WEATHERING PROCESSES AT THE BOUNDARY BETWEEN THE MERCEDES (CRETACEOUS) AND ASENCIO (EOCENE) FORMATIONS, SOUTHWESTERN URUGUAY

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ABSTRACT – The boundary between the Mercedes (Late Cretaceous) and Asencio (Eocene) formations has been a subject of controversy in the past. The morphological evidence about the contact between both formations obtained in this paper indicate that the geochemical weathering processes that took place during the early Eocene forming the paleosols found in the Asencio Fm. would have penetrated deeply in the light coloured sandstones of the top of the Mercedes Fm. This is shown by a transitional level composed of a marked irregular boundary, where ferruginous materials co-exist with relicts of the greyish sandstone, as well as with pouches of ferrugination within the body of the Mercedes Fm., several meters below that boundary. Likewise, the obtained evidence shows also that the nodular strata present at the base of the Asencio Fm. are the result of the weathering of the greyish sandstones of the Mercedes Fm., due to their fragmentation and ferrugination. As a consequence, it is herein proposed that the columnar structures of the so-called Gruta del Palacio and other similar sites correspond to that transition level at the top of the Mercedes Fm.; the nuclei of the columns would be composed of the ferruginous tongues whereas the hollows would be the result of the selective water erosion of the sandstone. On the base of the field evidence, the stratigraphical nomenclature of the cited levels is discussed.
Keywords: Cretaceous-Paleogene boundary, weathering, ferrugination, columnar structures, Uruguay.

RESUMEN – *H. Morrás, O.R. Tófalo, L.Sánchez-Bettucci - Procesos de erosión en la frontera entre las formaciones Mercedes (Cretácico) y Asencio (Eoceno), suroeste del Uruguay.* El límite entre la Formación Mercedes (Cretácico superior) y la Formación Asencio (Eoceno) es objeto de controversia. Las evidencias morfológicas del contacto entre ambas formaciones obtenidas en este trabajo indican que los procesos de meteorización geoquímica que tuvieron lugar durante el Eoceno temprano generando los paleosuelos de la Formación Asencio, habrían penetrado profundamente también en las areniscas claras del techo de la Formación Mercedes; esto se evidencia por un nivel transicional constituido por un límite marcadamente irregular donde coexisten materiales ferruginizados con relictos de la arenisca grisácea, así como por ¨bolsones¨ de ferruginación en el cuerpo de la Formación Mercedes varios metros por debajo de ese límite. Por otro lado las evidencias obtenidas también demuestran que los estratos nodulares presentes en la base de la Formación Asencio son el resultado de la meteorización de las areniscas grisáceas de la Formación Mercedes, a través de un proceso de fragmentación y ferruginación de las mismas. Como consecuencia se propone que las estructuras columnares de la denominada Gruta del Palacio y de otros sitios similares, corresponden a ese nivel de transición en el tope de la Formación Mercedes; el núcleo de las columnas estaría constituido por las lenguas ferruginosas en tanto los huecos serían el resultado de la erosión hídrica selectiva de la arenisca. Sobre la base de las evidencias de campo se discute la nomenclatura estratigráfica en los niveles considerados.
Palabras clave: límite Cretácico-Paléogeno, meteorización, ferruginación, estructuras columnares, Uruguay.

INTRODUCTION

According to Bossi (1966), the late Cretaceous sedimentary record of the Paraná Basin, in southwestern Uruguay, is composed of the Guichón, Mercedes and Asencio formations, which Bossi &

Navarro (1988) proposed to name as the Paysandú Group. The Mercedes Fm., assigned to the late Cretaceous, is composed of fluvial sedimentary rocks which were later calcretized and silcretized. This unit is bearing dinosaur egg nests. The Asencio Fm., attributed to the early Eocene, is rich in fossil insect ichnites and it is composed at the base of fluvial sedimentary rocks deposited by low hierarchy stream channels (Pazos et al., 1998), which underwent weathering processes and pedogenesis under wet-warm climate, forming Ultisol type soils as well as ferricrete levels. Bellosi et al. (2004) studied in detail the pedogenetic features of the reddish levels of the Asencio Fm., suggesting an interpretation about the genesis of the ferrugineous duricrusts and the nodular strata that are forming them.

The boundary between the Mercedes and Asencio formations has been the subject of frequent controversies and several papers have suggested different interpretations in particular with respect to the age and the number and names of the subunits forming the Asencio Fm. Besides, an original feature which appears in these deposits in the contact between the greyish sandstones characteristic of the Mercedes Fm. and the typical iron stained levels of the Asencio Fm. are the columnar structures and hollows or caves developed in between them, whose genesis has not had a conclusive explanation until today.

Undoubtedly, the different stratigraphical interpretations about these deposits are conditioned by the deep diagenetic and pedogenetic modifications that they have suffered, including the series of various sedimentation-pedogenesis episodes along the early Eocene. Recently, in a synthesis work about the climatic changes exposed by the sedimentary rocks of SW Uruguay, Tófalo & Morrás (2009) assumed the interpretation of Bellosi et al. (2004) on the genesis of the Asencio Fm. facies, including the consideration of the sedimentary discontinuity between the Mercedes and Asencio formations as proposed by Pazos et al. (1998) and clearly illustrated by Tófalo & Pazos (2010). However, in this paper several morphological features are described, recently found at the boundary between the greyish sandstones and the iron stained sandstones, which allow new interpretations of the stratigraphical sequence, of the weathering processes and of the genesis of the caves and columnar structures cited.

STRATIGRAPHICAL FRAMEWORK AND PREVIOUS WORKS

THE MERCEDES FORMATION

The Mercedes Fm. was defined by Serra (1945) taking as type section the perforation made in the city of Mercedes, in which the unit presented a maximum thickness of 71 m. The formation outcrops in western Uruguay and particularly, in the Río Negro Department, extending also to the SW of the Tacuarembó Department, the Soriano Department and western Durazno Department (Bossi et al., 1975; Figure 1).

