Sedimentary Geology 240 (2011) 85–96

Contents lists available at SciVerse ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Large ferruginized palaeorhizospheres from a Paleogene lateritic profile of Uruguay

Jorge F. Genise [a,*], Eduardo S. Bellosi [a], Mariano Verde [b], Mirta G. González [a]

[a] CONICET, División Icnología, Museo Argentino de Ciencias Naturales, Av. Angel Gallardo 470, 1405 Buenos Aires, Argentina
[b] SNI-ANII, Departamento de Evolución de Cuencas, Facultad de Ciencias, Universidad de la República, Montevideo, Uruguay

ARTICLE INFO

Article history:
Received 23 June 2011
Received in revised form 27 August 2011
Accepted 29 August 2011
Available online 6 September 2011

Editor: B. Jones

Keywords:
Ferruginized palaeorhizospheres
Lateritic profile
Paleogene
Uruguay

ABSTRACT

It is proposed herein that columns included in the unconformity between Mercedes (Upper Cretaceous) and Asencio (Lower Eocene) formations of Uruguay, forming "caves" known since the XIX century, are large ferruginized palaeorhizospheres. Diagnostic characters are concentric internal structure, radiating secondary prolongations, preservation of original lamination, trace fossils, and other attributes of the original deposit. In contrast with rhizoliths, which originated as root casts or by roots and their peritrophic zones, palaeorhizospheres are originated from peritrophic zones to a few tens of centimeters in the soil surrounding the roots. In many cases, like those presented herein, rhizoliths are not preserved inside the palaeorhizospheres. Specimens were studied in 6 localities from central Uruguay, where 5 different morphological types were recognized according to its internal structure: (1) rimmed, (2) concentric, (3) concentric disrupted, (4) nodular or mottled, and (5) brecciated. The palaeorhizosphere hypothesis can explain this diversity of internal structures, which may be compatible with different stages of root and rhizosphere development. Types 1 and 2 could be produced by living roots, whereas 3 to 5 more probably by percolation and staining by Fe solutions coming from the overlying Asencio Formation through decaying or dead roots. The rim that surrounds most structures may be interpreted as the boundary of the original rhizosphere, where Fe ions translocated outward from the root by chelation, found oxidizing conditions. Concentric pattern would result from the centrifugal displacement of the oxidizing rim. Type 3 to 5 structures would start when most biologic processes around the living or decaying root cease, and periodic formation of rings stops. Even when palaeorhizospheres are included in the Mercedes Formation, their possibility to be produced during Mercedes times is unlikely because the strong oxidation processes involved were exclusive of the Asencio times, when favored by the Early Eocene Climate Optimum laterites reached the latitude of Uruguay. Large palaeorhizospheres are probably common features in many continental successions, but mostly overlooked or misinterpreted until now.

1. Introduction

Cylindrical concretions around living or decaying roots were known a century ago (Barrel, 1913; Kindle, 1923, 1925; Frenguelli, 1926), although root-shaped concretions had been still recorded previously (Todd, 1903). Klappa (1980) reviewed the information on root traces and proposed the term "rhizolith" to include accumulation and/or cementation around, cementation within, or replacement of higher plant roots by mineral matter, recognizing different types: root molds, root casts, root tubules, rhizocretions, and root petrifactions. Drab-haloed root mottles (Retallack, 2001) or rhizohalos (Kraus and Hasiotis, 2006) is another type of rhizolith produced by anaerobic decay of buried organic matter.

Rhizoliths described by Klappa (1980), and most recorded in the bibliography elsewhere, are cemented by carbonate, and can show columnar morphology (Wanas and Abu El-Hassan, 2006; Alonso-Zarza et al., 2008). Likewise, ferrous ions mobilized in the soil surrounding roots can oxidize and precipitate around them forming ferruginous (ferric) rhizoconcretions (Bates, 1938; Smith, 1948; Claxton, 1970; Bown, 1982; Stieglitz and Van Horn, 1982; Retallack, 2001; Gregory et al., 2004; Kraus and Hasiotis, 2006).

McNamara (1995) coined the term "megarhizolith" for large calcified root systems involving large columnar structures or pinnacles from the Nambung National Park of Australia (Lowry, 1973; Lipar, 2009). Alonso-Zarza et al. (2008) utilized the same term for describing similar structures from the Canary Islands. However, and besides the subjective connotation of size involved in the use of "mega" for describing a large structure, another question arises: are these structures true rhizoliths sensu Klappa (1980)? This author, when claiming "Rhizoliths *and associated features of the rhizosphere*….." seemed to exclude rhizospheres from his definition of rhizoliths. The rhizosphere is considered a part of the regolith immediately surrounding the plant root that provides habitat for microorganisms, and is altered by root growth, respiration, and nutrient uptake (Little and Field, 2003). Accordingly, McLaren (1995) called attention to the diagenetic effect of rhizospheres extending from the peritrophic zones of roots,

* Corresponding author. Tel.: +54 11 4981 9282×150.
E-mail address: jgenise@macn.gov.ar (J.F. Genise).

0037-0738/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.sedgeo.2011.08.008

distinguishing rhizoliths, originated by roots and their peritrophic zones, from palaeorhizospheres, occurring from peritrophic zones to a few tens of centimeters in the palaeosol surrounding the rhizoliths. Large palaeorhizospheres and megarhizoliths are probably common features in many continental successions, but are mostly overlooked or misinterpreted until now (Alonso-Zarza et al., 2008). In some cases they were confused with termite nests (Bordy et al., 2004; Hasiotis, 2004; Salgado et al., 2007) (but see Genise et al., 2005; Roth et al., 2006; Bromley et al., 2007; Alonso-Zarza et al., 2008).

The early Eocene Asencio Formation is renown for its insect trace fossil content (Genise et al., 2004) and also for the presence of columns that form "caves" known since the XIX century, such as the Gruta del Palacio. Caves and columns appear in some of the Asencio outcrops, where they have been mentioned as trunk casts (Rivas, 1884), man made structures (Isola, 1900), or diagenetic concretions (Pazos et al., 1998; Goso and Perea, 2003). In this contribution we present the evidence for the interpretation of columns from the Asencio Formation of Uruguay as ferruginized large palaeorhizospheres, and the first record and analysis of this type of structures elsewhere. In addition, it is also a contribution to the complex interpretation of the stratigraphic relationship between the Asencio Formation and the underlying Mercedes Formation, which is still matter of discussion (Bellosi et al., 2004; Martínez and Veroslavsky, 2004; Alonso-Zarza et al., 2011).

2. Geologic setting

2.1. Stratigraphy and sedimentology

The studied interval where columns are preserved (Fig. 1) comprises the Mercedes (Late Cretaceous) and Asencio (Early Eocene) formations. They crop out to the west and north of the Piedra Alta Terrane, the Paleoproterozoic crystalline basement of Uruguay that is the northern part of the Río de la Plata Craton (Dalla Salda et al., 1988; Oyhantçabal et al., 2010). The Mercedes Formation is a light colored (white, pink, gray) unit, up to 100 m thick that represents the partial infill of the "Litoral del río Uruguay" basin. It is composed of medium to fine-grained, poorly sorted sandstones, fine to medium conglomerates, and scarce pink or greenish mudstones (Bossi and Navarro, 1991). Sandstones present 10% of porosity, abundant (35%) grayish or yellowish clay matrix and correspond to feldspathic wackes. Carbonate or siliceous pore-filling cement is frequent in these sandstones. Pazos et al. (1998) described lenticular channel bodies with fining-upward, cross-bedded sandstones, conglomerates, and pedogenized inter-channel deposits formed in a meandering fluvial depositional setting. Locally and in the upper section, white limestones and siliceous rocks also occur (Alonso-Zarza et al., 2011). The Mercedes Formation bears sauropod eggs and bones (Perea et al., 2009), and is considered Late Cretaceous in age.

The Asencio Formation is a thin (5–15 m), dark red and indurated siliciclastic sequence composed by quartz arenites, which exhibits a widespread and advanced modification by soil-forming processes (ferrallitization and lessivage) and contains a very diverse ichnofauna (Genise et al., 2004). The stacked palaeosols show strong to very strong development and moderate to intense bioturbation (Genise et al., 2004). The top of the unit is denoted by an erosive unconformity below the Late Oligocene Fray Bentos Formation. Locally, it can be also overlaid by the Queguay Formation (Alonso-Zarza et al., 2011). Palaeosols of the Asencio Formation were interpreted as Ultisols (González, 1999). These well-drained and oxidized palaeosols are enriched in clay and Fe sesquioxides.

Two interfingering and superposed facies were distinguished by Bellosi et al. (2004): ferruginized duricrusts and nodular beds. Combination of these two facies produces complex polygenetic profiles of the Asencio Formation. Such facies are common in erosional or slightly depositional wet-tropical settings that contain laterites. Ferruginized duricrusts correspond to indurated, well-structured and argillic palaeosols with abundant red clay-hematitic microgranules. The main clay minerals are kaolinite and smectite (Ford, 1988; Goso and Guérèquiz, 2001). Root traces generally appear as vertical or inclined, bifurcating external molds or voids. The most common type is a thin (2 to 3 mm wide) vertical and rectilinear (5 to 15 cm long) rhizolith without rootlets. Another frequent type is a very sinuous, frequently subhorizontal and wider (up to 9 mm) rhizolith. Occasionally root traces with drab haloes also occur. Duricrusts or pedogenic ferricretes present a widespread cementation of iron oxides (ferrallitization) responsible for the strong induration. Hematite precipitation occurred under dehydration conditions (not water-saturated) and gradual glaebulization due to epigenic replacement of the matrix by a plasmic constituent (iron oxyhydroxides) accumulated secondarily and selectively (Tardy and Roquin, 1992). Thus, crust formation represents subsequent drier conditions than the nodular beds. Preservation of most stable minerals in the soil (i.e. quartz, kaolinite and hematite) was favored by this geochemical differentiation (Bellosi et al., 2004). Nodular beds look as disorganized, matrix or clast-supported "conglomerates", presenting a non-regular bed morphology and a light-colored clayey matrix. Lateral changes from one facies to the other may be gradual or less frequently abrupt. Subspherical nodules vary from 1 to 10 cm in size and are similar to duricrusts in composition and texture. Clay mineralogy of the matrix differs from duricrusts, being richer in smectite (Bellosi et al., 2004). Root traces were not observed. Nodular beds are comparable with pisolithic layers (McFarlane, 1976; Tardy, 1992), interpreted as residual accumulations by disintegration or dismantling of the duricrusts due to leaching or chemical weathering in wetter conditions (Bellosi et al., 2004). Post-burial diagenetic modification of the Asencio Formation is negligible considering the shallow burial depth supported by this succession. Cumulative thickness of units above Asencio Formation (i.e. Fray Bentos Fm, Queguay Fm and younger units) is less than 40 m. All post-depositional features observed in thin-sections can be easily related to soil-forming processes (González, 1999; Bellosi et al., 2004). Absence of datable body fossils or rocks precludes a direct and precise chronologic determination of the Asencio Formation. Based on stratigraphic, ichnologic and palaeoclimatic considerations, it was suggested an Early Eocene age (Genise et al., 2002; Bellosi et al., 2004).

