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NEW MICROSCOPIC EVIDENCES OF THE AUTOCHTHONY OF THE FERRALLITIC PEDOLOGICAL MANTLE IN THE MISIONES PROVINCE, ARGENTINA

Lucas M. MORETTI and Héctor J. M. MORRAS

INTA-CIRN, Instituto de Suelos. N. Repetto y Los Reseros S/N (1712) Castelar, Buenos Aires, Argentina, moretti.lucas@inta.gob.ar; morras.hector@inta.gob.ar

Abstract: The Misiones province is characterized by a pedological mantle with Ultisols, Oxisols and Alfisols. This ferrallitic clayey material frequently shows one or more siliceous or ferruginous nodular “stony horizons” close to the saprolitized basalt, which are generally associated with “structured horizons”. The autochthonous or allochthonous origin of the materials composing these complex profiles has been controversially discussed. In this work, we present the results of new microscopic analyses of thin sections and of sand and silt fractions from several profiles of this pedological mantle. The results show that the “nodular horizons” are formed in the massive basalts by weathering and segregation of saprolitized fragments, which become progressively rounded, ferruginized and indurated. Concurrently, the groundmass in- between the nodules is enriched in clay and iron oxides, developing blocky peds, which gives rise to the “structured horizons”. On the other hand, the vesicular porosity fossilized by chalcedony in the solum of a profile demonstrates the residual origin of the soil parent material, developed by the weathering of a vesicular-amygdaloidal basalt bearing hydrothermal quartz veins. In turn, the morphology and the surface texture of quartz grains from the sand and silt fractions analyzed by optical microscopy and by scanning electron microscopy reveal processes of silica dissolution and precipitation and show no signals of eolian transport. In accordance with previous studies, these microscopic results provide clear evidence that the parent material of soils in the Misiones province and the “stony horizons” usually included in these profiles are the result of *in situ* weathering of the diverse basaltic flows outcropping in the region.

Keywords: soils, microscopy, weathering, basalt, Misiones province.

Resumen: La provincia de Misiones está caracterizada por un manto pedológico en el que predominan Ultisoles, Oxisoles y Alfisoles. Este material ferralítico arcilloso presenta frecuentemente cerca del basalto saprolitizado uno o más horizontes o “líneas de piedra” constituidos por cuarzo o por nódulos ferruginosos, los que están en general asociados a “horizontes estructurados”. El origen autóctono o alóctono de los materiales que constituyen estos perfiles complejos ha sido objeto de controversias en la literatura. En este trabajo se presentan los resultados de nuevos análisis microscópicos de cortes delgados y de las fracciones arena y limo de diversos perfiles de este manto pedológico. Los resultados obtenidos muestran que los “horizontes nodulares” se forman en los basaltos masivos por meteorización y segregación de fragmentos saprolitizados, los que adquieren forma esferoidal y devienen progresivamente ferruginizados e indurados; paralelamente la masa basal entre nódulos se enriquece en arcilla y óxidos de hierro desarrollando una estructura en bloques que da lugar a los “horizontes estructurados”. Por otro lado, la porosidad

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vesicular fosilizada por calcedonia en el solum de un perfil, demostró el origen residual del material parental del suelo formado a partir de la meteorización de un basalto amigdaloide-vesicular que incluye venas de cuarzo hidrotermal. Además, los análisis morfoscópicos y exoscópicos de los granos de cuarzo en las fracciones limo y arena mediante microscopía óptica y electrónica revelan procesos de disolución y precipitación de sílice y no muestran evidencias de transporte eólico. En consecuencia, y en coincidencia con estudios previos, estos resultados microscópicos confirman que el material parental de los suelos de la provincia de Misiones y los "horizontes pedregosos" usualmente incluidos en los perfiles son el resultado de la meteorización *in situ* de las diversas coladas basálticas aflorantes en la región.

Palabras clave: suelos, microscopía, meteorización, basalto, provincia de Misiones.

INTRODUCTION

A pedological mantle with Ultisols and a lower proportion of Oxisols and Alfisols covers most of the landscape in the Misiones province, in northeastern Argentina. This ferrallitic highly clayey material usually has a depth of 3 to 7 meters above the weathered basalt, and frequently shows one or more "stony horizons" in its lower part. Following the more traditional sedimentological conception, these gravelly levels would be named "stone lines" or "stone layers". Considering the autochthonous interpretation, and for the reasons that will be progressively developed through this work, they are here named and considered as pedogenic horizons. According to their mineral composition, morphology and origin, two main types of stony horizons have been distinguished in the study mantle: the "ferruginous nodular horizons" and the "siliceous horizons". The coarse materials included in these horizons, are generally superposed or associated at the same depth with thin "structured horizons" constituted by strong polyhedral aggregates, in contrast to the small granular peds and weak blocks characterizing most part of the solum (Morrás *et al*., 2009).

The allochthonous or autochthonous origin of materials composing this type of complex profiles, frequent in tropical and subtropical environments, is a controversial matter that has deserved numerous interpretations and proposals (Stoops, 1967; Ségalen, 1994; Morrás *et al*., 2009). Referring specifically to the area of the Misiones province and to the neighboring regions of Brazil and Paraguay, Iriondo and Kröhling (1997; 2004) and Kröhling and Iriondo (2010) postulated that the material covering the basaltic rock and on which the red soils have developed is an eolian sediment (a "tropical loess", named "Oberá Formation") of late Pleistocene to late Holocene age, deflated from the alluvial plains of the Paraná and Uruguay rivers. These authors assume the "gravelly" siliceous "stone lines" as torrential deposits, and the structured material below as a buried Ultisol, both features thus regarded as evidence for a paleosurface subsequently covered by the loessial sediment. Concurrently, in the Oberá Formation, the authors have distinguished the "Upper member" from the "Lower member", separated by the sedimentary "stone line".

Fedoroff *et al*. (2010) recently reported the results of the micromorphological study of some samples of these complex profiles from the Misiones province, taken from the bottom of the transition from the weathered zone to a ferralic horizon. Based on the features observed, for instance the presence of silt-sized quartz grains, some in the form of splinters, and a homogenized groundmass throughout the profile, these authors considered the soil parent material above the saprolite as an eolian sediment resulting from complete reworking of Ferralsols during episodes of strong eolian activity. Although their interpretation about the provenance and composition of the material above the basaltic saprolite is different, these authors also subscribe to the allochthonous theory of Iriondo and Kröhling (1997).

In contrast, several other authors such as Riggi and Riggi (1964), Sanesi (1965) and Marengo *et al*. (2005) considered the surface materials in the Misiones province as derived from the *in situ* weathering of the basalt rocks. In our case, based on geographically extensive and locally detailed field work together with a combination of several analytical techniques, we have concluded that the deep red soils in the Misiones province and their siliceous or ferruginous gravelly horizons are the result of *in situ* weathering of the massive and/or vesicular basaltic flows occurring in the area (Morrás *et al.*, 2005; 2006; 2009; 2010; Moretti *et al.*, 2006). The results obtained also provide evidence of paleoclimatic changes and of a polygenetic origin for these highly weathered soils.