This unit has been attributed to the late Cretaceous and it is composed of a fluvial succession of lens-like conglomerates and sandy beds, in which upper portion calcretes, palustrine limestones and silcretes are developed (Tófalo & Pazos, 2010). The thickness of the limestones rarely exceeds 15 m and both their origin, as well as their stratigraphical position have been a matter of discrepancies. Goso Aguilar & Perea (2004) proposed the name of Queguay Fm., placing them in the early Tertiary. Recently, Tófalo et al. (2001, 2006), Tófalo & Morrás (2009), and Tófalo & Pazos (2010) considered them as of Paleocene age, differentiating the calcretes of phreatic origin which form most of the limestones of this formation, from the palustrine limestones of a lesser extension; the transitional boundary between both facies would indicate a progressive ascent of the phreatic layer.

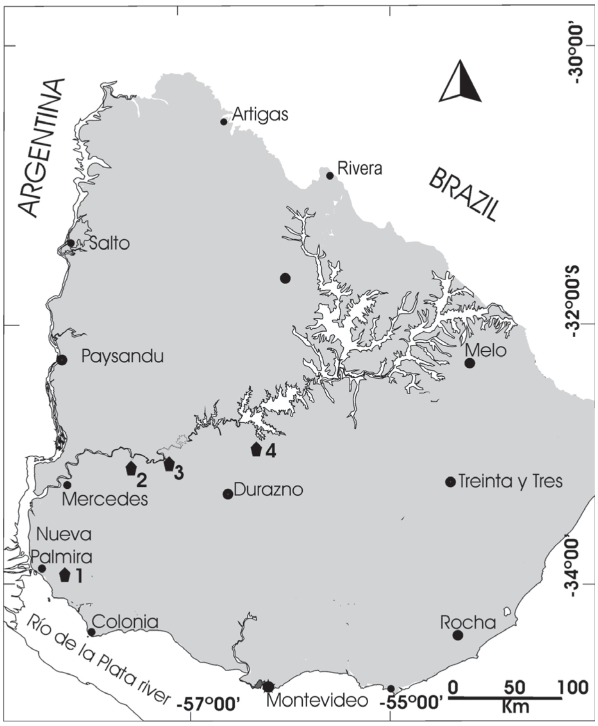


FIGURE 1. Approximate location of the described sites in southwestern Uruguay.

The Asencio Formation

The “sandtones with dinosaurs” (as they were called by Serra, 1945) were given the name of Asencio Fm. by Caorsi & Goñi (1958). This formation is restricted to SW Uruguay, having been correlated with the Puerto Unzué Fm. of NW Entre Ríos province (Argentina) by Gentile & Rimoldi (1979) and Genise & Zelich (2001). This unit was initially considered of a late Cretaceous age by Bossi et al. (1975); later on, Veroslavsky & Martínez (1996) and Goso & Guérèquiz (2001) proposed that the sediments of this formation were accumulated in the late Cretaceous, but were lateritized during the late Paleocene-Eocene; more recently, Genise et al. (2002) and Bellosi et al. (2004) suggested that the unit dates from the early Eocene. The maximum thickness does not exceed 30 m, according to observations in the arroyo Vera basin (Morales, cited by Bossi et al., 1975), whereas Bellosi et al. (2004) estimated that the maximum thickness is smaller than 15 m in other localities.

This unit is lying on the cretacic Mercedes Fm. and is covered unconformably by the loess-like silts of the Fray Bentos Fm., Oligocene-early Miocene. According to Bossi (1966) and Bossi et al. (1975), the lower contact with the Mercedes Fm. is conformable and transitional (Paso Vera, route 14) though for other authors (Veroslavsky & Martínez, 1996; Bellosi et al., 2004) the contact is not well defined. Bossi (1966) and Bossi et al. (1975) divided the Asencio Fm. in the Yapeyú (lower) and del Palacio (upper) members (Table 1). The first one is composed of pinkish to whitish fine sandstones, with feldspar rounded grains and either illitic clayey or calcareous cement (Bossi et al., 1975; Bossi & Navarro, 1988) and it has dinosaur egg nests. The del Palacio member, very rich in insect fossil tracks, is composed of the same sandstones that were affected by important and generalized ferrification processes and occasional silicification phenomena (Bossi & Navarro, 1988), which transformed the typical sandstone of the unit in a deep reddish, hard rock (Bossi et al., 1975). The boundary between both members is appreciated by the colourful variation, from brownish to intense red tones (Pazos et al., 1998).

Preciosi et al. (1985) divided the Asencio Fm. in three members: the basal one, Yapeyú, composed of yellowish sandstones, the middle del Palacio formed by reddish, ferrified sandstones, and the upper one, Algorta, integrated by calcarenites and whitish carbonate layers (Table 1). Besides, Ford (1988a) and Ford & Gancio (undated) proposed a type section for this unit which is composed, from the base to the top, of: a) yellowish whitish, quartzitic, fine to medium sands; b) similar composition and texture sandstones, but with reddish mottled; c) the same sandstones, now strongly impregnated with reddish iron oxides and hydroxides. The authors indicated that the reddish levels of this sedimentary body, which they called “ferrification

TABLE 1. A comparative scheme of various stratigraphic propositions referred to the late Cretaceous-Paleogene interval in SW Uruguay.