2.2. Mercedes–Asencio unconformity

Columns occur within the unconformity that separates the Mercedes and Asencio Formations. Although these formations display contrasting lithofacies, diagenetic features and colors, the stratigraphy of this succession in terms of subdivisions and boundaries has been controversial (Bossi, 1966; Ford and Gancio, 1988; Bossi and Navarro, 1991; Veroslavsky and Martínez, 1996; Martínez and Veroslavsky, 2004). The Asencio Formation was not considered a depositional record but a "residual" unit corresponding to the modified upper part of the Mercedes Formation by some authors (Bossi et al., 1998; Goso, 1999; Goso and Perea, 2003). However, the intercalation of palaeosols with unmodified sandstones and mudstones (Martínez and Veroslavsky, 2004) and the presence of stacked composite palaeosols (Bellosi et al., 2004) indicates that Asencio Formation records probable short periods of sedimentation followed by prolonged ones of non-sedimentation and pedogenesis. Accordingly, several authors considered the Asencio Formation a distinct lithostratigraphic unit (Genise and Bown, 1996; Pazos et al., 1998; Bellosi et al., 2004; Genise et al., 2004; Tófalo and Pazos, 2009; Alonso-Zarza et al., 2011).

The regional unconformity that separates the Mercedes and Asencio formations was called Yapeyú Paleosurface by Pazos et al. (1998). These authors described within it indurated and poorly-defined columns associated with fractures filled with iron oxides. Genise et al. (1998) described fossil termite nests and meniscate burrows from the contact between both formations.

A more detailed characterization of the Mercedes–Asencio contact, where the columns occur allowed distincion of a number of morphological and ichnological features (Fig. 2). The most frequent are: (A) Irregular, steep and vertical surfaces at top of the Mercedes Formation, followed by a dark red massive sandstone. (B) A red-colored stained zone with ferric oxides, up to 1 m depth in the uppermost part of the Mercedes Formation. (C) Large cracks and subcircular or heart-shaped structures up to 1.7 m high (Fig. 4E). These structures show distinct boundaries and are filled with a dark red massive sandstone including white angular clasts (breccia) of Mercedes composition. Above them, very large subhorizontal blocks (up to 1.5 m thick and 12 m long) and core stones of saprolitized rock are also present. (D) Brecciated zones with an Asencio-type matrix. (E) Meniscate burrows and termite nests (Genise et al., 1998). (F) Columns. (G) Densely fractured or cracked zones cemented with red iron oxides (Fig. 4F). (H) Red rhizoliths following fracture planes (Fig. 4B, D). (I) White, relatively small, and dispersed rhizoliths.

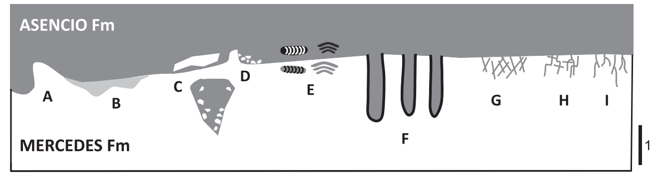

Fig. 2. Morphological and ichnological features observed at the unconformity between Mercedes and Asencio formations, interpreted as a weathering profile. A: Irregular erosion relief. B: Red (iron oxide) stained zones. C: Large wedges with clasts, megablocks and core stones of saprolitized rock. D: Brecciated zones. E: Termite nests and meniscate burrows. F: Columns interpreted herein as large palaeorhizospheres. G: Ferruginized fractures. H: Ferruginized root traces following fracture network. I: Small rhizoliths.

3. Localities with columns

The six studied localities with columns are located at the central region of Uruguay in Soriano and Durazno departments (Figs. 1 and 3). They were the following: (1) Route 5, km 216 (33° 6′ 38.80″ S, 56° 27′ 36.29″ W), (2) Egaña (Walther's locality) Route 2, km 229 (33° 35′ 21.1″ S, 57° 42′ 43.6″ W), (3) Carlos Reyles (33° 3′ 25.64″ S, 56° 28′ 18.54″ W), (4) Route 4, km 245 (33° 0′ 55.30″ S; 56°37′ 20.80″ W), (5) Route 4, km 229 (33° 3′ 12.92″ S, 56° 28′ 25.38″ W) and (6) Gruta del Palacio (33° 16′ 48.5″, 57° 08′ 34.1″ W).

Locality 1 shows low, mostly red, columns exposed on a whitish bedding plane (Mercedes Formation) extended over an area of almost 800 m^2. There is no crust capping them (Fig. 3A). No detailed observations on columns were accomplished at this locality. Locality 2 is probably the one described by Walther (1931) according to its location near the Egaña rail station. His figure of the outcrop shows a cave that no longer exists. Presently, columns are exposed as cross sections or low pillars, mostly red, but with yellow-brown and white patches in some cases on a whitish bed (Mercedes Formation) (Fig. 3B), or as higher (up to 2.5 m) structures in an overlying vertical section capped by a ferruginized duricrust of the Asencio Formation. This vertical section bears the only horizontal specimen found in this study (Fig. 4C). Column diameters range from 11.0 cm to 96.6 cm (mean: 39.8 cm, N: 53), and they were separated by 0.7 m to 1.0 m approximately. The whole area with columns extends over more than 1800 m^2. Carlos Reyles outcrop is about 135 m long showing a vertical section, 2.20 m high, composed of columns supporting a ferruginized duricrust, 90 cm thick, as a roof (Fig. 3C). Whitish rock matrix among columns (Mercedes Formation) was weathered out in some places resulting in a typical "cave" (*gruta*) outcrop. Diameters of columns range from 18.5 cm to 86.1 cm (mean: 35.9 cm, N: 7). Close to the cave, numerous and more isolated columns also occur along few hectares. Localities 4 and 5 are small outcrops (about 2000 and 2700 m^2 respectively) beside the Route 4, where on a whitish horizontal bed (Mercedes Formation), short, red or yellow-brown columns and cross sections are exposed (Fig. 3D, E). There is no duricrust capping the columns. Diameters range from 9.3 cm to 82.3 cm (mean: 31.5 cm, N: 58). In some sectors, column are more densely grouped, being separated by less than 35 cm. At locality 4, the matrix (Mercedes Formation) bears dinosaur eggshells and white, small, silicified rhizocretions (Fig. 4B). At locality 5, red, small rhizoliths are also present (Fig. 4D). Locality 6 is the classic one known as Gruta del Palacio since the XIX century (Rivas, 1884; Benedetti, 1887) (Fig. 3F). It shows a typical cave aspect with mostly red columns, in many cases weathered out from a whitish rock matrix (Mercedes Formation), and supporting a ferruginized duricrust as roof (Asencio Formation). The vertical exposure, 70 m long, shows remains of the original lamination intersecting columns and matrix. In a map showing distribution of two hundred columns at Gruta del Palacio (Goso and Guérèquiz, 2001), estimated areal density is 0.6 column per square meter. Apart from the vertical exposure, low columns and cross sections are spread at the front of the cave, indicating that this outcrop would be larger in the past. Diameters of columns taken from cross sections range from 32.8 cm to 94.0 cm (mean: 65.8 cm, N: 19). Gruta del Palacio shows the largest columns in average, whereas the other localities show smaller columns, of about 30 cm in mean diameter. The smallest ones are in locality 5, which also shows the greater dispersion.

Fig. 1. Map showing studied localities. A: Egaña (at Route 2, km 229) (locality 2). B: Gruta del Palacio (locality 6). C: Route 4, km 245 (locality 4). D: Carlos Reyles (locality 3). E: Route 4, km 229 (locality 5). F: Route 5, km 216 (locality 1).

4. Description of columns

Where matrix is preserved, columns occur in a light gray, fine to medium-grained sandstone, showing horizontal bedding or low-angle cross-bedding. Grain-size and mineral composition of the framework fraction is similar to the material surrounding the columns. Beside columns, two types of small rhizoliths (up to 3 cm in diameter) are common in this matrix. The most frequent are ferruginized, irregular and sinuous presenting the same red color than columns. Less frequent rhizoliths are silicified, whitish, sinuous and cylindrical.

Measured columns from all localities range in diameter from 9.3 cm to 94 cm (mean: 43.2 cm, N: 137) and the highest recorded was 2.70 m high, at locality 2. Diameters recorded in the bibliography range from 76 cm to 1 m (Goso and Guérèquiz, 2001), whereas maximum high is 2.20 m (Isola, 1900; Goso and Guérèquiz, 2001). Contact between columns and matrix is generally sharp. In cross section, columns are mostly circular, although few specimens are elongated, or