In the present work, we present new microscopic evidences about the autochthony of the surface materials in the Misiones province, based on the study of representative soil profiles with ferruginous nodular horizons as well as with siliceous horizons.

GEOLOGICAL SETTING

The Misiones province, located in northeastern Argentina (Fig. 1), belongs to the southern part of the Parana Basin Igneous Geological Province. This is characterized by the presence of basaltic tholeiitic rocks originate from a great volcanic event during the Late Jurassic-Early Cretaceous times. These basaltic flows are called Serra Geral Formation in Brasil and Posadas Formation in Argentina (Teruggi, 1955; Ciccioli *et al.*, 2005; Lagorio and Leal, 2005; Marengo and Palma, 2005; Marengo *et al.*, 2005). From a geomorphological point of view, the basaltic rocks form a plateau characterized by faulted blocks in steps that increase progressively in altitude from 300 m a.s.l. in its southern part to 600 m a.s.l. in the central part of the Misiones province. The relief is undulated, with slopes between 5% and 9%, and with deep red soils. The present vegetation is a subtropical forest, except in a narrow strip along the southern border where savanna type vegetation occurs, and the climate is subtropical humid without a dry season. These environmental conditions have persisted since the Late Mesozoic promoting a continuous and deep weathering of the rock (Rabassa *et al.*, 2010), although pedological and geochemical studies also indicate climatic fluctuations during the Pleistocene and Holocene (Morrás *et al.*, 2009; Zech *et al.*, 2009).

MATERIAL AND METHODS

The present study includes micromorphological and mineralogical analysis of representative soil profiles with the two main types of stony horizons

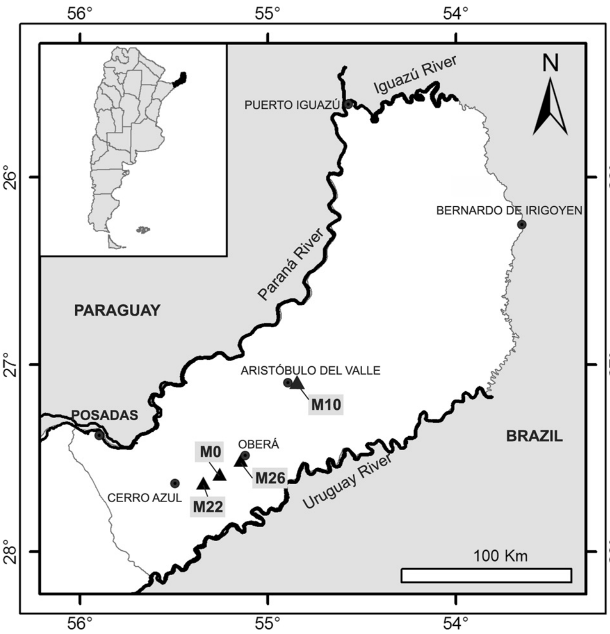

Figure 1. Geographical situation of the Misiones province and location of the studied profiles.

recognized on hilltops in the central plateau of the Misiones province. The studied soils are localized in the southern part of this province, between the localities of Cerro Azul and Aristóbulo del Valle (Fig. 1). Both the entire profile M0 and the transitional soil-saprolite horizon of profile M26 shown in Morrás *et al.* (2009) are described as examples of soils with ferruginous nodular horizons developed from the tholeiitic massive basalt. Profiles M10 and M22 (also from Morrás *et al.*, 2009) are selected as examples of soils with siliceous horizons developed on vesicular basaltic flows. It is worth mention that profile M10 was considered as a "key profile" by Iriondo and Kröling (1997) for the development of their "tropical loess" theory (Cf. Morrás *et al.* 2009; 2010). Seemingly, the eolian interpretation proposed by Fedoroff *et al.* (2010) for the material above the saprolite was based on the study of some samples from this profile.

Thin sections of undisturbed samples from profiles M0, M26 and M22 were analyzed by transmission and reflection optical microscopy with Leitz DMRXP and Wild MZ8 microscopes. Micromorphological descriptions were performed following the guidelines by Stoops (2003). Some terms are used according to Delvigne (1998). The medium fine sand fraction (250-500 μm) of the M0 profile was obtained by dry sieving, and analyzed by optical microscopy. The silt fraction (2-50 μm) from different horizons of profile M10 was also obtained by sieving and studied by scanning electron microscopy (SEM) with a Zeiss Supra40 equipment. Complementary observations to those reported previously on the sand fraction of the M10 profile (Morrás *et al*., 2009) were also performed by SEM. The criteria and results presented by Krinsley and Doorkamp (1973), Le Ribault (1977) and Eswaran and Stoops (1979) were considered for the exoscopical analysis of coarse grains.

RESULTS

Profile M0 (27º 35' 09''; 55º 15' 16'').

Field description. The profile M0 shows an Ultisol characterized, from top to bottom, by a thin A horizon and a Bt plus a Bw reaching together about 6 m thick. Several transitional BC horizons follow: the upper BC horizon about 0.25 m thick with a concentration of goethitic and hematitic nodules (the ferruginous nodular horizon), a BC horizon with a conspicuous blocky structure about 0.10 m thick (the structured horizon), and a lower BC horizon about 2 m thick with somewhat less developed blocks. The saprolite Cr horizon is about 2 m thick in the exposure studied (Fig. 2a and sketch on Fig. 3).

Microscopic studies. The upper part of the Bt horizon at about 0.6 m below the surface presents mainly planar voids defining an angular-subangular microstructure. Between 2-4 m depth, short straight and curved planar voids reflect a subangular blocky microstructure which is strongly modified by an intense biological activity expressed by packing voids, tubular voids, infillings and fecal pellets (Figs. 2b, c). Between 4-6 m, excrements and packing voids are less abundant but tubular voids are frequent. Below the ferruginous nodular horizon, the microstructure of BC horizons shows a clear contrast with the upper part of the solum: abundant short planar voids are mainly curved, subangular and angular blocks are separated and accommodated and only slighted modified by biological activity (Figs. 2d, e). In the saprolite, some planar voids as well as some biological channels are the main types of voids observed (Fig. 2f).

The groundmass above the saprolite is red colored and the coarse-fine (c/f) related distribution open porphyric. The b-fabric of the fine mass is undifferentiated. The main pedological features in the Bt horizon are orange-red clay coatings, infillings and orange, reddish or black iron nodules with undifferentiated or rock fabric (Fig. 2b). In the BC horizon, the illuvial features are also common, whereas the number of dark iron nodules with rock fabric is higher than BC horizon (Fig. 2d). In the saprolite, reddish clay coatings are observed on the walls of some planar and tubular voids (Fig. 2f).