Bossi (1966)	Preciozzi et al. (1985)	Ford (1988)	Pazos et al. (1998)	Goso & Perea (2004)
	Algorta Mb (calcarenites)	Palmitas Fm (fluvial conglomerates)		
del Palacio Mb (ferrified sandstones)		------Paleosurface-------	Asencio Fm	del Palacio Mb (Geosol)
	del Palacio Mb (ferrified sandstones)	Asencio Fm (ferrallitic crusts)		
Asencio Fm Yapeyú Mb (pinkish whitish sandstones)	Asencio Fm Yapeyú Mb (yellowish sandstones)		---Yapeyú paleosurface--	Mercedes Fm Yapeyú Mb
			Mercedes Fm	
Mercedes Fm	Mercedes Fm	Mercedes Fm		del Chileno Mb

crusts", represented the basal levels of ferruginous-ferrallitic paleosols. The boundary with the underlying Mercedes Formation would be a silicified level of regional distribution (Ford and Gancio, undated).

On the other side, Ford (1988c) and Ford & Gancio (undated) proposed to restrict the name of Asencio Fm. to the Yapeyú member, as named by Bossi, and provisionally defined the Palmitas Fm., a new stratigraphic unit of intense reddish colour, composed of conglomerates of supposed fluvial origin developed from the erosion of ferrallitic soils that contain fossil insect nests and tentatively assigned it to the early Cenozoic (Table 1).

Contrarily, Pazos et al. (1998) limited the name of Asencio Fm. to the del Palacio member, because they found a regional unconformity which they named as the Yapeyú paleosurface, which separates the Yapeyú and Asencio members as named by Bossi. In descriptive terms, the authors named as Yapeyú and Palacio sections the levels located below and above the Yapeyú paleosurface. At the level of the Yapeyú section and below the paleosurface of that name, in the locality of Pedro Chico, these authors described biological features such as pedotubules as well as red mottled and conical columnar structures similar to pipes that progressively disappear with depth, among which the whitish host material occurs, since it has a smaller content of iron oxides and hydroxides. It should be noted that the paleosurface defined by Pazos et al. (1998) does not coincide with that one established by Ford and Gancio (undated) because the latter authors located it above the levels of "ferrallitic crusts", whereas the others placed them underneath (Table 1).

Pazos et al. (1998) denied as well the existence of the fluvial conglomerate levels corresponding to the Palmitas Fm., because no clean contacts or channel geometries are seen and the levels are internally massive, characteristics which are not compatible with fluvial flow action. The Yapeyú paleosurface would mark a change in the climatic conditions, indicating a notable interruption in sedimentation and acting as the boundary between two sedimentary cycles, because above it fluvial sediments are found, represented by low hierarchy stream channels and piled up, paleosol levels with an abundant ichnofauna (González et al., 1998). The ferrification processes would be younger than the whole section sedimentation, affecting in depth down to the paleosurface, which would have acted as a geological barrier for the migration of the iron carrying solutions under it (Pazos et al., 1998). According to these same authors, the paleosurface occurs clearly subhorizontal at Pedro Chico and Gruta del Palacio but, instead, it is clean and smoothly irregular in the arroyo Coquimbo basin, where fractures are observed that would have allowed the penetration of the iron bearing solutions which precipitated irregular and criss-crossed veins, with nodule development, although relicts of the primary sandstone are preserved as well.

Likewise, it should be mentioned that Pazos et al. (1998) stated the need of carefully analyze if true differences do exist between the Yapeyú member of Bossi (1966) and Bossi et al. (1975) with the underlying Mercedes Fm. or if it is just a "facies" located at its top. The authors propose specifically to reconsider the stratigraphic level of the so-called Yapeyú member, which could be assimilated to the Mercedes Fm. Besides, Goso Aguilar (1999, cited by Goso Aguilar & Guérèquiz, 2001) defined a single unit which he called the Mercedes-Asencio Fm. Later on, Goso Aguilar & Perea (2004) abandoned the Asencio denomination, considering the Mercedes Fm. as integrated by the del Chileno, Yapeyú and del Palacio members (Table 1).

With respect to the intense reddish, indurated levels of what would be the del Palacio Member of the Asencio Fm. according to Bossi (1966) and Bossi et al. (1975), the group formed with the Palmitas and Asencio formations according to the proposal of Ford & Gancio (1988), the Asencio Fm. in the sense of Pazos et al. (1998, 2002) or the del Palacio Member of the Mercedes Fm. according to Goso Aguilar & Perea (2004) (Table 1), several authors have interpreted them as a result of pedogenetic processes (Caorsi & Goñi, 1958; Ford, 1988b; Veroslavsky & Martínez, 1996; González et al., 1998; González, 1999). Goso Aguilar & Guérèquiz (2001) and Goso Aguilar & Perea (2004), in recognition of the pedogenetic character of the del Palacio Member, proposed that the latter should be considered of pedostratigraphic character, defining it as the del Palacio Geosol. Recently, Bellosi et al. (2004) offered an elaborated interpretation of the genesis of the Asencio Fm. in which they distinguished two facies: ferruginous duricrusts and massive nodular beds interfingered and repeated up to 3 and 4 times within the whole thickness of the formation.

In a synthetic manner, Bellosi et al. (2004) considered that the formation is composed of a series of superposed, strongly weathered profiles, resulting from the following sequence of events:

1. The fluvial sandy sediments were initially transformed in well developed, red Ultisols, under warm and wet conditions in a savanna environment.
2. In a subsequent stage Ultisols evolved to ferruginous crusts (authochtonous ferricretes or "cuirasses") during periods of prolonged dissecation.
3. The top of the ferricretes was dismantled by re-hydration due to a strong rainfall increase, what originated the nodular levels.