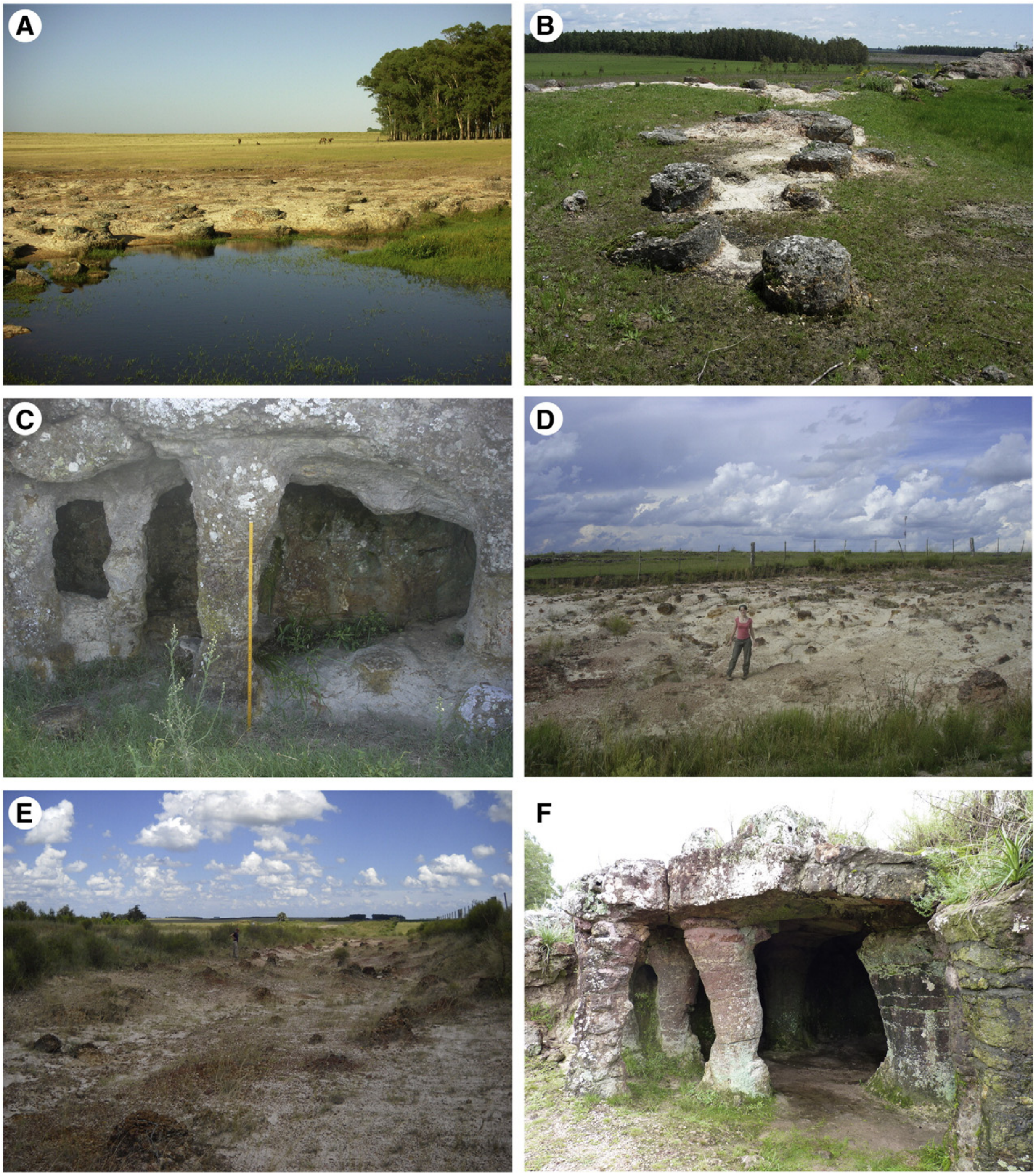

Fig. 3. Aspect of columns at the studied localities. A: Locality 1 at Route 5, km 216. B: Locality 2 (Egaña) at Route 2, km 229. C: Locality 3 at Carlos Reyles. D: Locality 4 at Route 4, km 245. E: Locality 5 at Route 4, km 229. F: Locality 6, Gruta del Palacio.

present a more irregular shape with lateral deformations. Some of them show sharpened, lateral extensions. According to its internal structure observed in cross sections, they may be grouped in five types. At the same locality, the diversity of these types and diameters may be high, even in sectors were column spacing is only few decimeters.

4.1. Rimmed

Some columns present a large, grayish and homogeneous core and a thick yellowish/orange or red rim (Fig. 5A). The simplest specimens are composed of a structureless grayish (or red) core surrounded by a single yellow-brown rim. In some cases, the core may include red mottles.

4.2. Concentric

Internal structures show different degree of iron oxidation or reduction reflected in red to yellow-brown rings intercalated with light gray ones, arranged in a concentric pattern. Well defined rings range from 0.5 cm to 2.0 cm wide. In some specimens, the grayish central core shows a concentric arrangement (Fig. 5B). More colored specimens show concentric yellow rings externally and a concentric yellow-red mottled pattern internally (Fig. 5C). The most complex ones show a central red area surrounded by concentric red rings in some cases surrounded by a yellow external rim (Fig. 5D). Diameters of concentric columns are small, ranging from 9.3 cm to 28.3 cm (N: 12).

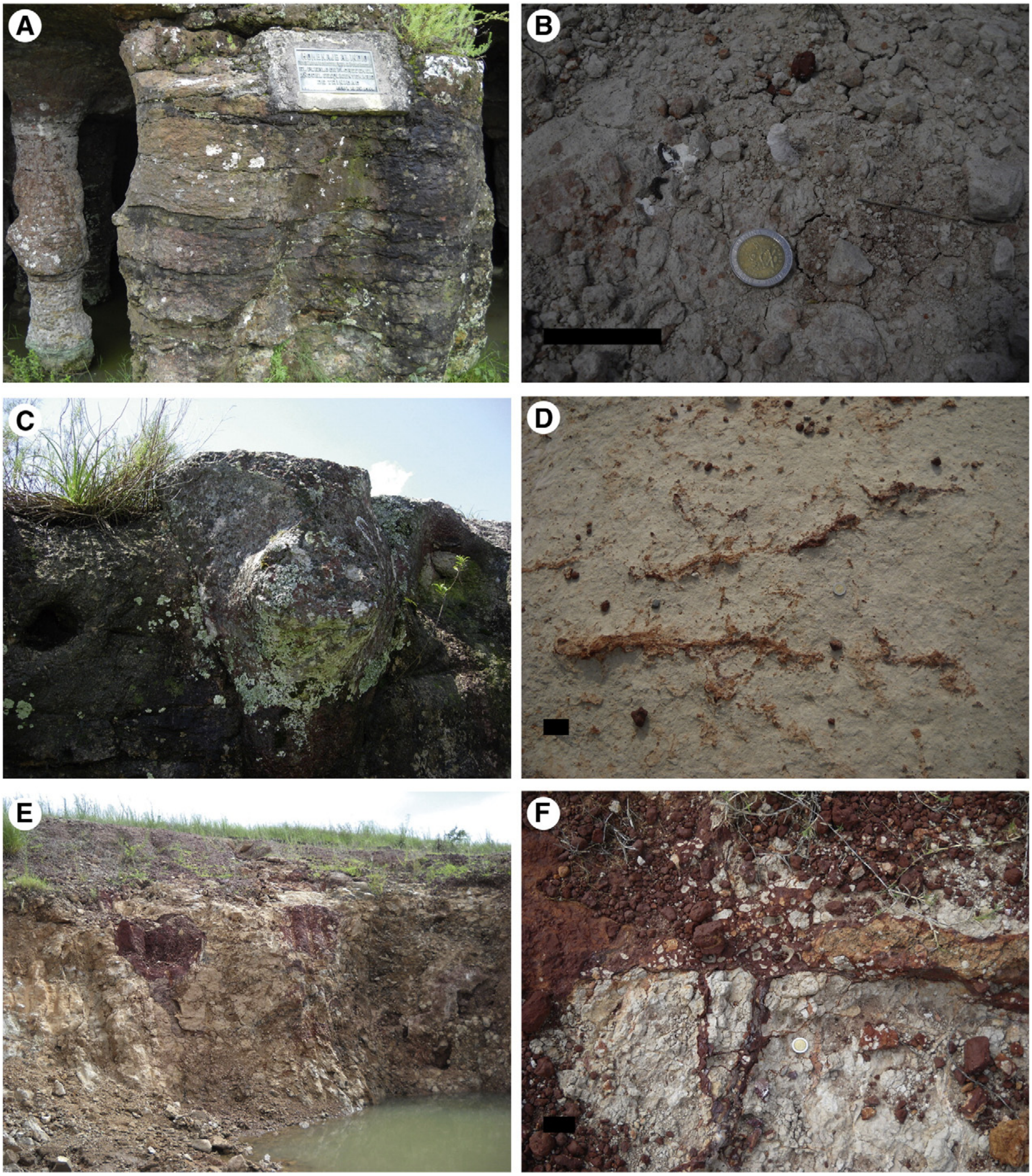

Fig. 4. A: Gruta del Palacio, remains of the original lamination intersecting columns and matrix. B: White, small, silicified rhizolith from Mercedes Formation at locality 4. C: Horizontal palaeorhizosphere from locality 2 (Egaña). D: Rhizoliths of small size from locality 5. E: Unconformity showing heart-shaped structures. F: Brecciated fillings of cracks at the unconformity. Scale bars: 5 cm.

Some columns have thin, tappering, radiating prolongations up to ten centimeters long (Fig. 5C).

4.3. Concentric disrupted

Some specimens from different localities show from 2 to 8 remains of concentric, yellow-brown, rings in the external part and red nodules in the whitish core (Fig. 5E). These specimens are large ones, diameters ranging from 46 cm to 52 cm and the area with disrupted rings is 12 cm wide. Another specimen, 40 cm in diameter and 38 cm high, is mostly whitish with yellow mottles and elongate pieces (9 cm) of former fractured rings scattered in its cross section (Fig. 5F). When breakage of rings is advanced, and pieces become disordered, the structure is more likely as the brecciated type described below.

4.4. Mottled or nodular

Most specimens studied show different amounts of red and/or yellow-brown mottles or full relief nodules lacking a particular concentric arrangement and surrounded by an external yellow rim (Fig. 6A). Some specimens show a yellow-brown matrix, with a few red nodules, and