In thin section, the sand fraction of all horizons is composed of quartz and magnetite, whereas the sieved sand also includes pseudosand grains (sand size aggregates composed of finer particles). As previously found in several soil profiles of the Misiones province (Mijovilovich *et al*., 1998; Causevic *et al*., 2004; Morrás *et al*., 2009), quartz is more abundant in finer sand fractions whereas magnetite is more abundant in coarser ones. The sand composition also varies with depth (Fig. 3): pseudosands and magnetite grains compose this fraction in the saprolite (Cr horizon); pseudosands in this level include reddish, yellowish and purple colored ferruginous aggregates together with a low proportion of whitish kaolinitic aggregates. In the transitional BC horizons, pseudosands (yellowish goethitic nodules and reddish hematitic aggregates) constitute most part of the coarse fraction, whereas quartz and magnetite grains appear in low proportion. In the Bt horizon, the estimated percentages of quartz, magnetite and pseudosands (hematitic aggregates) indicate similar proportions of these components. The pseudosand grains show vertical variations in percentages, reflecting the relative influence of rock weathering and pedogenetic processes along the profile. Most of quartz grains in the BC, Bw and Bt horizons are angular and rather irregular. Many quartz grains are entirely or partially clearly neoformed resulting from secondary silica crystallization. Some quartz grains, mostly whitish to milky in colour, are highly weathered with deep and interconnected peats of dissolution. Some traslucent neoformed single and polycrystalline quartz grains also show dissolution peats, particularly visible at high magnification.

Profile M26 (27º 30' 43''; 55º 08' 37'').

Field description. This profile is similar to the profile M0, although the process of nodulation is particularly evident (Figs. 4a, b, c). In the transition zone to the saprolite, below the hard geothitic

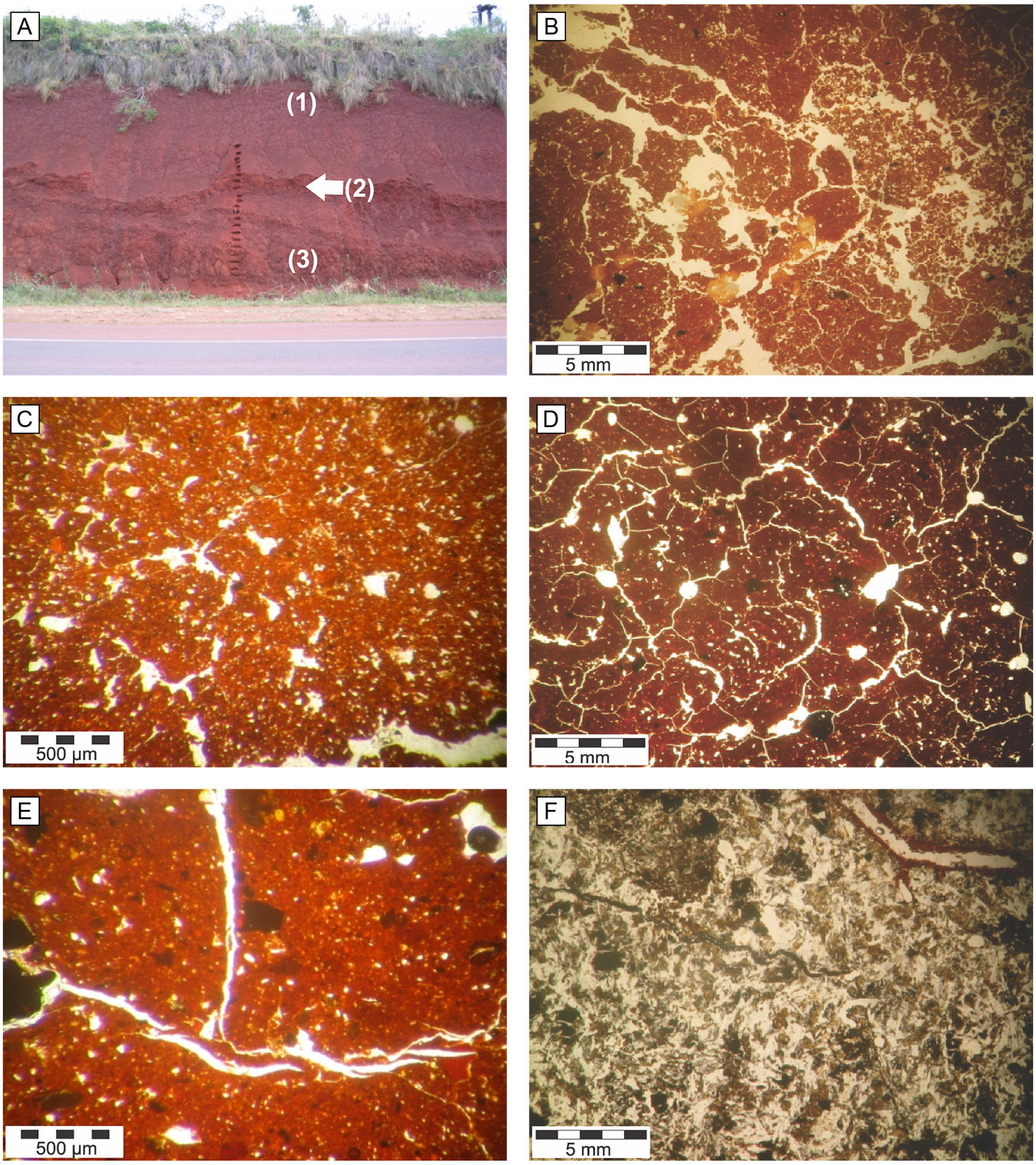

Figure 2. a: Profile M0; Ultisol with a ferruginous nodular horizon (white arrow) and a structured horizon below. b to f: Optical microscopy, plain polarized light (PPL). b: microstructure at 2 m depth (1, in Fig. 2a); subangular blocks and abundant biological features; clay coatings and infillings in the center of the photo; magnetite grains and iron nodules (in black). c: Same sample than Fig. 2b with a higher magnification: rounded aggregates and polyconcave pores of biological origin inside the polyhedral aggregates. d: structured horizon at 6.20 m depth (2, in Fig. 2a): subangular and angular blocks, few channels, clay coatings, magnetite grains and ferruginous nodules. e: Same sample than in Fig. 2d with a higher magnification: polyhedral aggregates are dense; the coarse components are magnetite grains and yellowish goethitic nodules. f: saprolite at 8.80 m (3, in Fig. 2a); ferruginous (mostly goethitic) concentrations, alumino-siliceous low birefringent to almost isotropic plasma, fragments of weathered plagioclases, magnetite grains, reddish clay coatings and some biological disturbance.

nodules of the nodular ferruginous horizon, a soft horizon displaying two different morphological and compositional phases appears (Fig. 4c): ferruginous yellowish nodules (1), and a clayey reddish groundmass in-between the nodules (2) in which a blocky structure develops (3).

