

Paleogene laterites bearing the highest insect ichnodiversity in paleosols

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ABSTRACT

Research on laterites deals mostly with geomorphological and geochemical characterization of extant tropical systems, with few examples of sedimentologic and paleosol analyses of mid-latitude detrital records. Extra-tropical, Lower Eocene laterites from Uruguay include Fe-rich indurated horizons (duricrusts) that preserve paleosol features, and nodular beds. Discrete trace fossils are generally absent in laterites, despite that they are formed in tropical ecosystems with high biodiversity. Uruguayan laterites bear abundant, highly diverse, and superbly preserved insect trace fossils. Association, distribution, orientation, and abundance of trace fossils preserved in strongly developed paleosols (Ultisols), are key for reconstructing cyclic depositional and weathering processes governed by hydrology and tectonics. Each cycle lasted ~420 ka and included iterative stages of fluvial sedimentation in a pericratonic scenario, pedogenesis and insect nesting and pupation in a seasonal tropical savanna, duricrust formation by desiccation and interruption of insect activities, and duricrust disaggregation (nodular beds) when rainfall increased. The proposed cycle can be used as a heuristic tool in the study of laterites.

INTRODUCTION

Research on iron-rich laterites has mostly focused on geomorphology of weathering profiles and landscape evolution of modern tropical regions (central Africa, northern South America) (Tardy, 1992; Beauvais and Roquin, 1996). Sedimentological and paleopedological analyses of ancient records are few and were performed on mid-latitude detrital examples (Sombroek, 1971; Bestland et al., 1996; Schwarz, 1997). Apart from the studies on termite nests (Grassé, 1986), trace fossils of ancient laterites are largely unknown. In contrast, the mid-latitude Paleogene laterites from Uruguay (Asencio Formation) constitute a Lagerstätte for trace fossils in paleosols (Genise et al., 2004). They also constitute the most diverse spot worldwide for bee trace fossils (Roselli, 1987) and the most diverse example of the *Coprinisphaera* ichnofacies (Genise et al., 2000).

Even though this unit has a long history of research (Ford, 1988; Martínez and Veroslavsky, 2004; Morrás et al., 2010), many questions related to its complex array of facies and ichnofauna have remained confusing. These questions were cleared up in our research, including facies, paleosol, and trace fossil analysis in 17 profiles from 12 localities (study area 31°25'S, 58°00'W to 33°50'S, 55°25'W) (Fig. 1A). Each profile was thoroughly examined. Outcrop tasks included taxonomic identification, ichnospecies counting, and detailed recording and mapping of the orientation and distribution of traces, according to facies and paleosol changes. More than 1500 specimens are housed at the Faculty of Sciences, Universidad de la República (FCDPI; Montevideo, Uruguay), and the Lucas Roselli Museum (MPFLR; Nueva Palmira, Uruguay). This contribution proposes a comprehensive model for the Asencio laterites that integrates depositional, weathering, and bioturbation processes into a cycle controlled by climate and tectonics.

FACIES AND PALEOSOLS

The Asencio Formation is a 5–15-m-thick sequence of red quartz sandstones modified by pedogenesis and other biogeochemical processes

