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History of pedogenesis and geomorphic processes in the Valley of Teotihuacán, Mexico: Micromorphological evidence from a soil catena

Historia de la edafogénesis y de los procesos geomorfológicos en el Valle de Teotihuacán, México: evidencias micromorfológicas de una catena de suelos

História da pedogénese e dos processos geomorfológicos no Vale de Teotihuacán, México: evidencias micromorfológicas de uma catena de solos

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ABSTRACT

The paper provides new evidence on the pedogeomorphic history of the Valley of Teotihuacán, Mexico. The soil landscape here consists of Luvisol and "black soil", the micromorphology of which allowed us to (a) distinguish between in situ and inherited processes and (b) establish spatial relationships of erosion and sedimentation along a toposequence of three soil profiles. Soil profiles sites were selected by photointerpretation followed by verification on a toposequence from middle mountain slope to colluvial piedmont. Samples of these profiles were characterized by physical and chemical analyses, including micromorphological observation under a petrographic microscope. The results are summarized as geomorphic observations, description and analysis of soil profiles along a catena, and micromorphological features. The final data set permits recognition and interpretation of both present-day pedofeatures and inherited pedofeatures due to past hillslope processes. In the "black soil", the key processes include development of vertic features, humification and $CaCO_3$ accumulation; while micromorphology revealed fragments of illuvial clay along with disorthic ferruginous nodules. In the Luvisol, clay illuviation dominates and is associated with redoximorphic features. Strongly weathered pumice fragments and less weathered mineral and rock fragments were observed in the vertic horizons. Because the pedofeatures of the "black soil" strongly differ from those of the Luvisol, we can readily identify the cases where Luvisol materials were inherited by the "black soil". Thus, the micromorphological observations allow us to propose that the "black soil" was likely to incorporate Luvisol materials that were earlier colluviated. The presumed erosional phase may correspond with climatic aridization.

RESUMEN

Este trabajo proporciona nuevas evidencias sobre la historia edafológica y geomorfológica en el Valle de Teotihuacán, México. El paisaje del suelo en este lugar está formado por un Luvisol y un "suelo negro", cuyos análisis micromorfológicos permitieron: (a) distinguir entre procesos in situ y procesos heredados, y (b) establecer las relaciones espaciales de erosión/sedimentación a través de una catena de tres perfiles de suelo. La selección de los suelos se realizó a partir de fotointerpretación y posterior verificación de una toposecuencia que mostraba una distribución desde ladera media hasta piedemonte coluvial. Las muestras de estos perfiles fueron caracterizadas de manera físico-química, incluyendo la observación micromorfológica de láminas delgadas con microscopio petrográfico. Los resultados obtenidos se resumen en las observaciones geomorfológicas, la descripción y el análisis de los perfiles de suelo de la catena Zacatlán, y los resultados micromorfológicos. El conjunto permitió interpretar y reconocer tanto los procesos edafogenéticos actuales como los heredados debidos al transporte por erosión de suelo en épocas pasadas. En el "suelo negro" los procesos clave son el desarrollo de propiedades vérticas, la humificación y la acumulación de carbonatos secundarios; la micromorfología también reveló fragmentos de arcilla iluviada y nódulos de hierro redepositados. En el Luvisol domina la iluviación de arcilla asociada con procesos redoximórficos. En los horizontes

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vérticos se observó la presencia de fragmentos de pómez fuertemente meteorizados coexistiendo con fragmentos de roca y minerales con débil meteorización. Los edaforrasgos del "suelo negro" difieren fuertemente de los del Luvisol, lo cual permitió reconocer rasgos heredados del Luvisol en los horizontes del "suelo negro". Por lo tanto, las observaciones micromorfológicas nos permiten proponer que el "suelo negro" probablemente incorporó materiales del Luvisol, los cuales fueron anteriormente coluviados. La presunta fase de erosión puede corresponder con una aridización climática.