Microscopic studies. In thin section, the nodules clearly show a basalt rock structure, with plagioclase phenocrysts and partially weathered mafic minerals (Fig. 4d). The groundmass of the nodules shows variations in color, from grayish and less weathered areas, passing through yellowish and reddish stained

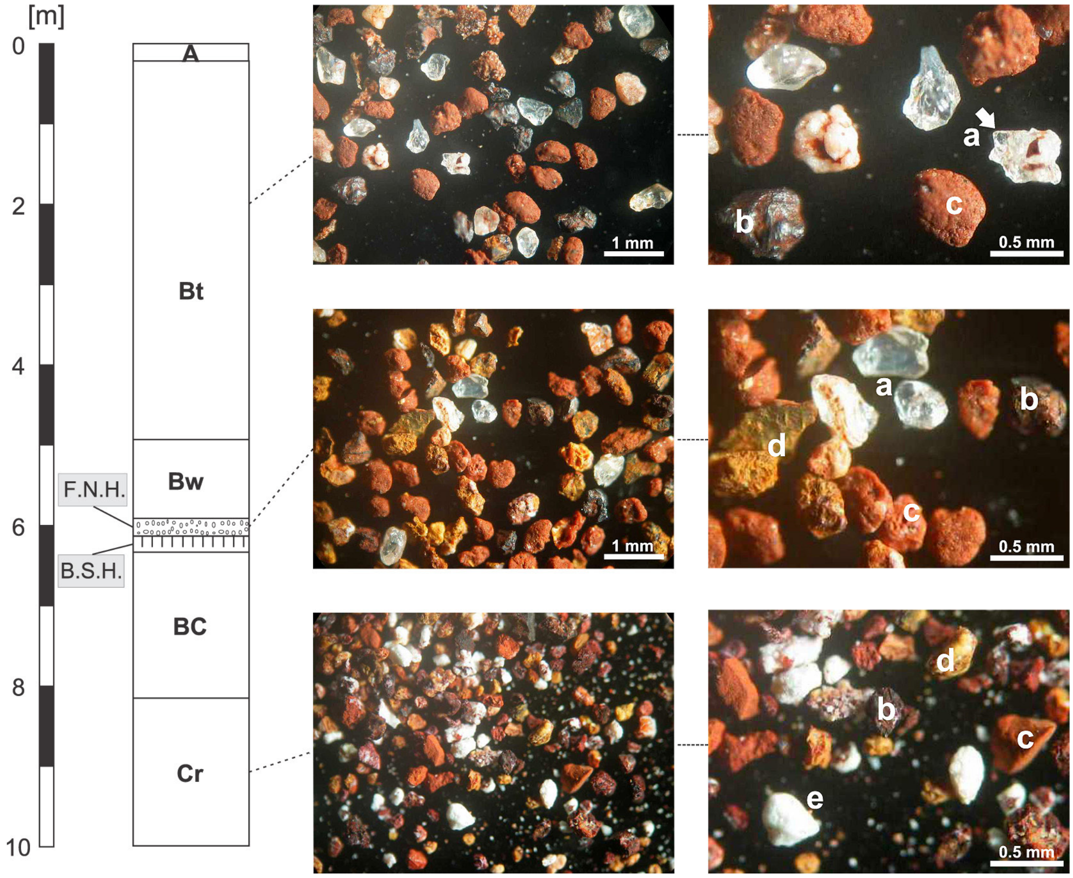

Figure 3. Profile M0 and composition of the sand fraction by reflection optical microscopy. Sketch of the soil profile showing the position of the ferruginous nodular horizon (F.N.H.) and the blocky structured horizon (B.S.H.). Photographs in the central column: general view of the sand fraction in the Bt, in the blocky structured and in the Cr (saprolite) horizons. Photographs in the column to the right: same samples under a higher magnification where a) quartz grains, most of them with irregular morphology and some with secondary crystal growth (white arrow); b) magnetite grains; c) reddish hematitic aggregates; d) yellowish goethitic nodules; e) whitish kaolinitic aggregates.

areas, to dark sectors mainly in the proximity of external or internal voids. Mineral weathering appears stronger in the border of the nodules, and particularly along fissures, together with an increase in dark reddish and yellowish iron oxides staining grain minerals. These dark sectors in the boundaries of the nodules are eventually detached and become incorporated into the soil groundmass (Figs. 4e, f). The latter is dark red colored in plain light, and the aggregates have angular edges and are separated by an intricate pattern of short planar voids.

Profile M10 (27º 05' 27''; 54º 51' 47'').
Field description. This profile is characterized from top to bottom by a thin A horizon, two Bt and two Bw horizons reaching in whole about 7 m thick. A thin siliceous horizon appears below the lower Bw, followed by a BC horizon of about 0.5 m thick. The saprolite Cr horizon is about 1.5 m thick in the exposure studied (Fig. 5).

Microscopic studies. Detailed studies of this paradigmatic profile representative of the soils with siliceous horizons, also including morphoscopy and exoscopy of the sand fraction, have been exposed in a previous paper (Morrás *et al*., 2009). In the present case, we present morphoscopic analysis of silt grains from different horizons of the profile M10.

The silt fraction of the saprolite, at 7.70-7.80 m below the surface, is characterized by a high proportion of ferruginous and kaolinitic aggregates (Fig. 6a). Most interesting from the perspective in this work is the presence of some quartz grains, appearing in this horizon partially coated with clay. These grains show crystalline faces and dissolution pits with inverted trigonal symmetry (Fig. 6b). The