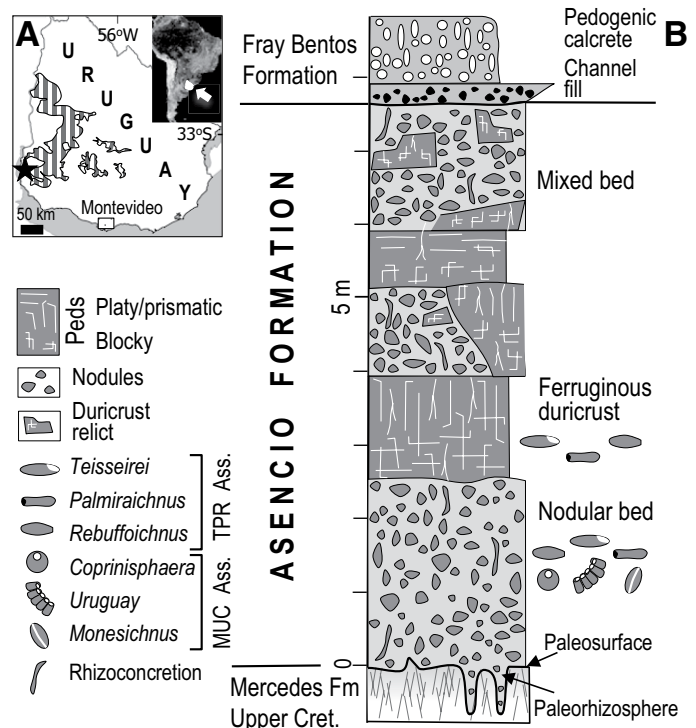


Figure 1. Asencio Formation. A: Outcrops in Uruguay (vertical lines). B: Profile near Nueva Palmira (star in A). Cret.—Cretaceous; TPR Ass.—*Teisseirei*, *Palmiraichnus*, *Rebuffoichnus* assemblage; MUC Ass.—*Monesichnus*, *Uruguay*, *Coprinisphaera* assemblage.

throughout (Bellosi et al., 2004). Exposures mostly consist of road gravel quarries on the boundary between the Paraná Basin and the Río de la Plata craton. The Asencio Formation overlies unconformably the Upper Cretaceous Mercedes Formation. The contact is a paleosurface showing numerous weathering features that gradually vanish downwards and abruptly disappear above (Genise et al., 2011). The top is erosive under Oligocene units. A Paleocene–Eocene age is inferred for the Asencio Formation according to stratigraphic relationships. Ichnologic and paleoclimatic considerations suggest a probable early Eocene age and a bond with the Early Eocene Climatic Optimum (Bellosi et al., 2004).

The Asencio Formation consists of ferruginized duricrusts and nodular and mixed beds, in similar proportions (Figs. 1B and 2A–2E). Contacts between all facies are mostly transitional (Fig. 2D). Mean thicknesses of the three facies are also alike (1.47 m). Finer and reworked deposits are absent. Duricrusts are formed by red indurated sandstones with abundant hematite cement. The fine fraction is composed of kaolinite, smectite, and some interstratified clay minerals (Ford, 1988; Bellosi et al., 2004). Sedimentary structures are mostly absent. Poorly defined trough cross-bedding and horizontal lamination were rarely observed. Ferruginized duricrusts preserve several pedogenic features (Figs. 2B–2D). The more prominent are thick argillic horizons showing distinct ped structure and micromorphology. Paleosols present a surface A horizon, 0.4 m thick, consisting of dark-red (5R2/6) clayey sandstone with platy or blocky peds and com-

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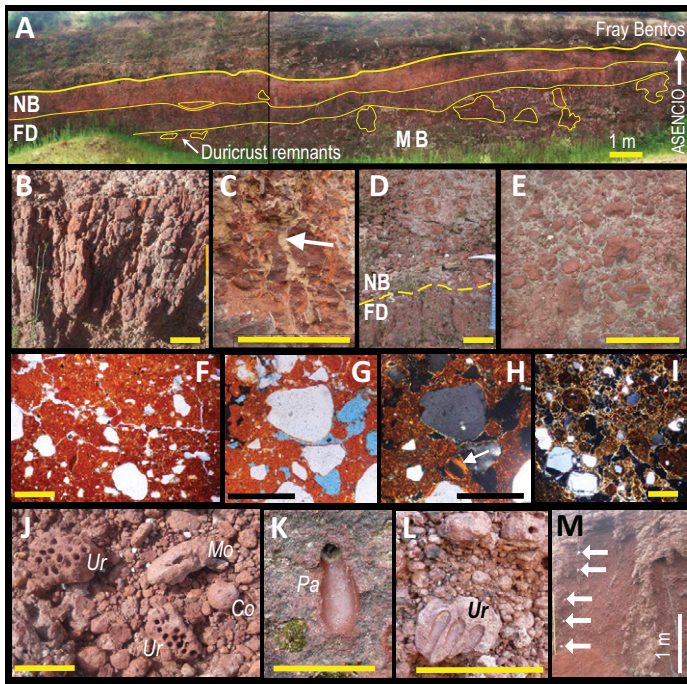


