thickness. The paleopedogenetic development degree was estimated based on Retallack (2001), using macromorphological characteristics associated with the development of soils, such as the soil structuring degree, the presence of pedogenetic carbonate, and the development and thickness of Bk and Bt horizons.

The rhizoliths described in the field according to Klappa (1980), Retallack (1988), and Kraus and Hasiotis (2006) included their lengths, thicknesses, branching angles, colors, and associations with other ichnofossils. After the collection of field data, a topological classification was applied for individual roots, which consists of the geometrical description of a root system (branching, pattern, distance and branching angles).

All measurements (Table 1) can be measured directly on the structure depending on the degree of preservation in the context of the field and have different functional meanings. These measures can be derived parameters that enhance the paleoenvironmental and paleoecological significance of rhizoliths because they are based on knowledge gained from analysis of modern roots. These parameters are alternatives to the methodologies used in body fossils and in the laboratory that are not suitable for analysis of trace fossils. In addition to the definition of these parameters, we can use the topological characterization of Fitter (1982) for architectural understanding of the rhizoliths. Topological characterization part of the mathematical bias that every system is organized into a binary structure with physiological relevance (Rellán-