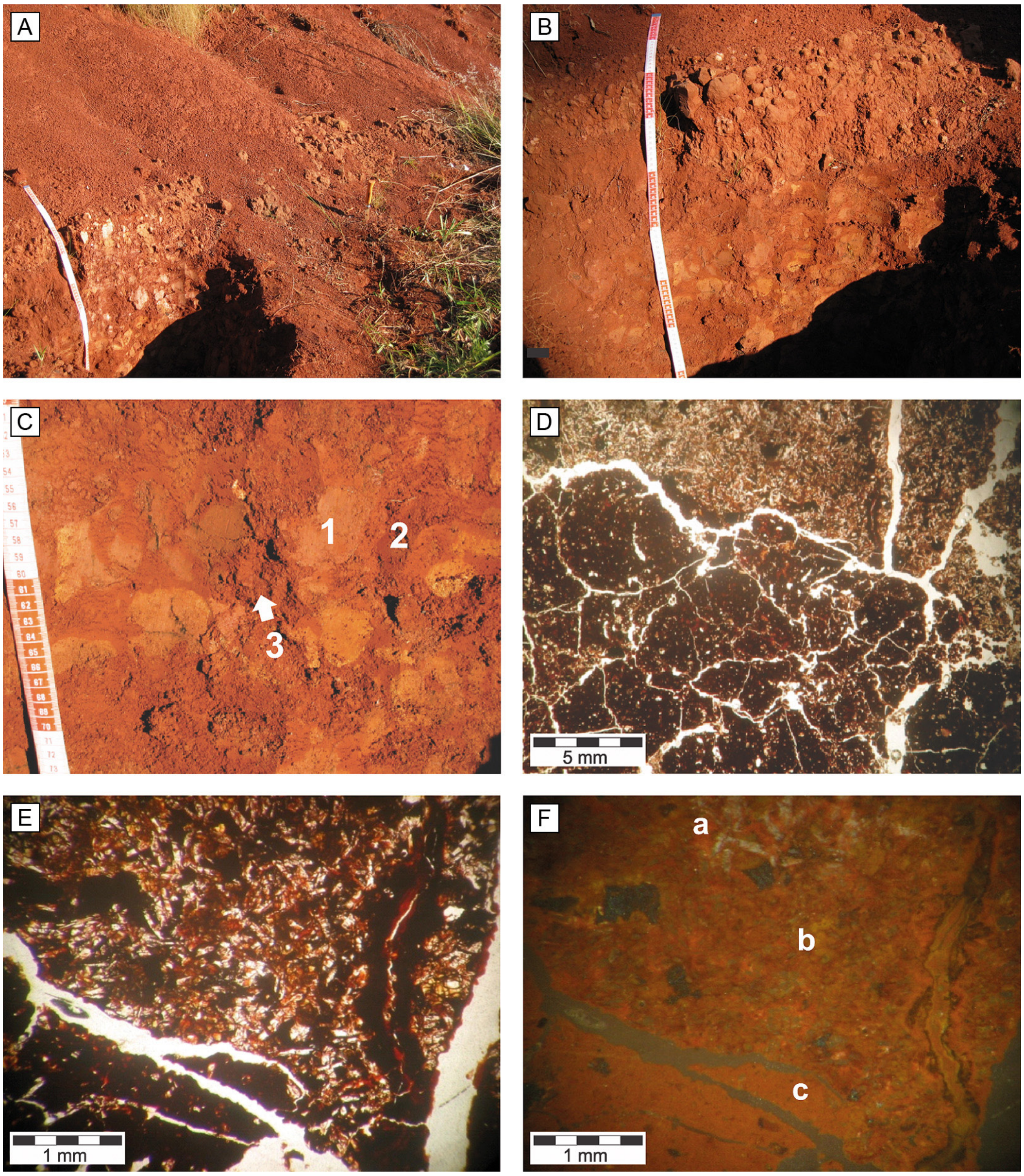

Figure 4. a: Profile M26, with a ferruginous nodular horizon. b: hardened nodules associated with the structured horizon, and a transitional saprolitic horizon with soft ferruginous nodules. c: closer view of the nodular horizon showing soft rounded nodules and a clayey structured groundmass in-between the nodules (scale in centimeters). d: thin section (optical microscopy, plain polarized light) from the area shown in the previous photograph: contact between an alteromorphic nodule displaying the fabric of the saprolite with the clayey ferruginous soil groundmass; observe the similarity between this microstructure and the microstructure of the structured horizon in figure 2d. e: higher magnification of the same sample as in Fig. 4d: reddish and black iron oxides segregate in the external part of nodules and in the walls of internal voids; dark colored fine grained (clayey and ferruginous) fragments become progressively detached from the weathered nodule. f: the same as in Fig. 4e, under incident light: a) inner part of the nodule showing a lower concentration of iron and less weathered plagioclase phenocrysts; b) transition area in the external part of the nodule, with a higher concentration of iron oxides; c) a small fine grained angular fragment of the nodule being incorporated into the fine groundmass make evident the process of argilliplasmation and development of a polyhedral structure.

presence and the characteristics of the quartz grains from this level can be considered as evidence of the filial relationship between the saprolitized basalt rock and the solum of the profile.

Silt sample from the siliceous horizon at 6.80-6.90 m depth presents a low proportion of ferruginous and clayey aggregates. In contrast, a high proportion of clean quartz grains showing crystalline forms

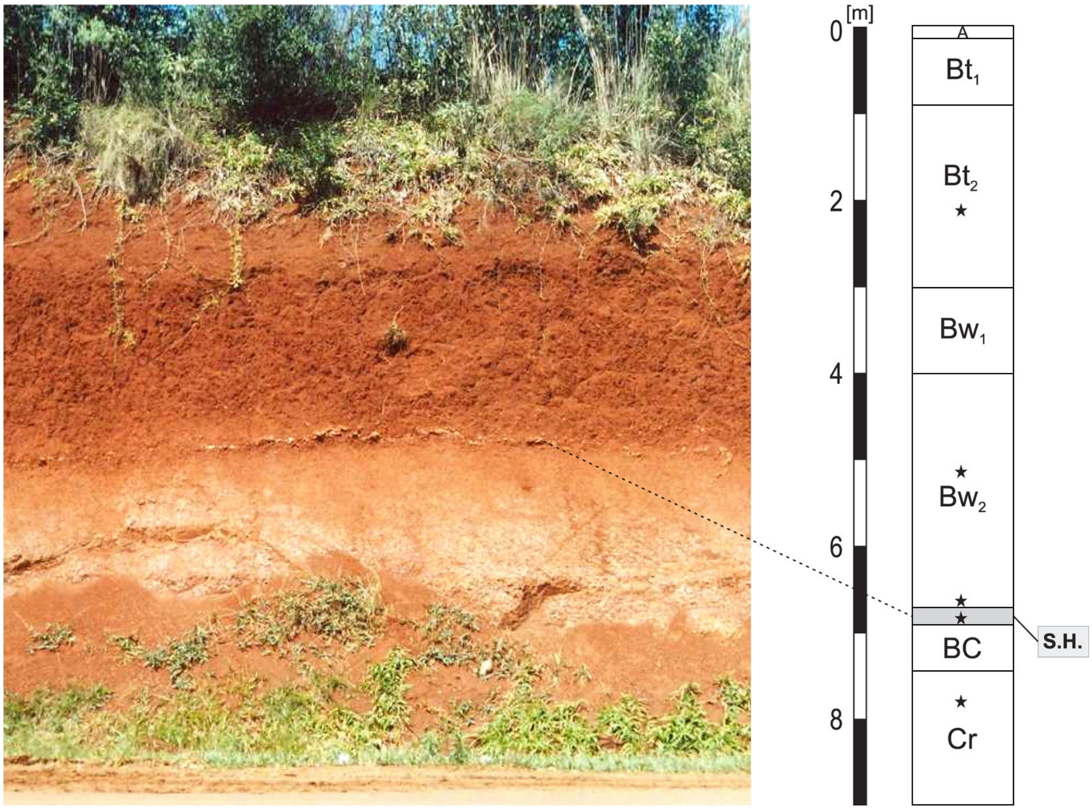

Figure 5. Profile M10 with a siliceous horizon (S.H.) close to the saprolite. Stars in the sketch of the profile indicate the position of silt samples shown in figures 6 and 7.

with well-defined faces and sharp edges is observed (Figs. 6c, e, f). These angular grains show typical and frequent marks of dissolution on their surfaces (Fig. 6d).