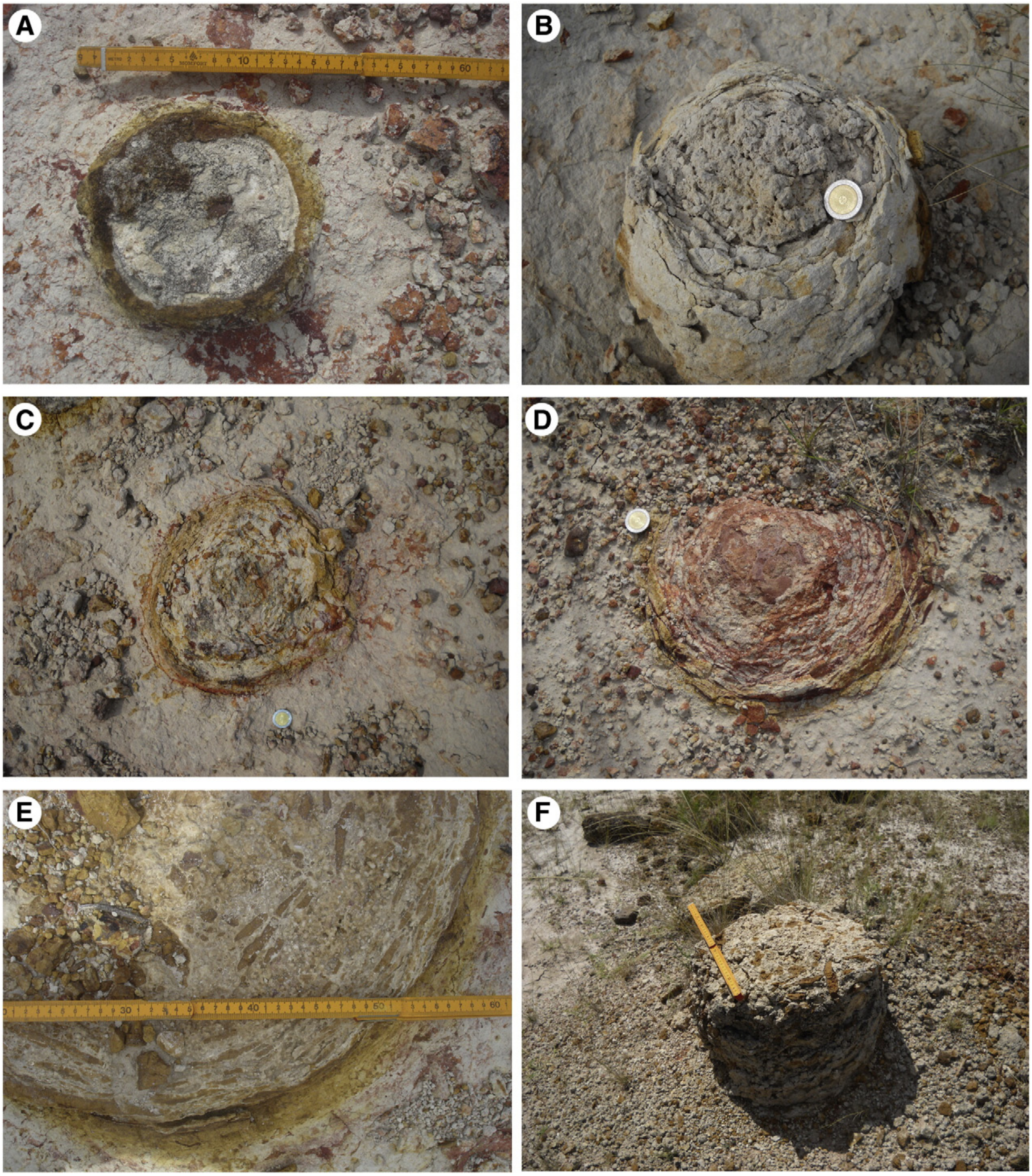

Fig. 5. Rimmed and concentric palaeorhizospheres. A: Structureless grayish core surrounded by a yellow rim. B: Grayish central core showing a concentric arrangement. C: Concentric yellow rings externally and concentric yellow and red mottled pattern internally. Note small secondary roots radiating from the outer rim. D: Central red core surrounded by concentric red rings with a yellow external rim. E: Disrupted concentric, yellow-brown, rings in the external part of the cross section and red nodules in the central grayish area. F: Grayish specimen with yellow mottles and elongate, angular, pieces of former rings scattered in its cross section. Coin: 2.3 mm.

a whitish boxwork resembling burrows (Fig. 6D). In some cases, particularly in columns of Gruta del Palacio, it is possible to observe mottles of very different sizes (Fig. 6B, C), from small, millimetric ones to entire columns mostly red, in which only some of the original nodules are separated by a decolored, whitish, thin network, whereas others are mostly welded (Fig. 6E). Nodular specimens are mostly the larger in diameter and comprise all columns of the Gruta del Palacio and most of locality 2.

4.5. Brecciated

In two observed cases of small columns, 12 cm and 16 cm in diameter, the internal structure shows a structureless red matrix with angular, whitish clasts (Fig. 6F).

Many columns show a combined internal structure: rimmed and nodular; concentric rings and nodules or rings and brecciated. In these cases, rings and the rimmed zone, are better developed in the outer part.

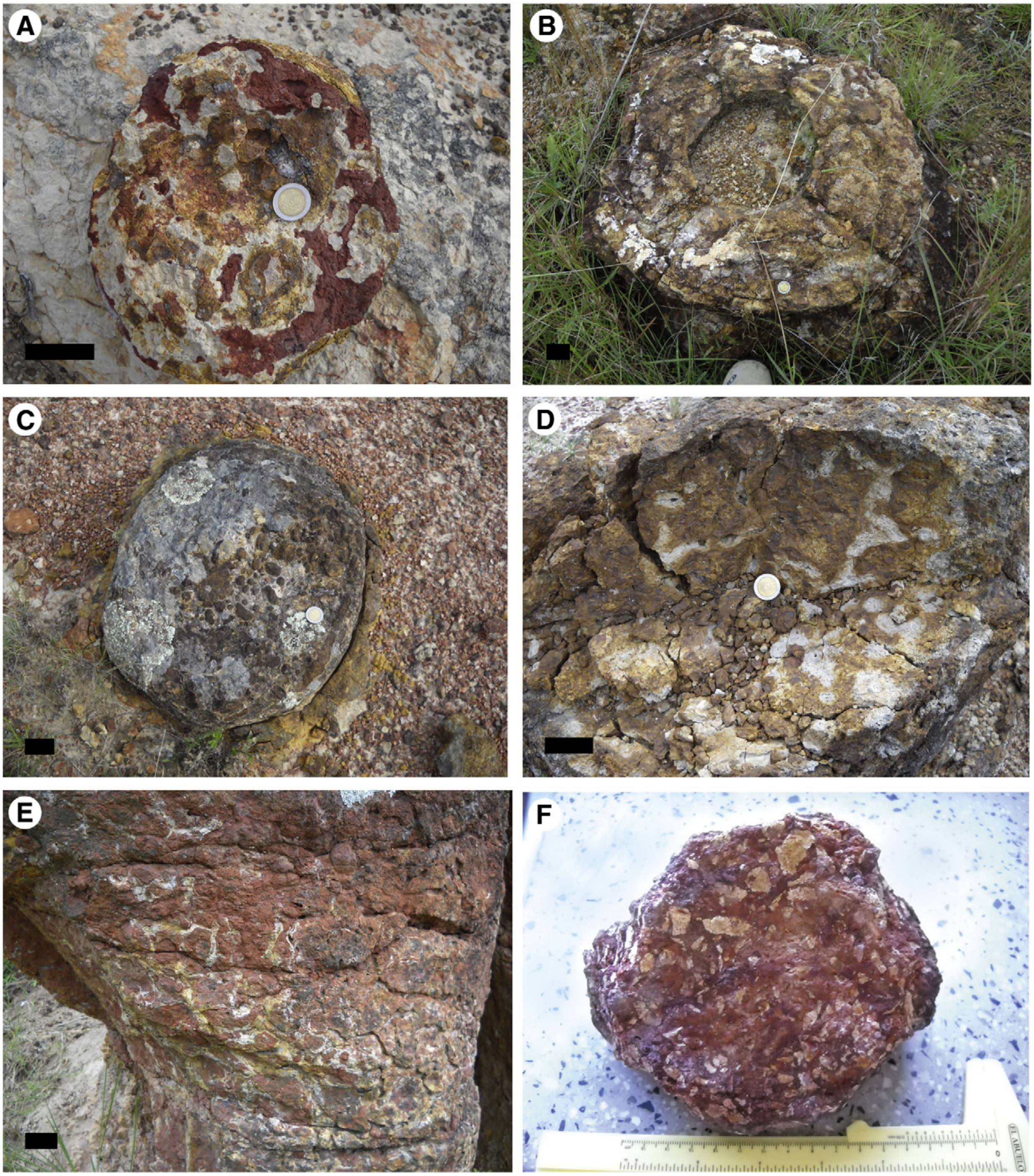

Fig. 6. Nodular, mottled, and brecciated palaeorhizospheres. A: Yellow and red mottles. B: Yellow and red mottles with remains of concentric arrangement evidenced by a central hollow. C: Nodular with remains of external concentric rings. D: Yellow-brown matrix with a whitish boxwork resembling burrows. E: Column mostly red, in which only some of the original nodules are separated by a decolored, grayish, thin network, whereas others are mostly welded. F: Brecciated specimen. Scale bars: 5 cm.

5. Micromorphological and geochemical data

Micromorphological observations were made with a petrographic microscope Nikon Optiphot and micromorphology described following the nomenclature by Bullock et al. (1985). Geochemical data (Fe content) were obtained by a XRF Niton XL3t analyzer. X-ray diffraction (XRD) analyses were carried out on fine meshed sample material (<20 μm), measured with a PANalytical X'Pert PRO diffractometer, with Cu lamp (kα = 1.5403 Å) operated at 40 mÅ and 40 kV. The samples were measured from 2 to 40° 2θ, with a scan speed of 0.04°/s and a time per step of 0.50 s. Contrasting micromorphological features observed in the studied units and structures will be highlighted in order to assess pedogenic and diagenetic changes related to the Mercedes–Asencio unconformity and column formation.

Poorly sorted sandstones of Mercedes Formation are medium-grained to gravelly, with subangular to sub-rounded clasts. They show a fine fraction formed by grayish to yellowish clay material, and scarce isotropic nodules of Fe oxides. The b-fabric is mainly stippled–speckled to weakly grainstriated. Some voids and grains show coatings of very well oriented clay minerals. Total mean Fe content is 10591.33 ± 253 ppm. Stained

zones, at the unconformity, present higher porosity (20%). An abundant, red to yellowish, highly birefringent clay matrix, irregularly distributed, coats grains and voids (i.e. illuviated clay). Frequent nodules of ferrous oxide are also present.

Columns are composed by the same type of sandstones recognized in the Mercedes Formation, in terms of mineral composition of the framework, grain-size, sorting and roundness. Quantity of total mean Fe is also similar (9816.78 ± 237 ppm). Homogeneous parts of concentric or rimmed columns show a massive microstructure with moderate porosity (20%), formed by equidimensional and elongated voids. Yellow, orange, or red patches of clay material are common. Groundmass presents a stippled-undifferentiated to grainstriated b-fabric with red nodules, or a well developed grain to porostriated b-fabric, respectively. Most grains and voids are coated by birefringent clay. Isotropic, red hematitic nodules along with brown to black nodules rich in MnO and FeO also occur. Brecciated columns have an irregular mottled aspect, defined by a heterogeneous groundmass, showing different types of stained clayey patches with net or transitional margins. Yellow patches present a highly birefringent, well developed grain to porostriated b-fabric. In orange patches birefringence is low and b-fabric punctuated. Deep red patches show very low birefringence related to high Fe oxide content forming red nodules. B-fabric is grain to porostriated or punctuated. Frequent clay cutans cover grains and pores. The latter is impregnated by ferric oxide. Nodular columns include yellow or red nodules. The former shows an argillaceous groundmass with variable hues due to different mineral concentration, from yellowish gray to orange and dark red. XRD shows that yellow nodules are pigmented by goethite. Small concretions showing a concentric internal arrangement surrounded by a coat of oriented clay with a punctuated undifferentiated or striated b-fabric are frequent. Red nodules present a groundmass with uniform red color, constituted by clay granules with ferric oxide (small concretions). Clay birefringence is attenuated by the abundance of Fe oxides. B-fabric is mainly stippled–speckled to granostriated. Thin clay cutans also occur around voids and grains. XRD shows that red nodules are pigmented by hematite. Total mean Fe content is 16347.11 ± 607 ppm. These features were also observed in ferruginized duricrusts of the Asencio Formation (González, 1999; Bellosi et al., 2004).