According to these authors, the morphology of the duricrusts is generally tabular, although it may occur as undulated, lens-like or wedge-shaped, with thicknesses of 0.5 to 2.5 m. Following these authors, the duricrusts are formed by clayey red sandstones, very massive and indurated. The more compact ones are dark red (5R 3/4), with abundant root marks, whereas those of lesser consolidation have a prismatic or blocky soil structure, and they include abundant bee and coleopteran nests (*Coprinisphaera* ichnofacies). The coarse fraction is formed mainly by monocrystalline quartz (85-90 %), accompanied by other silica varieties and a very small percentage of granitic rocks and feldspar fragments. The clay fraction is composed of smectite, kaolinite and possible interstratified clays, which agrees with the analysis performed by Goso & Guérèquiz (2001) and Ford (1988b); this latter author has also indicated an increase of the proportion of kaolinite towards the top of the sections. The microstructure is complex, predominantly spongy, grain and pore striated b-fabric, with a large enrichment in illuviated clay, which allows to characterize them as Bt horizons and to consider the original soils as Ultisols (González, 1999). The following climate change towards a marked contrast in the precipitations, with periods of extended desiccation, would have produced the des-hydratation of the soils and their induration due to a dense network of iron compound crystals which have a strong cementing effect, forming ferricretes or other duricrusts.

The nodular beds described by Bellosi et al. (2004) would be coincident with the "conglomerate levels" of Ford 1988c and Ford & Gancio (undated), forming irregular and discontinuous levels that do not present channel geometries but they are massive and clast-supported (González et al., 1998; Pazos et al., 1998). However, there are matrix-supported levels, formed by dark red (5R 3/4) to greyish red (5R 3/6) nodules, included in lighter clayey materials with tones that vary from greyish yellow (5Y 8/4) to greyish pink (5R 8/2) and yellowish grey (5Y 8/1).

According to Bellosi al. (2004), the lateral and vertical passages, transitional from crusts to nodular beds due to the increase of clay content, are frequent. These authors also indicated that in some outcrops (i.e, the Espiga quarry) the nodular beds include smaller sectors of duricrusts of around 1-2 m^2, keeping a gradational contact in between them. Due to this duricrust preservation in more extensive nodular beds, as well for the gradational contacts in all senses, these authors interpreted that the origin of the nodular beds was produced by chemical weathering and gradual disintegration of the ferruginized crusts. This process of superficial disintegration of the ferricretes, which has been called "dismantling", would have been due to an important increase in precipitation, producing re-hydratation and corrosion of hematite and the formation of residual nodular beds.

Following the interpretation of Bellosi et al. (2004), after the "dismantling", a new period of sedimentation followed with appropriate conditions for the Ultisols formation, with annual rainfall between 1300 and 1700, initiating a new cycle. In this way, they considered that the Asencio Fm. is the result of at least four laterization phases, each one of them including a sequence of sedimentation/pedogenesis/ferricretization/dismantling (nodule formation) in response to successive climatic changes. Finally, these authors indicated that these weathering paleosurfaces reflect an extension of the tropical environments towards southern South America, what suggests that this formation dates from the early Eocene, corresponding to the expansion of those conditions during the climatic optimum of the Paleogene.

MATERIALS AND METHODS

In this paper, observations and field descriptions at the Espiga quarry are presented, as well from another extensive unnamed quarry located nearby, close to Nueva Palmira (33°52´22.6´´S, 58°09´44,5´´W) (Figure 1, site 1). In these quarries, the thickness of the red levels of the Asencio Fm. is variable, with an average of 5 m. The Fray Bentos Fm. is overlying it, with an average thickness of 4 m, though in some sectors the Asencio Fm. is found at the surface, on which the present soils has developed, bearing the morphological characteristics of a Ultisol.

Likewise, the observations in a quarry nearby the locality of Cerro Vera, with access from route 14 (33°05´48,3´´S, 57°33´29,1´´W), are included as well (Figure 1, site 2). The obtained information from the profiles in the quarries is complemented with the observation of the columnar structures at the site known as "Gruta del Palacio", in the Flores Department, on route 14, km 235 (Figure 1, site 4), and of the relict structures found in the neighbourhood of route 14, at 2.4 km of its crossing with the arroyo Vera (Figure 1, site 3).

Diverse terms, such as laterization, ferrallitization, ferrification, have been used in the literature to describe the weathering processes and iron oxide accumulation in the materials of the Asencio Fm. In the present paper and according to the results presented by Bellosi et al. (2004), which indicate pedogenetic processes with illuvial accumulation of clays, the term ferrugination, corresponding to an intermediate phase of geochemical weathering and pedogenesis (Duchaufour, 1977), will be used.

RESULTS AND DISCUSSION

NATURE OF THE BOUNDARY BETWEEN THE MERCEDES AND ASENCIO FORMATIONS

In the observations performed at the Espiga quarry, and in the other one located nearby, the morphology of the boundary between the Asencio and Mercedes formations goes from markedly undulated to clearly irregular, with tongues of approximately conoid shape, between 1 and 3 m in depth, of ferruginized materials of the Asencio Fm., which vertically penetrate into weathered, fissured and fragmented, greyish whitish materials, belonging to the Mercedes Fm. (Picture 1A, B).

In some areas, the reddish colour tongues may include relicts of material coming from the Mercedes Fm., apparently more resistant due to a larger compaction and/or carbonatation, which, as they have a horizontal disposition, generate structures of the "stone layer" type (Picture 2). In other cases, the partially coalescent ferrugineous tongues generated the individualization and isolation of approximately spherical and strongly fragmented volumes of the Mercedes Fm. sandstones (Picture 3A, B).

Concerning the boundary indicated by the colour variations, in many cases this is gradual, passing along a few tens of cm from the greyish materials, through pinkish and orange colours to the intense reddish tones of the ferruginized materials (Picture 4). In other cases equally frequent, diffuse passages are observed, which may be in the order of 100 cm distance, between the sandstones and the ferruginous materials (Picture 3A, B). A transversal section to the ferruginous tongues allows the observation that, from the rock with calcium carbonate towards the central zone, the iron and clay material content increases progressively (Picture 5A). In a few cases, it has also been observed that the boundaries may be straight and the passages abrupt, what would be indicating the presence of fissures or small displacement faults (Picture 5B).