In the silt fraction at 6.60-6.70 m depth (Bw_2 horizon), just above the siliceous horizon, the abundant quartz grains are the most weathered grains in the profile. Many quartz grains here have no crystal faces and are characterized by a very irregular morphology resulting from deepening and interconnection of dissolution pits (Figs. 6g, h).

In the Bw horizon, sampled at 5.10 m depth, most part of silt grains are quartz. Unlike the previous sample (Bw_2 horizon), most of the grains in this level show well-defined faces and edges, together with sparse dissolution pits on their surfaces (Fig.7a). Also, the rough surface and the irregular morphology and angularity of many equidimensional quartz grains is the result of the intersection of dissolution pits (Fig. 7b). Interestingly, some of the silt grains can be described as near-idiomorphic crystals (Fig. 7c) with their surface covered by an undulating precipitate of amorphous silica (Fig. 7d). Both features are indicative of a neoformation process as the origin of these quartz grains.

Finally, at a depth of 2.10 m, in the Bt horizon, quartz grains also show angular faces and dissolution pits (Figs. 7e, f). Magnetite grains seem to be somewhat more abundant in this level than in lower horizons. Besides, despite their high stability, some magnetite grains in this fraction also show clear figures of weathering on their surfaces (Figs. 7g, h).

Profile M22 (27º 37' 58''; 55º 20' 33'').
Field description. Site M22 shows an Ultisol profile characterized by a short, red Bt, about 2 m depth, a pinkish transitional horizon to the saprolite, about 1 m thick, and a yellowish massive "micrograined" quartz layer above the grayish weathered vesicular-amygdaloidal basalt, 0.5 m thick. This vesicular saprolite bears several thin parallel quartz veins distanced about 0.3 m from each other (Fig. 8a).

Microscopic studies. The Bt horizon, at about 1.3 m depth, shows a porphyric groundmass, planar voids and blocky microstructure, abundant reddish-

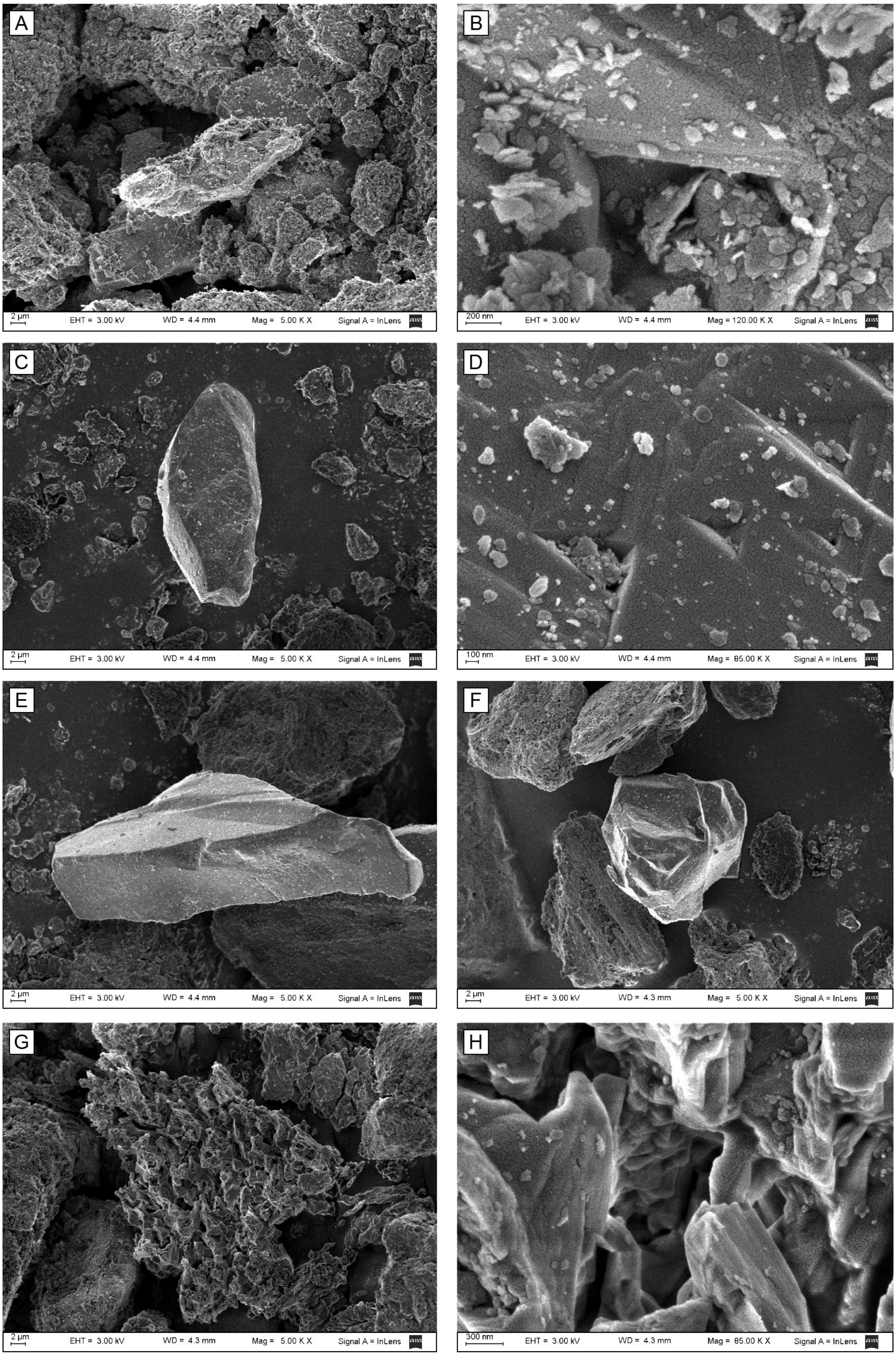

Figure 6. Silt fraction of profile M10 observed by scanning electron microscopy (SEM). a and b: sample from the saprolite (Cr horizon) between 7.70-7.80 m depth. c, d, e, f: sample from the siliceous horizon between 6.80-6.90 m depth. g and h: sample from the lower part of the Bw2 horizon taken between 6.60-6.70 m depth, just above the siliceous horizon. Scales are below each photograph. Details on the composition of the samples are given in the text.