6. Discussion

6.1. Lateritic profile at Mercedes–Asencio unconformity

Columnar structures from different localities occur within the stratigraphic interval that marks the boundary between Mercedes and Asencio formations. Despite the irregular relief of this contact, truncations of strata or transported clasts were not observed. Thus, this interval denotes a time of substrate modification, along with prolonged tectonic quiescence and deep chemical, biological and physical weathering during the Paleogene (Retallack, 2001; Rossetti, 2004).

Apart from columnar structures, most of characteristics observed at the Mercedes–Asencio unconformity have been reported from lateritic profiles or weathered surfaces of tropical regions. Large-size cracks bearing giant blocks and angular clasts are frequent in these cases (Millot, 1970; Bourman and Ollier, 2002; Rossetti, 2004). In situ weathered blocks, also known as core stones, red stained zones and fractures in the upper part of the Mercedes Formation are typical features of saprolite rocks formed in a weathering profile of a substrate. Biological weathering at the unconformity is denoted by the presence of meniscate burrows, termite nests, and medium-size rhizoliths, some of them following fracture planes. Heart-shaped and subcircular structures observed in some quarries could be interpreted as casts formed by infilling of large horizontal roots because of their morphology and brecciated composition.

Consequently, the studied columnar structures are intimately associated to a number of morphological and ichnological features suggesting modification of a substrate exposed to physical, chemical and biological weathering. Lateritic profiles do not form within the soil solum, but within deeper and thicker zones of the saprolite or regolith (Schau and Henderson, 1983; Ollier and Pain, 1996), in this case represented by the Mercedes Formation. Fig. 7 shows the position of original rhizospheres, and the zones defined by Tardy (1992), within a reconstructed lateritic profile that developed at the contact between Mercedes–Asencio formations. Subsequent exposition of this interval and erosion of saprolitized and cracked parts of the substrate (Mercedes Fm.) resulted in present-day exhumed columns (former rhizospheres) and caves (roof corresponds to former ferricrete duricrust).

Accordingly, some of the features, such as rhizoliths, columns, meniscate tubes, and *Krausichnus* considered by Pazos et al. (1998) as belonging to the Yapeyú paleosurface were more likely produced deep in the Asencio soils within the uppermost section of the underlying Mercedes Formation. The record of similar meniscate tubes and *Krausichnus* in the Asencio Formation (Genise et al., 1998) in contrast with their absence below the uppermost section of the Mercedes Formation attest also for such assumption.

6.2. The origin of columnar structures

The particular morphology of caves (i.e. a roof supported by many columns) in some of the northeastern Asencio Formation outcrops, have made them a renown item of the Uruguayan geology since the XIX century, when the Gruta del Palacio was described for the first time (Rivas, 1884; Benedetti, 1887; Isola, 1900). By that time, the first interpretations were subjective and at first glance. Rivas (1884), who recorded columns ranging from 50 cm to 60 cm in diameter, believed that they were palm stumps filled with ferruginous sandstone. Benedetti (1887) also claimed that they resembled tree stumps, whereas Isola (1900) believed that the cave was made by aborigines. Later, Walther (1931) and Caorsi and Goñi (1958) interpreted that the columns were the result of differential ferruginization of the deposits. Pazos et al. (1998) considered that the columns were concretions, but without any explanation for their genesis. Goso (1999), Goso and Guérèquiz (2001), who recorded and mapped about 200 columns for the Gruta del Palacio ranging in diameter from 76 cm to 100 cm, and Goso and Perea (2003) proposed that iron solutions coming from the upper level (ferruginized duricrust) deposited concentrically in fracture planes or intersections from the lower clayish horizon and that this kind of concentric mottles had a posterior vertical development forming the columns. The latter authors mentioned the concentric

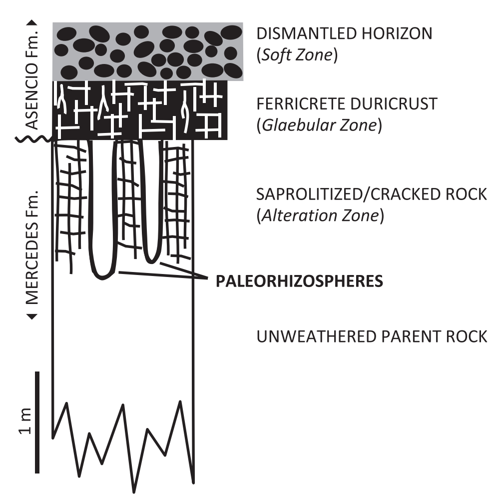

Fig. 7. Reconstructed lateritic profile developed at the boundary between Mercedes-Asencio formations, showing zones or domains defined by Tardy (1992) (between brackets) and the original location of the rhizospheres.

pattern for the columns of the Gruta del Palacio, which had been also noticed by Pazos et al. (1998), Goso (1999) and Goso and Guérèquiz (2001). However, they recognized only a central core surrounded by a more external ring (rimmed type), which is the only one that occurs at Gruta del Palacio, where most columns are of the nodular type.

The new information presented herein, which enables a more accurate interpretation, is based mostly on new localities discovered along Route 5. These localities show smaller columns with a well developed concentric pattern, radiating prolongations, specimens bearing a boxwork pattern resembling burrows (i.e. mottled pattern), and several distinctive micromorphological pedofeatures indicating the action of soil forming processes inside the columns. In addition, at the classical locality of Gruta del Palacio, remains of the original lamination of the deposit extending inside columns was the most important new character recorded for interpreting the origin of these structures. Large columnar structures that show the following combination of characters: (1) concentric internal structure (Fig. 5D) as that found in rhizoconcretions, (2) radiating secondary prolongations (Fig. 5C) as those originated in secondary roots, (3) preservation of the original lamination of the deposit extending inside them (Fig. 4A), and (4) trace fossils (Fig. 6D) as in the surrounding paleosol, are only compatible with megarhizoliths (sensu Alonso-Zarza et al., 2008) or palaeorhizospheres (sensu McLaren, 1995).

Other possible hypotheses for Asencio columns are more unlikely because they cannot explain either some of the characters described or their combination. For instance, trunk casts is a tempting explanation when looking at the external aspect of these columns (Rivas, 1884; Benedetti, 1887). Mossa and Schumacher (1993) described Quaternary vertical cylinders presenting comparable sizes, which were interpreted as infillings of voids left after large taproots died and decomposed. Similar vertical shafts hosted in sandstones were interpreted as casts of decayed large roots (Gregory et al., 2004) or palm stems (Hearty and Olson, 2011). These examples differ clearly from those observed in the Uruguayan columns in many characters and particularly in the presence of concentric internal patterns (Fig. 5D) and remains of the original lamination that extends inside the columns (Fig. 4A), proving that the latter are not the result of previous cylindrical empty voids filled with material from the overlying deposit. In addition, dispersion of diameters in the same locality (Fig. 3D) and internal bioturbation (Fig. 6D) also argue against this hypothesis. Some specimens showing a dense nodular internal structure may suggest passive filling with Asencio-type nodules. However, specimens showing different stages of mottle development, particulary those with few and/or small mottles (Fig. 6C), indicate that mostly nodules grew inside the rhizosphere instead of coming as fallen material from the overlying Asencio Formation. The proposal of columnar concretions with a concentric internal pattern arising from fractures (Goso, 1999; Goso and Guérèquiz, 2001; Goso and Perea, 2003) is unlikely and lacks appropriate explanation for concentric arrangement, vertical and cylindrical development, not to mention that fractures are not an observable pattern in the columns. Other proposals are less explained yet (Walther, 1931; Pazos et al., 1998).

Other probable origins to be considered for the columns are subsurface fluid escape pipes or chimneys, soil material fused by lightning strikes (fulgurites), and vertebrate caves. Cylindrical concretions formed by cold seep systems of hydrocarbon (e.g. methane) or other fluids, are discarded because their carbonate composition, central hollows or conduits and common association with marine deposits (Peckmann and Thiel, 2004; Campbell, 2006; De Boever et al., 2009; Pearson et al., 2010). On the other side, the regular morphology and internal structure of the studied columns, as well as the absence of glass or exotic minerals, is not compatible with fulgurites (Retallack, 2001). Finally, the possibility of passive or active fillings of burrows excavated by a large animal, probably a vertebrate, is very low. Firstly, the lateral continuity of sedimentary structures from matrix to columns discards the existence of hollows or large burrows, and secondly, the structure observed in the interior (concentric rings, outer rim) is also incompatible with a fill.

Roots, through the release of polysaccharides, organic acids, electrons and protons, packing of soil, evapotranspiration, and association with microorganisms, have the capacity to change the physicochemical conditions of the surrounding soil, producing cementation and precipitation of iron oxides or carbonate in the rhizosphere (Calvet et al., 1975; Klappa, 1980; Cramer and Hawkins, 1984; Robert and Tessier, 1992; Retallack, 2001; Violante et al., 2003). This precipitation, in some cases, produces concentric arrangements or external rims (Stieglitz and Van Horn, 1982; Fitzpatrick, 1993; McCarthy et al., 1998; Retallack, 2001; Kraus and Hasiotis, 2006). In addition these fossil rhizospheres may contain features of the original soil, as traces of other roots and organisms, and remains of lamination, among others (Alonso-Zarza et al., 2008). All of which are present in the columns studied herein.