Another very interesting and indicative feature, regarding the interpretation of the processes that have taken place at the boundary between both formation, is the common existence of isolated "poaches" of ferruginized material typical of the Asencio Fm., of varied morphology and dimensions but in many cases of up to 0.5 – 1.0 m in diameter or length, which are deeply included within the Mercedes Fm., in most cases at 2 or 3 m below the contact between the ferruginized beds and the material bearing calcium carbonate. (Picture 6A, B).

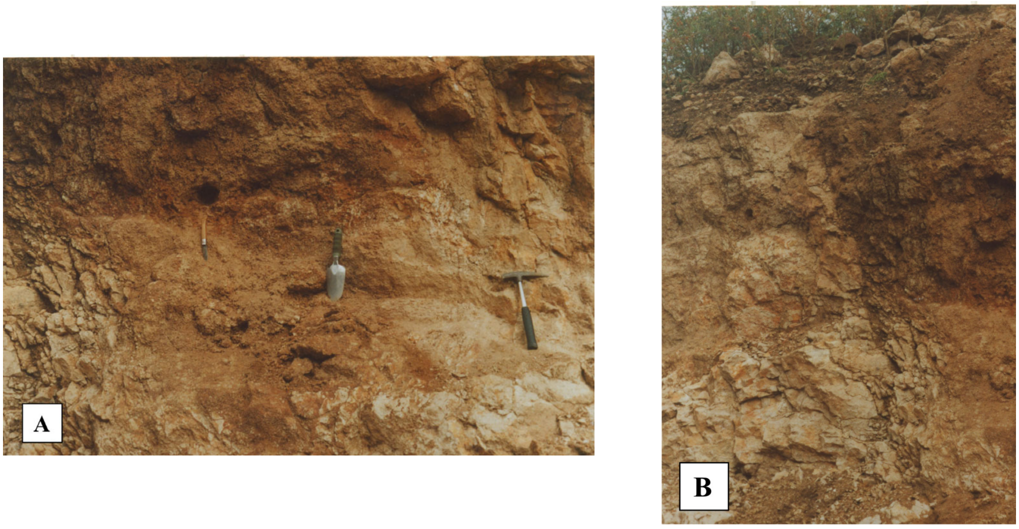
In addition to these larger features, which are evident even at a certain distance from the quarry front, the detailed proximal observation also revealed small isolated fissures and cavities with ferruginized and clearly clayey material belonging to the Asencio Fm., deeply included within the Mercedes Fm. (Pictures 7A, B, C).

PICTURE 1. A) a section of approximately 13 m depth in a sector of the Espiga quarry, where the sequence of the Mercedes, Asencio and Fray Bentos formations is presented. It can be observed the clearly irregular boundary of the weathering front between the Mercedes and Asencio formations; **B**) a detail of the front of the quarry where the dimensions of the weathering tongues penetrating into the Mercedes Fm. can be noticed.

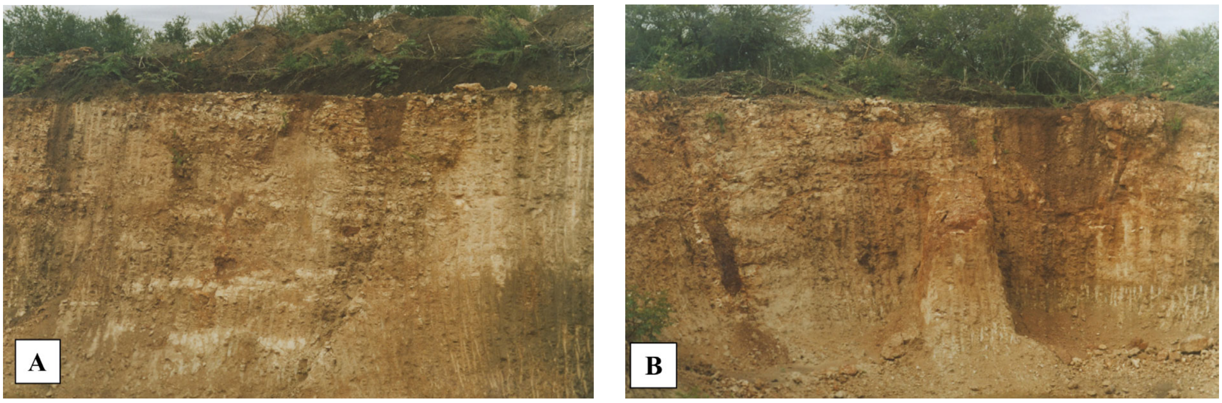
PICTURE 2. The contrast between the greyish whitish sandstone of the Mercedes Fm. and the ferruginous materials can be observed. In this case, the weathering tongue includes relicts of apparently more resistant materials of the Mercedes Fm., generating a structure of the "stone layer" type.

PICTURE 3. A) although the boundary between the ferruginous materials and the Mercedes Fm. sandstones generally varies between abrupt to gradual, occasionally diffuse passages may also be observed. It is also appreciated the individualization of spherical relicts of the sandstone; **B**) another sector of the weathering front with diffuse passages and individualization of more resistant relicts of the Mercedes Fm. In this sector, the Asencio Fm. outcrops and in between the greyish sandstone relicts, the base of one Ultisol type paleosol can be observed at the present surface.