Figure 2. A: Asencio Formation and facies distribution. FD—ferruginized duricrust; NB—nodular bed; MB—mixed bed. B–E: Facies and paleosol features; bars are 20 cm. B: Bt horizon in FD showing prismatic and blocky peds. C: Thick clay cutan (arrow) in Bt horizon. D: Transitional contact between FD and NB. E: Close-up of NB showing abundant clay matrix. F–I: Microphotographs; bars are 500 μ m. F: Blocky microstructure with interconnected planar porosity. G: Granular microstructure formed by granules, spongy microstructure and corroded quartz grain (center). H: Similar to G (crossed nicols), showing clay cutan (arrow) and circular b-fabric. I: Pore filled by microgranules coated by illuviated clay (crossed nicols). J–L: Trace fossils; bars are 10 cm. J: Trace fossils in NB (*Uruguay* [Ur], *Monesichnus* [Mo], *Coprinisphaera* [Co]). K: *Palmiraichnus* [Pa] in FD. L: Rotated *Uruguay* in NB. M: *Uruguay* at different depths (arrows) in NB.

mon rhizoliths; and a subsurface Bt horizon, 1.1 m thick, composed of a more clayey, dusky red (5R3/4) sandstone with larger rhizoliths and thick blocky peds. These peds are polyhedral-subangular with shiny faces and demarcated by cutans of light-brown loose clay. Prismatic aggregates occur locally inclined (Fig. 2B). Following Bullock et al.'s (1985) nomenclature, microstructure of both horizons is granular and subordinately spongy and blocky (Figs. 2F–2H). Microgranular aggregates (50–200 μ m) consist of authigenic clay and sesquioxides (Figs. 2G–2I). Spongy structure includes chambers, channels, and planes (Fig. 2G). Coarse/fine distribution is porphyric (Fig. 2F), and partially enaulic gefuric (Fig. 2G). The b-fabric is continuous circular-striated and grain- to pore-striated (Figs. 2H and 2I). The coarse fraction is formed by etched quartz and scarce lithic and feldspar grains. Voids, grains, and microgranules are generally coated by ferriargillans (Figs. 2H and 2I).

Nodular beds are non-erosive, disorganized, and poorly consolidated deposits with a light-orange or gray argillaceous matrix (Figs. 2A, 2D, and 2E). Nodules are similar to duricrusts and do not exhibit orientation or sorting. They are hematitic and angular-subrounded. Matrix percentage and nodule roundness decrease with size. Root traces are preserved as rhizoconcretions. Mixed beds include remnants of duricrusts surrounded by nodular beds (Fig. 2A).

TRACE FOSSIL ASSEMBLAGES

The Asencio ichnofauna includes 14 ichnogenera and 19 ichnospecies (Table 1). Preservation is superb, including spiral caps in bee cells and scratches in the wall of moth and beetle pupation chambers. Diversity and abundance are also outstanding. This ichnofauna shows three remarkable characteristics:

(1) Abundance and distribution of trace fossils in duricrusts versus nodular beds are dissimilar. Duricrusts show lower abundance. Diversity is restricted to *Teisseirei barattinia*, *Palmiraichnus castellanosi* (Fig. 2K), *Rebuffoichnus casamiquelai* (TPR assemblage), and uncommon *Krausichnus* isp., *Taenidium barretti*, and *Cellicalichnus* isp. Other ichnotaxa are scarce or absent. Nodular beds show the highest abundance and diversity (Fig. 2J) including TPR assemblage and abundant *Monesichnus ameghinoi*, *Uruguay* isp., *Coprinisphaera* isp. (MUC assemblage), and scarce