Accordingly, the palaeorhizosphere hypothesis can explain the diverse types of internal structures found in the columns, which may be compatible with different stages of root and rhizosphere development. Within a wet rhizosphere, hydrolysis liberates drab ferrous iron from silicates (Fe^{2+}); while red, brown or yellow ferric (Fe^{3+}) oxides and oxyhydrates form when soil conditions became oxidizing (Retallack, 2001). Concentric arrangements and external cortexes of orange goethite and red hematite around nodules and roots are commonly recorded in Fe rich oxidized soils (Stieglitz and Van Horn, 1982; Nahon, 1991; Tardy, 1992; Fitzpatrick, 1993; McCarthy et al., 1998; Retallack, 2001; Kraus and Hasiotis, 2006; Chan et al., 2007; Parry, 2011). In red soils, transportation of water along channel roots may produce drab haloes by the reduction of Fe close to the root and an external, single, oxidized cortex (Pipujol and Buurman, 1997; Retallack, 2001; Kraus and Hasiotis, 2006). Many of the palaeorhizospheres described herein (the rimmed type), developed in a drab C horizon, show a single oxidized cortex, mostly of goethite. Different authors postulate that rims are formed at, or slightly beyond, the interface between rhizosphere and unaltered soil. Stieglitz and Van Horn (1982) postulated that a goethite ring precipitates in the equilibrium interface between the zone from which the root takes water from the soil and the zone of the soil (rhizosphere) affected by the biological activity and release of fluids from the root. Kraus and Hasiotis (2006) proposed that Fe ions are traslocated outward from the root channel and precipitated where conditions were more oxidizing to form a rim. A similar process involving iron mobilization and precipitation, changes in pH, and bacterial activity is recorded for iron concretions composed of an external rim of goethite including a central host-rock core (Parry, 2011). Experimentally, the rims can be formed when reduced water rich in Fe^{2+} come in close proximity with fresh water, rich in oxygen (Chan et al., 2007). In carbonates, Klappa (1980) noted that the outer diameter of the root tubule, where cementation took place, is just slightly beyond the rhizosphere. Rhizospheres are comparatively more humid than the surrounding soil (McLaren, 1995; Alonso-Zarza et al., 2008) and so, a moisture gradient occurs between the root and the soil. Accordingly, the single goethite and hematite cortexes that surround most structures may be interpreted as the boundary of the original rhizosphere, where Fe ions traslocated outward from the root by chelation (Nahon, 1991), found oxidizing conditions.

The concentric rings that show some of the palaeorhizospheres deserve a particular analysis. Banded cortexes of goethite may develop concentrically at the expense of nodules of hematite by degradation, or on the contrary may grow at the expense of surrounding matrix by aggradation (Nahon, 1991). Iron nodules in soils form as pore fillings and as a result of alternating oxidizing and reduction cycles due to seasonal variations in soil moisture, producing segregation and concentration of oxides. McCarthy et al. (1998) interpreted that sesquioxide nodules showing concentric rings formed by segregation of iron-manganese oxides due to wetting and drying over numerous redox cycles. More recently, Chan et al. (2007) proposed for iron concretions that concentric pattern is the result of a repeated migration of the reduction/oxidation front boundary. These authors demonstrated that

"onion-layered" iron concretions could be experimentally produced when the outer rim broke and some of the exterior iron-rich solution passed through precipitating in new rings of rozenite. Also, the inward growth of an outer non-broken rim could generate some concentric bands close to it (Chan et al., 2007). These authors concluded that inward growth of the external rim produced layered patterns because of diffusion (Chan et al., 2007).

However, there is no unequivocal explanation for concentric ferruginous rings around roots. Stieglitz and Van Horn (1982) believed that successive rings precipitated after the former one in zones of similar chemical conditions because of a combination of climate, ground water, and plant growth, but that they represent no annual or seasonal deposits. They compared these structures with concentric rings that form in saturated soils around root traces, which Fitzpatrick (1993) interpreted as multiple traces of smaller roots preferentially occupying a former root tubule. In carbonate rhizoliths, concentric bands are interpreted as reflecting alternant cycles of wet and acidic conditions (dissolving carbonate) with dry and alkaline (precipitating carbonate) ones (Retallack, 2001). Calvet et al. (1975) for decaying roots and Klappa (1980) for living ones, proposed centripetal processes, involving centripetal filling following root decay and death (Calvet et al., 1975) or involving rhizosphere decrease and precipitation of cements increasingly nearer the root surface because of the continuous decay of the root hairs as root grows (Klappa, 1980).

In contrast with inward growth of concentric layers, observed in iron concretions (Chan et al., 2007) and in rhizolith forming processes in carbonates (Calvet et al., 1975; Klappa, 1980), it is more likely that a centrifugal process is involved in the production of concentric palaeorhizospheres considering that largest ones lack concentric internal structure, which is more usual in the smaller. A centripetal growth would indicate that the cycle started with a full grown root than later decayed, when red microrhizoliths from the contact attest for oxidation processes also in small roots. Kraus and Hasiotis (2006) proposed that when gleying continues around roots the bleached zones enlarge and the red cortexes intensify, dissolving or modifying previous rings and depositing another outer red rim. Despite other process than gleying is involved, some examples presented herein (Fig. 5E) show internal rings partially broken, composing mostly as mottled concentric bands, and well defined outer rings, indicating that probably the oxidizing younger rim move outwards, whereas older rings are the inner ones already broken by later processes. The absence of a recognizable rhizolith or any original central nucleus inside the palaeorhizospheres may be the result, as in iron concretions, of later consumption by chemical reactions (Chan et al., 2007).

The other type of disrupted concentric and nodular internal structures would start when most biologic processes around the living or decaying root cease and periodic formation of rings stops. The dead rhizosphere bearing a larger amount of iron oxides, produced by the former root, undergoes the same processes that the overlying lateritic soils in the Asencio Formation (Bellosi et al., 2004), producing seasonal cycles of nodule growth and welding during dry periods, and dismantling and breakage during humid ones. This process would have produced in the rhizospheres the sharp breakage of previous rings in angular pieces resembling clasts shown by the concentric disrupted type. In addition, the dead root channel provides a conduit for percolating Fe-rich water and oxygen along the former rhizosphere, which will constitute a differential locus in the soil for more oxidation to take place in a kind of positive feedback. The filling and staining of root channels by soil solutions coming from the overlying bed (the Asencio Formation), which is a common process in rhizolith formation (Klappa, 1980; PiPujol and Buurman, 1997; McCarthy et al., 1998; Retallack, 2001; Kraus and Hasiotis, 2006), may be considered in some specimens showing massive red central cores or a complete and weathered nodular composition. Structures showing massive goethite internal structure crossed by gray tunnel-like mottles (Fig. 6D), could represent bioturbated rhizospheres in which invertebrate traces produce later iron depletion (bleaching) around them.

Another question still remains: where did the hematite of the columns come from? Does it come from the overlying Asencio Formation or it was produced from the oxidation of Fe original of the Mercedes Formation? The latter is a grayish formation, with no Fe oxides in thin sections and strikingly different in the field from the intense red overlying Asencio Formation. However, geochemical analysis proved that its Fe content is relatively high (7358 ppm), somewhat lower than that recorded in a reddish palaeorhizosphere (9817 ppm) and about half of that of the Asencio Formation (16,347 ppm). Thus, the hematite of the red columns within the whitish Mercedes Formation may have come from concentration and oxidation of the original Fe present in rhizospheres of roots that penetrated this unit, as well as by filling and staining of Fe solutions coming from the overlying Asencio Formation.

Differences in the biological activity of roots of different species of plants can explain also the presence of red rhizoliths of small size and large palaeorhizospheres in the same level. Stieglitz and Van Horn (1982) speculated about probable causes for the occurrence of the ferruginous rhizoliths, mentioning: variations in ground-water composition, differences in permeability or composition of enclosing material, changes in vegetation, and availability of iron. Among these causes, similar lithological characteristics of the Asencio and Mercedes Formations in all studied outcrops suggest that the presence of a particular group of plants, probably with a differential biological activity in their roots, produced the large palaeorhizospheres, in contrast with other plants producing small rhizoliths. Microorganisms, such as bacteria and fungi, are important agents in the formation of rhizoliths, which also aid in the mobilization of iron solutions (Robert and Tessier, 1992; Retallack, 2001; Violante et al., 2003). They are responsible in the formation of iron concretions in which no roots are present (Chan et al., 2007; Parry, 2011). Accordingly, it is proposed herein that some species of plants were associated with more microorganisms or a distinct kind of them, whose differential activity produced high rates of mobilization of iron oxides and larger rhizospheres. Records of large palaeorhizospheres restricted to a bow-shaped zone in a northeastern area of the basin would indicate the original distribution of such plants (Fig. 1).

6.3. Asencio or Mercedes palaeorhizospheres?

Relationships between Mercedes and Asencio Formations have been a matter of discussion since the beginnings of Uruguayan geology (Genise et al., 2004; Martínez and Veroslavsky, 2004 and references therein) and still they are. In this contribution, a number of attributes present in the Mercedes–Asencio contact are shown for the first time, which demonstrates that a regional weathering profile developed at the beginning of the Asencio time. Thus, the boundary between both units is considered an unconformity.

Large palaeorhizospheres occur at or near the contact of the Asencio and Mercedes formations, as in the case described by Stieglitz and Van Horn (1982), in which rhizoliths penetrate from an overlying oxidized horizon into an unoxidized underlying one. As discussed previously, the palaeorhizospheres and small rhizoliths described herein may be the result of iron oxidation and cementation of Mercedes parental material produced by living and decaying roots, with a possible later addition of oxides by percolating iron-rich waters and staining along channels of dead roots.

Still, were the original living roots from Mercedes or from Asencio times? The oxidation and mobilization of iron to produce laterites is typical of tropical or subtropical climates, with MAT of 30 °C and MAP of 1300–1700 mm, with a marked dry season (Nahon, 1991; Tardy, 1992; Tardy and Roquin, 1992). A recent review of modern and ancient lateritic profiles indicates that the great majority of them form by weathering in soils of intertropical regions (Retallack, 2010). This particular climate is known from the Late Paleocene

(LPTM) or Early Eocene (EECO) (Zachos et al., 2001), and accordingly the Asencio Formation, is considered of this age (Bellosi et al., 2004), when lateritization could have reached the latitude of Uruguay (Tardy and Roquin, 1992). More precisely it is considered of early Eocene age because of the abundance of dung beetle fossil brood balls, which depend on the presence of large herbivore excrements that are unlikely from the Paleocene (Genise et al., 2002). Tropical and subtropical humid climates produce a high biological activity, reflected in high diversity and large size of plants, more roots and organic matter in the soils, high metabolism of organisms, and high diversity of microorganisms including those associated with roots, all of which, along with high temperatures itself (Parry, 2011), favors iron oxidation and chelation finally resulting in laterites, exclusive of intertropical areas (Tardy, 1992). Laterites are preserved in the Asencio Formation (Bellosi et al., 2004), and so the possibility of palaeorhizospheres to be formed during Mercedes times, even when they are included in this formation, is unlikely. By the late Cretaceous, the age of the Mercedes Formation, laterites were restricted to northern South America (Tardy and Roquin, 1992). The hypothesis of iron oxides produced during Asencio time just staining previously formed rhizoliths and palaeorhizospheres during Mercedes times is also unlikely considering that rhizoliths from Mercedes times were originated from roots that were alive at least 10 m.y. before Asencio oxidation processes took place, and Mercedes rhizoliths would have been already consolidated by Asencio times. Probably, true Mercedes rhizoliths are those small, white and silicified, recorded from locality 4 (Fig. 4B).