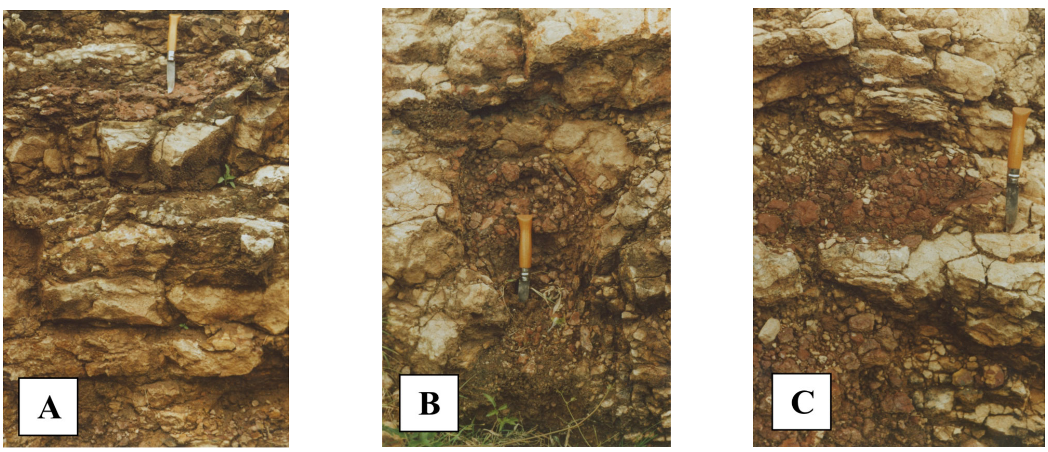
PICTURE 4. At the base of a weathering tongue the gradual contact between the sandstone and the ferruginized materials can be seen.



PICTURE 5. A) a transversal profile, in the three sites where the working tools are placed, allows to observe that from the rocks of the Mercedes Fm. to the central zone of a weathering tongue the iron and clay contents grow progressively; **B**) detail of other lateral contact of the same ferrugination tongue; although in general the passages between the sandstone and the ferruginized material are gradual and diffuse and the boundaries are undulating, in some sectors the contacts are abrupt and the boundaries are straight, which would correspond to the presence of fissures or small fractures of negligible displacement.



PICTURE 6. In **A**) and **B**) pouches of ferrified Asencio Fm. typical materials are observed, included deeply within the Mercedes Fm. and wedge like structures (particularly in 6A) as a result of the weathering process of the sandstone along fractures.



PICTURE 7. Details of small fissures and cavities away from the weathering front with ferruginized materials within the Mercedes Fm. In **A**) a clayey reddish accumulation is observed; in **B**) and **C**) the concentric fragmentation of the sandstone and the formation of ferruginous nodules is observed.

As it appears from the referred morphological evidence, in the herein studied sites and at the level of the contact between the ferruginous materials and the calcium carbonate bearing sandstones, a stratigraphic discontinuity or paleosurface between the Asencio and Mercedes formations which would act as barrier for the ferruginization, is not present. Contrarily, the observed morphological features show that in these localities the boundary between these formations is transitional. The definition of the boundary presents variations that correspond to the more or less progressive increment of the iron oxi-hydroxides and clay fraction contents between the described tongues and pouches, which would result from weathering processes of the sediments of both formations under warm-wet climate conditions.

Origin of the Nodular Beds

The sectors of the Asencio Fm., composed of varied size nodules but which could be estimated around 2-4 cm in mean diameter in the herein studied sites, were called “conglomerate levels” and interpreted as of sedimentary origin by Ford (1988c). On the contrary, Bellosi et al. (2004) suggested that these “nodular beds” are of residual origin, as a result of the gradual disintegration of the ferruginized crusts, by a superficial process of “dismantling”. It should also be noted that Bellosi et al. (2004) indicated the existence of some complex stratigraphic relationships between the ferricretes and the nodular beds, which could hardly be interpreted as superficial dismantling processes. Consequently, these authors also proposed sub-superficial dismantling processes due to phreatic layers “perched” under the ferricrete that would produce the solubilization of the iron and the instability of the aggregates due to the circulating waters. These authors, in particular, pointed that “the relict crusts surrounded by the nodular beds at the Espiga quarry could be an example of non superficial dismantling”.

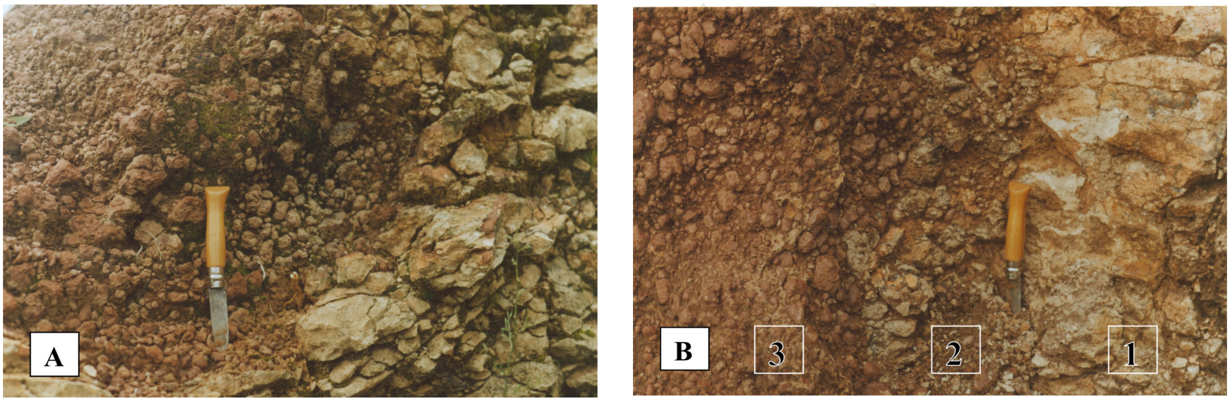
On the contrary, our observations in the herein cited sites, and particularly at the Espiga quarry, suggested a different interpretation to that one proposed by Bellosi et al. (2004) about the nodulation process within the Asencio Formation.