TABLE 1. PRODUCER, INTERPRETATION, AND FACIES OF ASENCIO FORMATION ICHNOSPECIES

Ichnospecies	Ichnofamily	Producer	Type of trace	Facies
<i>Coprinisphaera murguiai</i>	Coprinisphaeridae	Dung beetles	Brood ball	NB
<i>Coprinisphaera kraglievichi</i>	Coprinisphaeridae	Dung beetles	Brood ball	NB
<i>Coprinisphaera</i> isp.	Coprinisphaeridae	Dung beetles	Brood ball	NB
<i>Monesichnus ameghinoi</i>	Coprinisphaeridae	Cicadas	Feeding chamber	NB
<i>Rebuffoichnus casamiquelai</i>	Coprinisphaeridae	Beetles	Pupation chamber	NB/D
<i>Teisseirei barattinia</i>	Coprinisphaeridae	Moths	Pupation chamber	NB/D
<i>Krausichnus</i> isp.	Krausichnidae	Ants	Nest	D
<i>Palmiraichnus castellanosi</i>	Celliformidae	Bees	Cell	NB/D
<i>Corimbatichnus fernandezii</i>	Celliformidae	Bees	Cluster of cells	NB
<i>Uruguay auronormae</i>	Celliformidae	Bees	Cluster of cells	NB
<i>Uruguay rivasi</i>	Celliformidae	Bees	Cluster of cells	NB
<i>Uruguay</i> isp.	Celliformidae	Bees	Cluster of cells	NB
<i>Elipsoideichnus meyeri</i>	Celliformidae	Bees	Nest	NB
<i>Cellicalichnus</i> isp.	Celliformidae	Bees	Nest	NB/D
<i>Taenidium barretti</i>	Indeterminate	Earthworms	Burrow	D
<i>Guerraichnus poligibbus</i>	Indeterminate	Indeterminate	Burrow	Indeterminate
<i>Tombownichnus plenus</i>	Indeterminate	Wasps?	Trace in trace	NB/D
<i>Tombownichnus parabolicus</i>	Indeterminate	Wasps?	Trace in trace	NB/D
<i>Lazaichnus fistulosus</i>	Indeterminate	Earthworms	Trace in trace	NB

Note: NB—nodular bed; D—duricrust.

Corimbaticnus fernandesi and *Elipsoideichnus meyeri*. *Guerraichnus poligibbus* probably came also from nodular beds. Traces in traces are related to *Palmiraichnus*, *Uruguay*, *Coprinisphaera*, and *Monesichnus*.

(2) The same ichnotaxon occurs at different levels along the profiles (Fig. 2M). In a complete section, specimens of *Uruguay* span 6 m from the lowest in a nodular bed to the uppermost one in a duricrust. In the same section, *Uruguay* specimens are separated vertically from each other by 25–45 cm, and *Teisseirei* by 28–32 cm. Nodular beds from another quarry exhibit specimens of *Uruguay* 110 cm apart. Several specimens of *Teisseirei* in stacked duricrusts and nodular beds are separated by 48–68 cm.

(3) Specimens of TPR assemblage in duricrusts are always oriented horizontally, with emergence holes located at one side. Contact between their walls and matrix is mostly undistinguishable. In nodular beds, TPR ichnofossils, *Coprinisphaera*, and *Uruguay* show emergence holes oriented in different directions including downwards (Fig. 2L). The walls are discrete and the trace fossils, which preserve their external shape, are as distinguishable as nodules.

SEDIMENTATION AND TROPICAL WEATHERING

The scarce primary features point to a fluvial setting characterized by tectonic quiescence that promoted landscape stability and lengthy weathering of deposits. Absence of finer lithologies suggests that floodplains were sandy or their deposits cannibalized. The latter option is discarded because of the lack of reworked materials, particularly in nodular beds where the absence of structures argues against any possibility of transport. Burial diagenesis probably produced limited dehydration of ferric hydroxides and reddening, although observed deep weathering is compatible with modern tropical red soils. Thick argillic horizons, high pedality, scarcity of unstable minerals, kaolinite, and a high proportion of illuviated and recrystallized clay in Asencio paleosols are properties of well-drained, highly weathered, oxidized, and strongly developed Ultisols. Granular microstructure is similar to that described by Stoops (2003) and assigned to termites or ants; however, beyond the scarce *Krausichnus*, there is no ichnological evidence of the massive presence of those groups. Overthickened (cumulic) Bt horizons resulted from slow overbank accumulation during pedogenesis. A subsequent stage in laterite metabolism is duricrust disintegration or dismantling by rehydration and biological agents (Tardy, 1992), represented by Asencio nodular beds. Chemical degradation occurs in patches involving iron dissolution, cement goethitization, and increase in clay (Bitom et al., 2003). Biophysical factors include rupture by roots and burrowing by invertebrates (Beauvais, 2009). Breakage of duricrusts initiated according to ped geometry and progressed through the opening of cavities, detachment of peds and traces, increase of clay matrix, and nodule reduction. Geometry, lack of tractive structures, nodule fabrics, and transitional contacts of nodular beds support its in-situ origin. Dismantling produced nodular beds below, above, and adjacent to ferricretes, as observed in African laterites (Temgoua et al., 2002).