The Asencio Formation can be correlated to the Early Paleogene worldwide phase of weathering under humid-warm conditions. This event conducted to the formation of ferralitic duricrusts and bauxitization recognized in Brazil, central Africa and India (Grandin and Thiry, 1983; Valenton, 1999; Rossetti, 2004). In contrast, development of these large palaeorhizospheres was a unique event, at the beginning of Asencio time. The absence of such traces in palaeosols (ferrugineous duricrusts) of the rest of the unit indicates that a type of vegetation or particular taphonomic or climatic conditions was never repeated again, despite of lateritization occurred several times. Deep penetration of roots inside Mercedes substrate reflected by palaeorhizosphere lengths indicate well-drained soils and probably a stage of relative drier conditions at the beginning Asencio time.

7. Conclusions

1. Columnar structures composing renown cave-shaped architectures of Uruguay are interpreted as palaeorhizospheres according to their concentric internal structure compatible with rhizoconcretions, radiating prolongations compatible with secondary roots, preservation of remains of the original lamination and trace fossils. They developed in a weathering profile dominated by lateritization processes, which involve the contact between the Mercedes Formation and the overlying Asencio Formation.
2. Five types of palaeorhizospheres were recognized. Rimmed and concentric ones were produced by living roots by mobilization and precipitation of iron triggered by chemical changes and biological activity in the rhizospheres, whereas concentric disrupted, nodular/mottled and brecciated were favored by percolation and staining by Fe solutions coming from the overlying Asencio Formation through conduits produced by decaying or dead roots.
3. Palaeorhizospheres formed in a subsurface horizon of a palaeosol at the beginning of Asencio time, when a ferricrete developed probably during a dry period, which triggered deep penetration of roots in the saprolitized substrate (i.e. the underlying Mercedes formation) seeking for water.
4. Palaeorhizospheres would be a more common feature of terrestrial palaeonvironments than previously recorded but in some cases they were misinterpreted as rhizoliths, trunk casts, or even epigean insect nests.

Acknowledgments

This paper is a contribution to grants FONCYT-PICT 07/1972 of the ANPCYT (Argentina) to Jorge F. Genise, and DINACYT FCE 2005/010 and ANII FCE 2007/44 from Uruguay to Mariano Verde. Authors thank Wilfredo Fernández and Jorge Frogoni from the Museo Municipal Lucas Roselli of Nueva Palmira (Uruguay), Laura Sarzetti and M. Victoria Sánchez of the Museo Argentino de Ciencias Naturales of Buenos Aires (Argentina) for the help with field work, and Mr. Maldonado and Mr. Espiga, who allowed the access to their quarries. Fernando Larriestra and Francisco Ferrer (Larriestra Geotecnologias) facilitated the use of a XRF analyzer and Daniel Poiré made the DRX analyses at the Centro de Investigaciones Geológicas de La Plata. Daniel Speranza composed the figures. Authors thank the editor, Brian Jones, and two anonymous reviewers for manuscript improvement.

References

Alonso-Zarza, A.M., Genise, J.F., Cabrera, M.C., Mangas, J., Martín-Pérez, A., Valdeolmillos, A., Dorado-Valiño, M., 2008. Megarhizoliths in Pleistocene aeolian deposits on Gran Canaria (Spain): ichnological and palaeoenvironmental significance. Palaeogeography, Palaeoclimatology, Palaeoecology 265, 39–61.

Alonso-Zarza, A.M., Genise, J.F., Verde, M., 2011. Sedimentology, diagenesis and ichnology of Cretaceous and Paleogene calcretes and palustrine carbonates in Uruguay. Sedimentary Geology 236, 45–61.

Barrel, J., 1913. The upper Devonian delta of the Appalachian geosynclines. Pt.1: the delta and its relations to the interior sea. American Journal of Science 36, 429–472.

Bates, R.L., 1938. Occurrence and origin of certain limonite concretions. Journal of Sedimentary Petrology 8, 91–99.

Bellosi, E.S., Genise, J.F., González, M., 2004. Origen y desmantelamiento de lateritas paleógenas del sudoeste del Uruguay (Formación Asencio). Revista del Museo Argentino de Ciencias Naturales 6, 25–40.

Benedetti, A., 1887. Apuntes de Geografía Militar. Tipografía de la Escuela Nacional de Artes y Oficios, Montevideo, pp. 1–107.

Bordy, E.M., Bumby, A.J., Catuneanu, O., Eriksson, P.G., 2004. Advanced early Jurassic termite (Insecta: Isoptera) nests: evidence from the Clarens Formation in the Tuli Basin, Southern Africa. Palaios 19, 68–78.

Bossi, J., 1966. Geología del Uruguay. Universidad de la República, Departamento de Publicaciones, Colección Ciencias, 2, pp. 1–164.

Bossi, J., Navarro, R., 1991. Geología del Uruguay. Universidad de la República, Departamento de Publicaciones, Montevideo, pp. 1–966.

Bossi, J., Ferrando, L., Montaña, J., Campal, N., Morales, H., Gancio, F., Schipilov, A., Piñeyro, D., Sprechmann, P., 1998. Carta geológica del Uruguay. Escala 1: 500.000. Geoeditores, Montevideo. 145 pp.

Bourman, R.P., Ollier, C.D., 2002. A critique of the Schellmann definition and classification of laterite. Catena 47, 117–131.

Bown, T.M., 1982. Ichnofossils and rizoliths of the nearshore fluvial Jebel Qatrani Formation (Oligocene), Fayum Province, Egypt. Palaeogeography, Palaeoclimatology, Palaeoecology 40, 255–309.

Bromley, R., Buatois, L., Genise, J.F., Labandeira, C., Mangano, G., Melchor, R., Schlirf, M., Uchman, A., 2007. Comments on the paper "Reconnaissance of Upper Jurassic Morrison Formation ichnofossils, Rocky Mountain Region, USA: paleoenvironmental, stratigraphic, and paleoclimatic significance of terrestrial and freshwater ichnocoenoses" by Stephen T. Hasiotis. Sedimentary Geology 200, 141–150.

Bullock, P., Fedoroff, N., Jongerius, A., Tursina, T., Babel, U., 1985. Handbook of Soil Thin Section Description. Waine Research Publications, Albrighton. 152 pp.

Calvet, F., Pomar, L., Esteban, M., 1975. Las rizocreciones del Pleistoceno de Mallorca. Instituto de Investigaciones Geológicas de la Universidad de Barcelona 30, 35–60.

Campbell, K.A., 2006. Hydrocarbon seep and hydrothermal vent paleoenvironments and paleontology: past developments and future research directions. Palaeogeography, Palaeoclimatology, Palaeoecology 232, 362–407.

Caorsi, J.H., Goñi, J.C., 1958. Geología Uruguaya. Boletín del Instituto de Geología del Uruguay 37, 1–73.

Chan, M.A., Ormö, J., Park, A.J., Stich, M., Souza-Egipsy, V., Komatsu, G., 2007. Models of iron oxide concretion formation: field, numerical and laboratory comparisons. Geofluids 7, 356–368.

Claxton, C.W., 1970. Cylindrical tapering structures in the alluvial sands of the Trent Valley. Mercian Geology 3, 265–267.

Cramer, M.D., Hawkins, H.J., 1984. Aphysiological mechanism for the formation of root casts. Palaeogeography, Palaeoclimatology, Palaeoecology 274, 125–133.

Dalla Salda, L., Bossi, J., Cingolani, C., 1988. The Río de la Plata cratonic region of Southwestern Gondwanaland. Episodes 11, 263–269.

De Boever, E., Birgel, D., Thiel, V., Muchez, P., Peckmann, J., Dimitrov, L., Swennen, R., 2009. The formation of giant tubular concretions triggered by anaerobic oxidation of methane as revealed by archaeal molecular fossils (Lower Eocene, Varna, Bulgaria). Palaeogeography, Palaeoclimatology, Palaeoecology 280, 23–36.

Fitzpatrick, E.A., 1993. Soil Microscopy and Micromorphology. Wiley, New York. 304 pp.

Ford, I., 1988. Asociación caolinita-montmorillonita en perfiles tipo de la Formación Asencio (Ks). Actas del 6to Panel de Geología del Litoral y 1ra Reunión de Geología del Uruguay. Salto, Uruguay, pp. 42–46.