As it may be observed in contact areas between both materials (Pictures 8 and 9A, B), from the more or less homogeneous sandstones of the Mercedes Fm., a transition to a fissured and fragmented sandstone sector takes place, with irregular and equidimensional, as well as laminar, fragments, and with varied sizes oscillating between 5 and 20 cm in diameter. From the fragmented sector, a relatively abrupt transition to a “nodulation” sector takes place, generally of small thickness, in which the fragments of still greyish colour and undoubtedly derived from the Mercedes Fm. achieve a nodular morphology, and among which a reddish clayey material is found. From this transitional sector with greyish nodules, the sequence passes towards the interior of the tongues composed by totally ferruginized nodules, of intense reddish colour and a larger content of clayey plasma in between the nodules.

Other morphological evidence related with the previously described process is the nodulation observed in the inner part of the Mercedes Fm., at sites quite away from the boundary between both formations. As it may be observed in Pictures 7B and 7C, the weathering process in the interior of the Mercedes Fm. is initiated undoubtedly from pores connected with the weathering front from which the meteoric waters have penetrated, initially generating a process of fissuration and concentric fragmentation of the sandstone, which is progressively nodulated and ferruginized, and parallel increasing the clay fraction content. Consequently, without outruling the interpretation of Bellosi et al. (2004), which could be valid at more superficial levels of the formation, it is herein proposed that the nodular beds of the Asencio Fm. –an particularly those present at the base- are the result of a ferruginous type, geochemical weathering of the sandstones of the Mercedes Fm.

These nodules, through a process of firstly fragmentation and then ferrugination of the calcareous

PICTURE 8. Nodular beds at the weathering front.



PICTURE 9. Details of the formation process of the nodular beds at the weathering front. **A**) the fragmentation of the Mercedes Fm. materials is observed and the formation of greyish nodules; in **B**) it is clearly seen the nodulation process through the progressive passage from the consolidated, homogeneous sandstone (1), the fragmentation and nodulation of the sandstone (2) and, finally, the ferrugination of the nodules (3).

sandstones, would be formed both at the weathering front (the Asencio-Mercedes boundary), in relicts of the Mercedes Fm., included and isolated in previously ferruginized levels of the Asencio Fm., as in the interior itself of the Mercedes Fm., where cavities or fissures in conection with the weathering front may be present.

Following this line of interpretation, it is interesting to mention that, according to Bellosi et al. (2004) the clay of the nodular material matrix is very rich in smectite, with possible participation of illite-smectite interstratified clay minerals, and consequently different to the kaolinite rich clay of the ferruginous duricrusts. Bossi & Navarro (1988) indicated also that the cement of the whitish sandstones of the Yapeyú member of the Asencio Fm. would have an illitic composition different from the kaolinitic composition of the del Palacio Member. Likewise, Ford (1988b) and Ford and Gancio (1991) found that the clay fraction of the Asencio Fm. would be composed of a kaolinite-smectite association, observing that there is a significant increase of the crystallinity of the smectite towards the base of the profiles and in parallel, a lowering of crystallinity in the kaolinite. Goso & Guérèquiz (2001) also pointed that the clays of the sandy mudstones underlying the ferruginized sandstones has a basically smectitic composition, with a proportion of this clay higher than 90 %. In other terms, these data indicate that the clay fraction of the sandstones and greyish whitish sandy mudstones at the base of the ferruginous materials of the Asencio Fm. –being these considered according to several authors as the Yapeyú Member of the Asencio Fm. or as the Mercedes Fm.- would be composed of minerals of the 2:1 type. Consequently, in coincidence with the field morphological observations, the fact that the nodules have a smectitic–illitic composition indicates that they may be considered as relicts of low grade weathering derived from the Mercedes Fm. and not as ferricrete relicts.

Genesis of the Columnar Structures in the Grutas del Palacio

In several localities of western Uruguay, caves of variable size occur which are sustained by cylindrical columns. At the Flores Department the so-called Gruta del Palacio is found, showing these highly indurated columnar structures, developed in the sandstones of the Mercedes Fm.; externally, the columns present the whitish colours of this formation and they are crowned by the typical ferruginous crusts of the Asencio Fm. (Picture 10A, B). In between the columns, a whitish, friable material occurs (Pazos et al., 1998); as it was mentioned before, according to Goso & Guérèquiz (2001), the sediments between the columns would be greyish sandy pelites smectitic composition. At this site, according to the description of the latter authors, these structures present a height of 2.20 m with an average diameter of 0.88 m; the diameter at the base and top of these columns is somewhat wider than the diameter at their middle portion. In front of the cave openings, which are presently receding, relicts of the base of the columns showing their internal structure may be observed. Both cited papers pointed at these transversal sections the existence of a concentric structure, with a central nucleus and an outer aureola. In a synthetic description, this concretion morphology would be composed of an outer aureola of very fine sandstone with ferruginous cement and by a central nucleus with iron concretions contained in ferruginous plasma. Pazos et al. (1998) also pointed out that the contact between the nucleus and the outer aureola presented a strong concentration of iron hydroxide.

PICTURE 10. A) front part of the Grutas del Palacio, with the typical columnar structures of greyish sandstone, sustaining the ferruginized material of the Asencio Fm.; **B**) the broken line indicates the boundary between the ferruginous nucleus of the columns and their cortex of greyish sandstone, suggesting the relationships with the geochemical weathering tongues described at the quarry front.

Concerning the genesis of the columnar structures, Pazos et al. (1998) interpreted them as the result of diagenetic process generating concretions and of subsequent differential erosion. In turn, Goso & Guérèquiz (2001) interpreted that the columns would result from the fracturing of the upper portion of a clayey pedogenetic horizon (an argillic Bt horizon), whose remnants would be found at the base of the columns, through which iron bearing waters coming from the weathering processes and the soil formation in tropical climates circulated; the concentric diffusion of these solutions would have led towards the column formation.