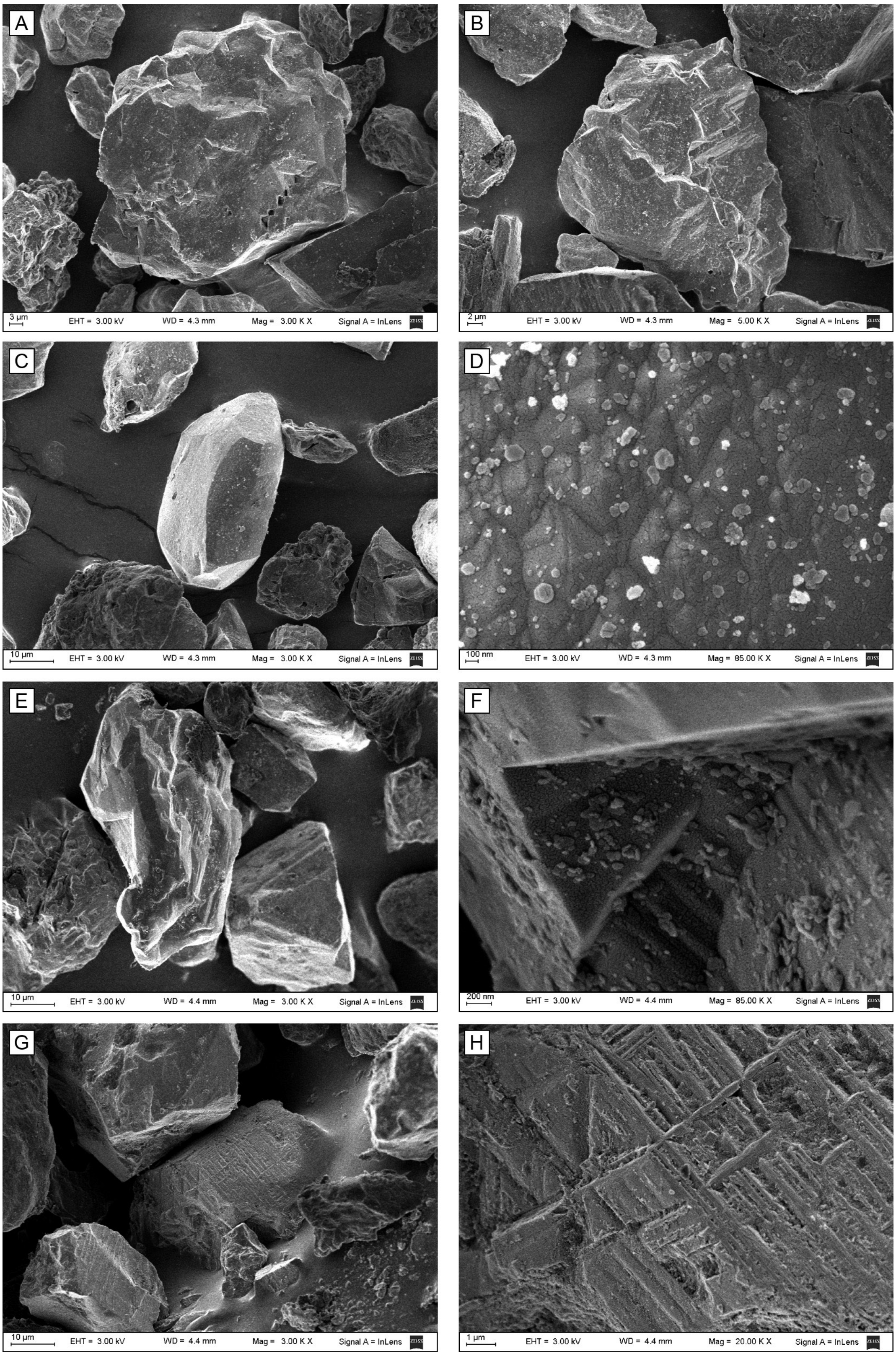

Figure 7. Silt fraction of profile M10 observed by SEM (continuation of Figure 6). a, b, c, d: sample from the Bw horizon at 5.10 m depth. e, f, g, h: sample from the Bt horizon at a depth of 2.10 m. Scales are below each photograph. Details on the composition of the samples are given in the text.

orange coatings and some ferruginous blackish alteromorphic nodules. Nevertheless, the most striking micromorphological feature is the high number of vesicular pores for the most part filled with chalcedony (Fig. 8b). The BC transitional horizon, at about 1.8 m depth, also presents red and orange coatings and infillings in a close porphyric groundmass. In this sample, almost all vesicles are filled with chalcedony (Figs. 8c, d). Thus, the relevant characteristic of both samples is their abundant coarse fraction composed mainly of irregular quartz and a higher proportion of rounded chalcedony grains.

DISCUSSION

Micromorphology of profile M0 shows clear differences in the microorganization between the horizons above and below the ferruginous nodular horizon. The whole BC horizon, which includes the structured horizon below the geothitic nodules, clearly presents transition features to the saprolite, thus confirming that this is not a buried Ultisol developed on an eolian sediment, as proposed by Iriondo and Kröhling (1997). The morphology of many quartz grains indicates that they are the result of *in situ* crystallization, and does not show evidences of eolian transport. On the other hand the detailed observation of the nodules and groundmass microstructure in this profile and in the profile M26, reinforce our interpretation that this type of stony horizon is not transported. On the contrary it derives from an *in situ* segregation and weathering process of soft saprolitized bodies which has become progressively ferruginized, indurated and insulated. At the same time, the groundmass in-between the relict alteromorphic nodules has become enriched in clay and iron oxides and a blocky microstructure develops. This structure is a consequence of the argilliplasmation of the saprolite and has no connection with a supposed paleosurface.

Regarding the material comprising the siliceous stony horizons, a number of evidences also indicate that they are not an accumulation of transported particles. In the profile M10, Iriondo y Kröhling (1997) argued a sedimentary origin for the siliceous material found at the “stone line” level. Also, Fedoroff *et al*. (2010), studying some thin sections of this same profile, argued the eolian origin of the soil material above the saprolite, basically based on “the presence of silt-sized quartz grains, some of them in the form of splinters”. However, our morphological and exoscopic analysis of the silt grains of this profile does not show signs of eolian abrasion. Instead of the rounded shape produced by transport, the grains here show an angular morphology, with well-defined faces and edges. Their surface texture does not show impact traces, also excluding eolian transportation. In contrast, quartz grains are marked by pits produced by chemical corrosion. This feature is common all along the profile, but appears more frequent just above the siliceous horizon. This may result from the abrupt reduction of water permeability in the contact with the stony siliceous horizon, thus causing longer periods of water saturation and an increase in silica dissolution.