Ford, I., Gancio, F., 1988. Asociación caolinita-montmorillonita en un paleosuelo del Terciario inferior del Uruguay (Fm. Asencio). Boletín de Investigaciones de la Facultad de Agronomía 12, 1–12.
Frenguelli, J., 1926. Sulle concrezioni calcaree intorno alle radici di vegetali viventi. Bolletino della Societá Geologica Italiana 45, 85–91.
Genise, J.F., Bown, T.M., 1996. *Uruguay* Roselli and *Rosellichnus* n. ichnogen. Two ichnogenera for clusters of fossil bee cells. Ichnos 4, 199–217.
Genise, J.F., Pazos, P.J., González, M.G., Tófalo, R.O., Verde, M., 1998. Hallazgo de termiteros y tubos meniscados en la Formación Asencio (Cretácico superior- Terciario inferior) R.O. del Uruguay. Resúmenes de la Tercera Reunión Argentina de Icnología y Primera Reunión de Icnología del Mercosur, Mar del Plata, pp. 12–13.
Genise, J.F., Laza, J.H., Fernández, W., Frogoni, J., 2002. Cámaras pupales fósiles de coleópteros: el icnogénero *Rebuffoichnus* Roselli. Revista del Museo Argentino de Ciencias Naturales 4, 159–165.
Genise, J.F., Bellosi, E.S., González, M.A., 2004. An approach to the description and interpretation of ichnofabrics in palaeosols. In: McIlroy, D. (Ed.), The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis: Special Publications of the Geological Society of London, 228, pp. 355–382.
Genise, J.F., Bellosi, E.S., Melchor, R.N., Cosarinsky, M.I., 2005. Comment — Advanced early Jurassic termite (Insecta: Isoptera) nests: evidence from the Clarens Formation in the Tuli Basin, Southern Africa (Bordy et al., 2004). Palaios 20, 303–305.
González, M.G., 1999. Los paleosuelos de la Formación Laguna Palacios (Cretácico Superior) de Patagonia y la Formación Asencio (Cretácico Superior-Terciario Inferior) de Uruguay. Boletim do 5º Simposio sobre o Cretáceo do Brasil, pp. 65–70.
Goso, C., 1999. Análise estratigráfica do Grupo Paysandú (Cretáceo) na Bacia do Litoral Uruguay. Tese de Doutoramento IGCE-UNESP, Río Claro, Brasil. 184 pp.
Goso, C., Guérèquiz, R., 2001. Hipótesis acerca del origen de las columnas en las Grutas del Palacio, Fm. Mercedes–Asencio (Ks), Depto de Flores (Uruguay). Actas del XI Congreso Latinoamericano de Geología y III Congreso Uruguayo de Geología, Montevideo. CDROM. Contribución 236, 1–13.
Goso, C., Perea, D., 2003. El Cretácico post-basáltico de la Cuenca Litoral del Río Uruguay: geología y paleontología. In: Veroslavsky, G., Ubilla, M., Martínez, S. (Eds.), Cuencas Sedimentarias de Uruguay: geología, paleontología y recursos minerales — Mesozoico. Facultad de Ciencias, Montevideo, pp. 141–169.
Grandin, G., Thiry, M., 1983. Les grandes surfaces continentals tertiaires des regions chaudes succession des types d'altération, Cahiers — ORSTOM. Serie Geologie 13, 3–18.
Gregory, M., Martin, A., Campbell, K., 2004. Compound trace fossils formed by plant and animal interactions: quaternary of northern New Zealand and Sapelo Island, Georgia (USA). Fossils and Strata 51, 88–105.
Hasiotis, S.T., 2004. Reconnaissance of Upper Jurassic Morrison Formation ichnofossils, Rocky Mountain Region, USA: paleoenvironmental, stratigraphic, and paleoclimatic significance of terrestrial and freshwater ichnocoenoses. Sedimentary Geology 167, 177–268.
Hearty, P.J., Olson, S.L., 2011. Preservation of trace fossils and molds of terrestrial biota by intense storms in mid–last interglacial (MIS 5c) dunes on Bermuda, with a model for development of hydrological conduits. Palaios 26, 394–405.
Isola, M., 1900. Gruta del Palacio. In: Araújo, O. (Ed.), Diccionario Geográfico del Uruguay. Imprenta Artística, Montevideo, pp. 545–548.
Kindle, E.M., 1923. Range and distribution of certain types of Canadian Pleistocene concretions. Bulletin of the Geological Society of America 34, 609–648.
Kindle, E.M., 1925. A note on rhizocretions. Journal of Geology 33, 744–746.
Klappa, C.F., 1980. Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance. Sedimentology 27, 613–629.
Kraus, M.J., Hasiotis, S.T., 2006. Significance of different modes of rhizolith preservation to interpreting paleoenvironmental and paleohydrologic settings: examples from paleogene paleosols, Bighorn Basin, Wyoming, U.S.A. Journal of Sedimentary Research 76, 633–646.
Lipar, M., 2009. Pinnacle syngenetic karst in Nambung National Park, Western Australia. Acta Carsologica 38, 41–50.
Little, D.A., Field, J.B., 2003. The rhyzosphere, biology, and the regolith. In: Roach, I.C. (Ed.), Advances in Regolith. CRC LEME, Canberra, Australia, pp. 271–274.
Lowry, D.C., 1973. Origin of the Pinnacles, Nambung, WA. ASF Newsletter 62, 7–8.
Martínez, S., Veroslavsky, G., 2004. Registros continentales no depositacionales del Terciario temprano. In: Veroslavsky, G., Ubilla, M., Martínez, S. (Eds.), Cuencas Sedimentarias de Uruguay: Geología, Paleontología y Recursos Minerales — Cenozoico. Facultad de Ciencias, Montevideo, pp. 63–82.
McCarthy, P., Martini, I., Leckie, D., 1998. Use of micromorphology for palaeoenvironmental interpretation of complex alluvial palaeosols: an example from the Mill Creek Formation (Albian), southwestern Alberta, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology 143, 87–110.
McFarlane, M.J., 1976. Laterite and Landscape. Academic Press, London. 151 pp.
McLaren, S.J., 1995. Early carbonate diagenetic fabrics in the rhizosphere of late Pleistocene aeolian sediments. Journal of the Geological Society 152, 173–181.
McNamara, K., 1995. Pinnacles. Western Australia Museum Press, Perth. 27 pp.
Millot, C., 1970. Geology of Clays. Chapman and Hall, London. 429 pp.
Mossa, J., Schumacher, B.A., 1993. Fossil tree casts in South Louisiana soils. Journal of Sedimentary Petrology 63, 707–713.
Nahon, D.B., 1991. Introduction to the Petrology of Soils and Chemical Weathering. John Wiley & Sons, New York. 313 pp.
Ollier, C., Pain, C., 1996. Regolith, Soils and Landforms. Wiley, Chichester. 326 pp.
Oyhantçabal, P., Siegesmund, S., Wemmer, K., 2010. The Río de la Plata Craton: a review of units, boundaries, ages and isotopic signature. International Journal of Earth Sciences 99, 1227–1246.
Parry, W.T., 2011. Composition, nucleation, and growth of iron oxide concretions. Sedimentary Geology 233, 53–68.
Pazos, P.J., Tófalo, O.R., González, M., 1998. La paleosuperficie Yapeyú: significado estratigráfico y paleoambiental en la evolución del Cretácico Superior del Uruguay. Actas del II Congreso Uruguayo de Geología, pp. 59–63.
Pearson, M.J., Grosjean, E., Nelson, C.S., Nyman, S.L., Logan, G.A., 2010. Tubular concretions in New Zealand petroliferous basins: lipid biomarker evidence for mineralization around proposed Miocene hydrocarbon seep conduits. Journal of Petroleum Geology 33, 205–220.
Peckmann, J., Thiel, V., 2004. Carbon cycling at ancient methane-seeps. Chemical Geology 205, 443–467.
Perea, D., Soto, M., Montenegro, F., Corona, A., 2009. Nuevo hallazgo de restos de titanosaurios (Dinosauria: Sauropoda) en la Formación Mercedes (Cretácico tardío), Uruguay. Ameghiniana 46, 42R.
PiPujol, M.D., Buurman, P., 1997. Dynamics of iron and calcium carbonate redistribution and palaeohydrology in middle Eocene alluvial paleosols of the southeast Ebro Basin margin (Catalonia, northeast Spain). Palaeogeography, Palaeoclimatology, Palaeoecology 134, 87–107.
Retallack, G.J., 2001. Soils of the Past (2nd Edition). Blackwell, Oxford. 404 pp.
Retallack, G.J., 2010. Lateritization and bauxitization events. Economic Geology 105, 655–667.
Rivas, S., 1884. Nociones sobre el Departamento de Soriano. Anales del Ateneo del Uruguay 6, 480–489.
Robert, M., Tessier, D., 1992. Incipient weathering: some new concepts on weathering, clay formation and organization. In: Martini, I.P., Chesworth, W. (Eds.), Developments in Earth Surface Processes, 2. Elsevier, Amsterdam, pp. 71–105.
Rossetti, D.F., 2004. Paleosurfaces from northeastern Amazonia as a key for reconstructing paleolandscapes and understanding weathering products. Sedimentary Geology 169, 151–174.
Roth, A.A., Hornbacher, D., Zoutewelle, T., 2006. Complex concretions in the Jurassic Morrison Formation. Geological Society of America 38, 7 Abstracts with Programs.
Salgado, L., Coria, R., Magalhaes Ribeiro, C.M., Garrido, A., Rogers, R., Simon, M.E., Arcucci, A.B., Curry Rogers, C., Carabajal, A.P., Apesteguía, S., Fernández, M., García, R.A., Talevi, M., 2007. Upper Cretaceous dinosaur nesting sites of Río Negro (Salitral Ojo de Agua and Salinas de Trapalcó-Salitral Santa Rosa), Northern Patagonia, Argentina. Cretaceous Research 28, 392–404.
Schau, M.K., Henderson, J.B., 1983. Archaean weathering at three localities on the Canadian Shield. Precambrian Research 20, 189–202.
Smith, L.L., 1948. Hollow ferruginous concretions in South Carolina. Journal of Geology 56, 218–225.
Stieglitz, R.D., Van Horn, R.G., 1982. Post-Pleistocene development of root-shaped ferruginous concretions. The Ohio Journal of Science 82, 14–18.
Tardy, Y., 1992. Diversity and terminology of lateritic Profiles. In: Martini, I.P., Chesworth, W. (Eds.), Developments in Earth Surface Processes, 2. Elsevier, Amsterdam, pp. 379–405.
Tardy, Y., Roquin, C., 1992. Geochemistry and evolution of lateritic landscapes. In: Martini, I.P., Chesworth, W. (Eds.), Weathering, Soils and Paleosols. : Developments in Earth Surface Processes, 2. Elsevier, Amsterdam, pp. 407–443.
Todd, J.E., 1903. Concretions and their geological effects. Bulletin of the Geological Society of America 14, 353–368.
Tófalo, O.R., Pazos, P.J., 2009. Paleoclimatic implications (Late Cretaceous–Paleogene) from micromorphology of calcretes, palustrine limestones and silcretes, southern Paraná Basin, Uruguay. Journal of South American Earth Sciences 29, 665–675.
Valenton, I., 1999. Saprolite–bauxite facies of ferralitic duricrusts on palaeosurfaces of former Pangaea. In: Thiry, M., Simon-Coincon, R. (Eds.), Palaeoweathering, Palaeosurfaces and Related Continental Deposits. : International Association of Sedimentologists, Special Publication, 27. Blackwell, Oxford, pp. 87–129.
Veroslavsky, G., Martínez, S., 1996. Registros no depositacionales del Paleoceno–Eoceno del Uruguay: nuevo enfoque para viejos problemas. Revista de la Universidade Guarulhos (Serie Geociencias) 1, 32–41.
Violante, A., Barberis, E., Pigna, M., Boero, V., 2003. Factors affecting the formation, nature, and properties of iron precipitation products at the soil–root interface. Journal of Plant Nutrition 26, 1889–1908.
Walther, K., 1931. Sedimentos gelíticos y clastogelíticos del Cretácico Superior y Terciario uruguayos. Boletín del Instituto Geológico del Uruguay 13, 1–94.
Wanas, H.A., Abu El-Hassan, M.M., 2006. Paleosols of the Upper Cretaceous–Lower Tertiary Maghra El-Bahari Formation in the northeastern portion of the Eastern Desert, Egypt: their recognition and geological significance. Sedimentary Geology 183, 243–259.
Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686–693.