Nevertheless, the morphological evidence obtained in this paper allows the proposition of a new interpretation of the genesis of the columnar structures of the del Palacio caves.

In fact, the irregular boundary formed by deep chemical weathering tongues at the top of the Mercedes Fm. as it has been described above, generated a transitional sector with an average thickness of around 2 m, composed of different composition discrete bodies, of vertical development and conoid morphology: some of them are composed by greyish whitish sandstones and others are so of the same ferruginized sandstones. Consequently, it is herein proposed that the columnar structures correspond to this transitional level; in this interpretation, the body of the columns would be composed of the ferruginous tongues whereas the hollows would be the result of carbonate dissolution and the erosion of the Mercedes Fm. material (Picture 10B). These erosion processes of the greyish sandstones with hollow formation would have taken place in a hydromorphic environment, following the incision of the surface and the genesis of the present landscape.

Other evidence, obtained in the same region where the Gruta del Palacio occurs, would seem to reinforce the previous interpretation. Effectively, in the proximities of the arroyo Vera, cylindrical bodies have been found which are similar to the columnar relicts found at the Gruta del Palacio (Pictures 11A, B and 12A, B, C). These cylinders have between 40 and 70 cm in diameter and their remnants, possibly the consequence of a combination of natural erosion processes and anthropogenic destruction, have between 20 and 70 cm. Like the columns at the Grutas, these cylinders present a ferruginous nucleus and a cortex composed of the greyish sandstone (Picture 12A). The nucleus of hematite composition is red and presents a wide variety of inner structures: in some cases it is fine grained, of pinkish colour, with significant clay amounts, with little ferruginous nodules included in the finer mass, and of friable consistency; in other cases, it occurs strongly indurated, with ferruginous nodules of 2-3 cm in diameter in a whitish sandstone matrix. In some of them, the ferruginous material presents concentric structure with a friable central portion and an outer layer strongly indurated (Picture 12B). The outer cortex of these columnar relicts is generally of a few mm in thickness, and the greyish sandstone is impregnated largely by iron oxi-hydroxides which vary in colour from yellowish –presumably of goethitic nature- to a very intense red of hematite composition (Picture 12C). Although the area has not been excavated, in some parts at the base between the cylindrical relicts, fine grained, greyish materials have been also observed, similar to those described by Goso & Guérèquiz (2001) at the base of the columns at Gruta del Palacio.

PICTURE 11. A) in a small cut, the tabular ferricrete typical of the Asencio Fm. is noted and at its foot, fragments of greyish cylindrical structures; **B**) relicts of the cylindrical structures at a few meters from the previously mentioned front.

PICTURE 12. Columnar relict in which a reddish ferruginous material and the outer cortex of greyish sandstone with yellowish impregnation of goethitic iron may be observed. **A**) details of the cylindrical structure, in which the friable character of the ferruginuos nucleus may be observed; **B**) in another cylinder, the friable nucleus is surrounded by an indurated ferruginous layer; **C**) in this relict, it may be seen that the cylinder is composed of ferruginous nodules in a sandstone matrix and with an indurated nodular nucleus.

The variety of inner morphologies of these columns corresponds with the different morphologies described in the inner portion of the ferruginous tongues at the top of the Mercedes Fm.: the more friable materials at the inner portion of the cylinders are comparable to the finer materials that are present towards the central part of some of the weathering tongues, whereas the nodular materials are comparable to the nodules developed at the edge of the tongues, as the initial weathering phase of the Mercedes Fm. sandstone weathering. Moreover, the presence of goethite in the greyish cortex of the columns would indicate partially reducing conditions, which could be related to the circulation of superficial waters generating cement dissolution and sandstone erosion, thus generating the hollows in between the most coherent ferruginized materials.

CONCLUSIONS

1. The morphological evidence found in the herein studied sites clearly indicates that the geochemical weathering processes that would have taken place during the early Eocene as a consequence of the southward displacement of the wet subtropical climate conditions, generating the paleosols of the Asencio Fm., would have penetrated deeply affecting also the Cretaceous sandstones of the top of the Mercedes Fm. In the herein referred observations there is no evidence of a paleosurface which would have acted as a limitation to these processes. Contrarily, a transitional level occurs, composed of an irregular boundary in which ferruginized materials co-existed with relicts of the greyish sandstone of the Mercedes Fm. Besides, it has been possible to prove that the weathering process has penetrated deeply –probably through fractures of varied nature- in the body of the Mercedes Fm., where ferrugination poaches may be found several meters below the described transitional boundary.
2. These results would support the proposition of other authors about the need of reconsideration of the stratigraphic rank of the Yapeyú member of the Asencio Fm., which at the studied sites occurs as a partially weathered and ferruginized facies of the Mercedes Fm.
3. The nodular beds of the Asencio Fm. have been considered of sedimentary origin or a result of the weathering and destruction of the ferricretes previously generated within the same formation. The herein presented observations show that nodulation is the result of the weathering of the greyish sandstones of the Mercedes Fm., through a process of fragmentation and ferrugination. Due to the fact that this paper has been restricted to the analysis of the boundary between the greyish sandstones and the ferruginous materials, it cannot be ruled out that the nodular beds in the overlying stratigraphic levels of the Asencio Fm. may have a different origin.
4. As a consequence of the existence of a transitional level at the top of the Mercedes Fm., characterized by deep weathering tongues, as well as for their internal characteristics, it is herein proposed that the columnar structures of the so-called Gruta del Palacio and other sites with similar structures would correspond to that transitional level. The nucleus of the columns would be composed of the ferruginous tongues whereas the hollows would be the result of the calcareous dissolution and the selective water erosion of the sandstones of this formation.

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