ICHOLOGIC INFERENCES

To understand the origin of Asencio laterites, it is critical to analyze the three ichnologic characteristics. Orientation of breeding structures (cells, brood balls) is constant for most bees and dung beetles (Halffter and Edmonds, 1982; Michener, 2007). The orientation of traces and emergence holes in different directions, including downwards, in *Uruguay*, *Palmiraichnus*, *Coprinisphaera*, and *Teisseirei* only in nodular beds implies that nests were rotated. In absence of evidence of transport, dismantling must have been responsible for this rotation. Dissimilar abundance and diversity of trace fossils in duricrusts versus nodular beds argues against a simple dismantling. Genise et al. (2004) proposed that MUC producers emplaced their traces in a shallower tier than TPR producers to explain these differences. According to this hypothesis, dismantling took place from the surface downwards resulting in upper nodular beds dominated by the MUC assemblage. New data on the emplacement of the same

trace at different levels contradict this hypothesis. How is it possible that *Uruguay*, a component of the upper tier, was recorded at different levels? Traces of the same species are always located at a precise depth range where temperature and humidity matches the requirements of larvae and their food (Genise et al., 2004). *Teisseirei* is also an indicator of surface horizons (Genise et al., 2013) rather than a component of deeper tiers. The explanation is that paleosols are cumulic and the emplacement of traces at different levels reflects continuous growth of upper horizons.

THE ASENCIO CYCLE

Facies and ichnoassemblages are arranged into cycles. Each cycle includes sedimentation, pedogenesis, ferricretization, and dismantling, according to changes in accommodation space and precipitation (Fig. 3). At least three cycles have been identified. Short tectonic pulses trigger fluvial sedimentation (Fig. 3A). This deposit is pedogenized and TPR producers shallowly locate their traces (Fig. 3B). Pedological proxies point to a warm, seasonal humid climate. A mean annual precipitation (MAP) of 1300–1100 mm is calculated using the climofunction of Sheldon et al. (2002), which agrees with minimal values of modern Ultisols: MAP >1186 mm, mean annual temperature (MAT) >10.8 °C (Retallack, 2008). Ultisols and ichnofossils suggest that the Asencio ecosystem was comparable to a tropical savanna. Pedogenesis simultaneous to sedimentation produces cumulic horizons (Figs. 3C–3E). TPR producers keep emplacing traces in new surface layers. When soil becomes thick enough, MUC producers place traces in a deeper tier (Figs. 3C and 3D), where they coexist with the old TPR located originally more shallowly. While precipitation