Thus, the results here obtained indicate two other origins for the quartz grains and support previous conclusions about the autochthony of the soil material in this profile. On the one hand, it is considered that some proportions of quartz in the silt fraction of the soil were derived from the quartz veins in the basalt rock. A main evidence of the residual origin of, at least, a part of quartz grains is its presence in the saprolite. Although only one relictual siliceous horizon is currently present in the M10 profile, it can be assumed that other quartz veins originally present in the solum would have disappeared as a consequence of intense weathering and bioturbation. This assumption is supported by the existence of soil profiles in the Misiones province with several superposed relictual siliceous horizons, clearly derived from hydrothermal veins in the basalt. Moreover, in a previous study on the vertical distribution of quartz gravels in this same M10 profile, we indicated their concentration at different depths and interpreted them as fragments of thin quartz veins, already dissolved (Cf. Morrás *et al*., 2009). On the other hand, another proportion of quartz grains in this profile is clearly neoformed *in situ* as a result of precipitation of silica provided by the weathering of rock minerals. The idiomorphic crystals and colloidal silica precipitations are unequivocal evidences of crystal growth. Partial results allow us to estimate a higher proportion of these authigenic grains in the middle part of the solum, although this should be confirmed by more detailed studies. It is worth mentioning that quartz grain overgrows developing near perfect crystalline forms has been frequently described in tropical

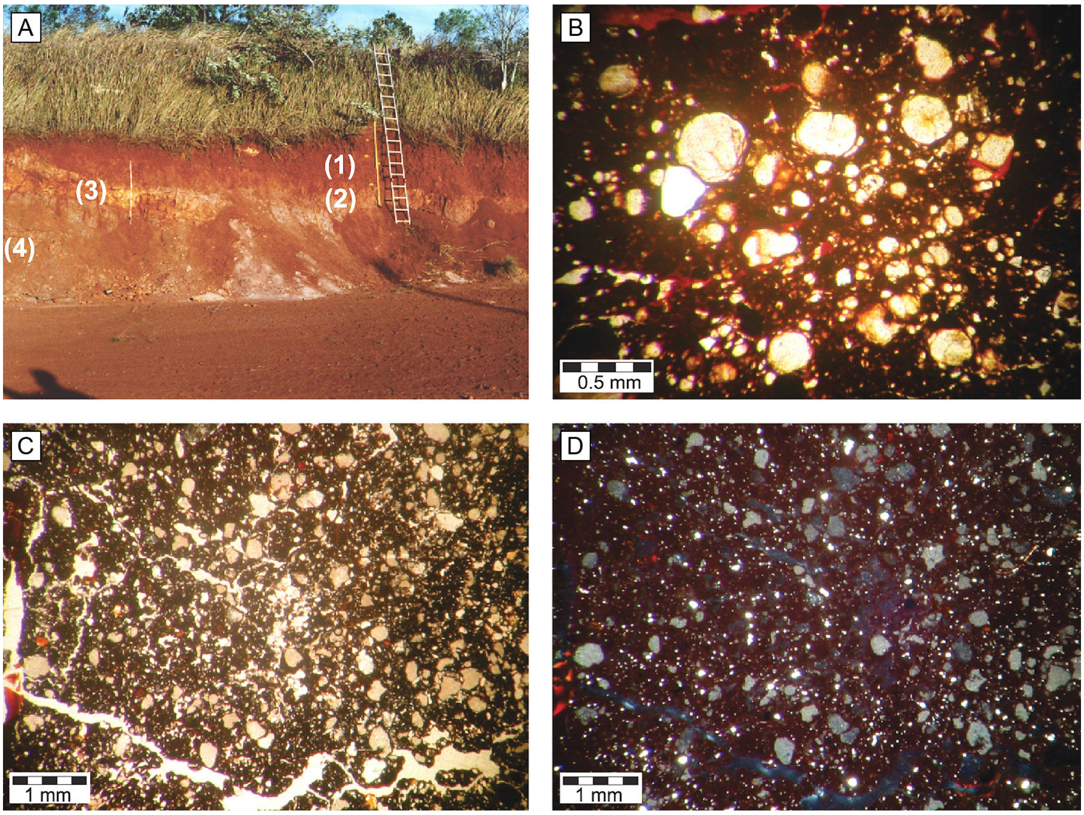

Figure 8. a: Profile M22, developed on vesicular-amygdaloidal basalt with quartz veins. (1) Bt horizon; (2) BC horizon; (3) quartz layer; (4) basalt with hydrothermal quartz veins. b: optical microscopy, plain polarized light (PPL): Bt horizon at 1.3 m depth (1, in Fig. 8a); most rounded grains are chalcedony grains; some quartz grains (brighter in the photo) and reddish clay coatings. c: PPL: transitional BC horizon at 1.80 m depth (2, in Fig. 8a); high proportion of rounded chalcedony grains together with quartz grains and clay coatings. d: crossed polarized light (XPL). The same area as in c; rounded grayish chalcedony grains contrast with smaller and whitish quartz grains.

soils and more recently also in Mediterranean soils (Márquez *et al.*, 2010; 2012). Besides, the colour of quartz grains and their degree of weathering as was observed in the sand fractions of profile M10 may be related to their origin: translucent quartz grains showing better developed crystal faces with less marked dissolution features would be those neoformed in the soil. Contrary, the more strongly pitted which are frequently whitish in colour may be those inherited from the saprolite.

Finally, the inherited vesicular porosity in the solum of profile M22, which has been “fossilized” by silica precipitation as chalcedony, clearly demonstrates the residual origin of its soil parent material. In this soil, quartz grains in the coarse fraction would be inherited from the hydrothermal quartz veins and vesicles included in the basalt rock, although it can be assumed that some part would be neoformed in the soil.

CONCLUSIONS

In accordance with our previous results, and unlike the eolian theory proposed by other authors, the microscopic study of representative Ultisol profiles from the Misiones province provides clear evidence of its autochthonous origin derived from different types of basalt rocks. Ferruginous nodular horizons result from *in situ* weathering of the massive basalt whereas siliceous horizons are inherited from hydrothermal layers included in vesicular and the amygdaloidal basalt flows. These horizons usually appear at the soil-saprolite interface, but in several cases one or both types of those relictic horizons also appear at different depths in the solum. The structured horizons underlying the former coarse horizons are developed by argilliplasmation and ferrugination of the saprolite. The conspicuous blocky structure thus developed is quite different from the microstructure in the solum, which is mainly characterized by rounded peds and a high biological activity. The quartz grains in the coarse fractions of the soils derive from dissolution and disruption of the hydrothermal veins and a redistribution of particles by physical and biological processes, or are the result of precipitation of silica provided by the weathering of rock minerals, a process particularly intense in these old polygenetic subtropical soils.

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