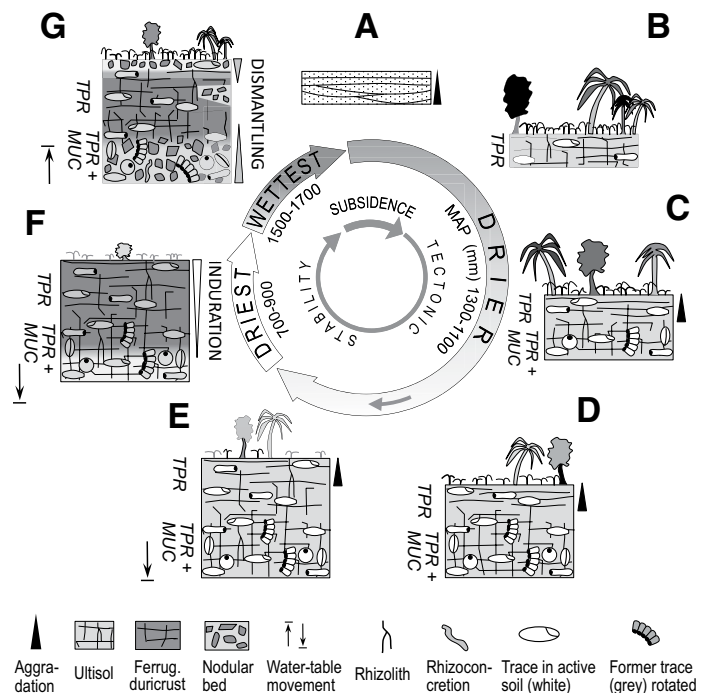


Figure 3. Asencio cycle. Climate and tectonic changes represented in central circles. Precipitation decreases from A to F (MAP—mean annual precipitation). A: Initial fluvial deposition triggered by tectonic pulse. B: Soil formation and colonization by insects (TPR: *Teisseirei*, *Palmiraichnus*, *Rebuffoichnus* assemblage). C: Development of cumulic horizons. Tiering of traces: shallow TPR assemblage, deep MUC (*Monesichnus*, *Uruguay*, *Coprinisphaera*) assemblage. D: Increased soil thickness and new emplacement of TPR and MUC assemblages. E: Precipitation decrease, water-table fall, and increased soil thickness, but only new TPR producers are emplaced. F: Desiccation and duricrust formation; no new traces (gray). G: Precipitation increase, water-table rise, duricrust dismantling, and origin of nodular beds; some traces are rotated. Ferrug.—Ferruginized.

drops and sediments are added (Fig. 3E), TPR producers remain active, locating new traces. In contrast, MUC producers stop their activities due to drier conditions and soil hardness. Reduced precipitation and vegetation probably impact the number of herbivores and available dung for beetles, flowers for bees, and suitable roots for cicadas. Components of the TPR assemblage are common in the *Celliforma* ichnofacies, which indicates drier conditions and lesser plant coverage than in the *Coprinisphaera* ichnofacies (Genise et al., 2010). Moths excavate pupation chambers using their own larval excretion to moisten soil (Genise et al., 2013), which is useful in dry soils. Duricrusts arise in the driest stage (Fig. 3F). Tardy (1992) estimated a MAP <900 mm and a fourth-month dry season for similar smectitic ferricretes. Duricrust precludes further activities of insects. Deeper layers with the MUC assemblage, the saturated zone, and humid topographic depressions support moderate desiccation but not enough for duricrust formation. This explains the absence of the MUC assemblage in duricrusts. Dismantling of duricrusts and less hardened parts of soils (Fig. 3G) is triggered by increasing precipitation (MAP of 1500–1700 mm) as occurs in central Africa (Beauvais, 2009). Soil properties, topography, and the water table control lateral extension and depth of induration and dismantling. Thus, facies become irregular and contacts transitional. Progressive dismantling produces mixed beds with duricrust remnants. Insect traces are rotated during dismantling. Dismantling length is short as indicated by the absence of new pedogenic evidence in nodular beds. Hardened patches of soil with the MUC assemblage, which never reached the stage of duricrust, become a component of nodular beds. Abundant nodules in soil also preclude nesting and pupating, which is resumed after new sand deposition. Aggradation records the beginning of a new Asencio cycle and landscape rejuvenation provoked by tectonic instability.

According to Bt horizon thickness, the age of Asencio paleosols ranges from 100 ka to 1050 ka (average of 372 ka). African and South American ferricretes are presently supporting dismantling after Holocene expansion of rainforests (Tardy, 1992). Tropical weathering rates are highly variable depending on climate and parent material (Eze et al., 2014); estimates vary from 0.13 to 40 m/m.y. Taking a mean rate of 6.9 m/m.y., no time involved in facies boundaries, and a complete profile of 2.9 m, each cycle records ~420 ka, a value similar to the major Earth orbital eccentricity period. The three Asencio cycles would represent 1.2 m.y.

In conclusion, Asencio laterites exhibit several striking features. They bear abundant and superbly preserved trace fossils, representing the most diverse insect fauna of paleosols. Ichnologic characteristics were key to reconstruct depositional, biological and weathering processes, in turn controlled by cyclic changes in tectonics and hydrology. The Uruguayan laterites developed by the Early Eocene when a tropical-seasonal climate prevailed in South America mid-latitudes.

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