RESUMO

Este estudo fornece novas evidências sobre a história pedológica e geomorfológica do Vale de Teotihuacán, México. A paisagem do solo neste local consiste num Luvissolo e num "solo negro", cujas análises micromorfológicas permitiram: (a) distinguir entre processos in situ e processos herdados, e (b) estabelecer as relações espaciais de erosão/sedimentação através de una catena de três perfis de solo. A selecção dos solos realizou-se com base na fotointerpretação e posterior verificação de uma toposequência que apresentava uma distribuição desde meia encosta até um depósito de sopé coluvial. As amostras destes perfis caracterizaram-se física e quimicamente e por observação micromorfológica de lâminas delgadas com microscópio petrográfico. Os resultados obtidos resumem-se nas observações geomorfológicas, descrição e análise dos perfis do solo da catena Zacatlán, e nos resultados micromorfológicos. O conjunto destes resultados permitiu interpretar e reconhecer quer os processos pedogenéticos actuais quer os herdados devidos ao transporte por erosão do solo em épocas passadas. No "solo negro" os processos chave são o desenvolvimento de propriedades vérticas, a humificação e a acumulação de carbonatos secundários; a micromorfologia também revelou fragmentos de argila iluviada e nódulos ferruginosos disórticos. No Luvissolo domina a iluviação de argila associada a processos redoximórficos. Nos horizontes vérticos observou-se a presença de fragmentos de pedra-pomes fortemente meteorizados coexistindo com fragmentos de rocha e minerais com fraca meteorização. As características pedológicas do "solo negro" diferem fortemente das do Luvissolo, o que permitiu reconhecer características herdadas do Luvissolo nos horizontes do "solo negro". Assim, as observações micromorfológicas permitem-nos sugerir que o "solo negro" provavelmente incorporou materiais do Luvissolo, anteriormente coluviados. A presumível fase de erosão pode coincidir com uma aridização climática.

KEY WORDS
Vertic properties, clay illuviation, soil erosion, in situ/ transported pedofeatures, pedosediment

PALABRAS CLAVE
Propiedades vérticas, iluviación de arcilla, erosión de suelo, edaforrasgos in situ/transportados, edafosedimento

PALAVRAS-CHAVE
Propriedades vérticas, iluviação de argila, erosão do solo, características in situ/transportadas, pedosedimento

1. Introduction

The Valley of Teotihuacán is of particular interest for different fields of study. Farming communities inhabited the area from ~1 100 BC and it eventually became the site of the first prehispanic city in the Americas (100 BC – AD 650). Although continually occupied, this region was also important in Aztec times (Sanders et al. 1979; León-Portilla 2005). This long archaeological legacy is of foremost significance in Mesoamerican history and provides an interesting case study of landscape change in the region.

Paleoecological studies in central Mexico have been extensive, through multiple records for the late Pleistocene and Holocene including lacustrine sediments, pollen, isotopic records and rock magnetic evidence (Watts and Bradbury 1982; Lozano-García et al. 1993, 2005; Ortega-Guerrero et al. 2000; Heine 2003; Lounejeva et al. 2006).

In the Valley of Teotihuacán, due to the absence of undisturbed lake sediments, a number of paleoecological studies have focused on the study of paleosols. Based on the study of several profiles, Solleiro-Rebolledo et al. (2006) propose a humid climate during the Last Glacial Maximum, with a semiarid climate trend towards the end of the Pleistocene that extends throughout the Holocene and modern times.

Paleopedological studies report a soil classified as a Luvisol, very well structured, with abundant clay coatings (Solleiro-Rebolledo et al. 2011; Sánchez-Pérez et al. 2013), dated to 18 740 ± 150 ^{14}C years BP and to 22 670 ± 290 ^{14}C years BP (McClung de Tapia et al. 2003); it developed during a long period of stability under humid climatic conditions in the late Pleistocene (Solleiro-Rebolledo et al. 2006). In another profile in which the Luvisol was identified, a horizon closer to the surface yielded an age of 13 340 ± 300 ^{14}C years BP (Solleiro-Rebolledo et al. 2006). Elsewhere, in upland areas, this soil is buried by a black-coloured soil with vertic features. The corresponding "black soil" in the alluvial floodplain was dated to 2 980 ± 40 ^{14}C years BP (Solleiro-Rebolledo et al. 2011; Sánchez-Pérez et al. 2013). Previous soil micromorphological research by Sedov et al. (2009) pointed out some of the in situ and redeposited features in the pedocomplex of the "black soil". This soil with vertic features suggests a semiarid seasonal climate, in which bioturbation processes provide the black colour of the soil, produced by slow humus mineralization accompanied by expansion-contraction processes due to the presence of expandable clays (Gama-Castro et al. 2005), causing fissures in the dry season and slickensides in the wet season (Dregne 1976).

The so-called "black soil" has been identified as the surface on which the Teotihuacán culture developed (or "Black San Pablo Paleosol", Sánchez-Pérez et al. 2013). According to the World Reference Base (IUSS 2006), this polygenetic soil meets the taxonomic requirements for a Vertic Cambisol. It has been studied from different points of view, including its age, genesis and agriculture potential (McClung de Tapia et al. 2003, 2005; Gama-Castro et al. 2005; Solleiro-Rebolledo et al. 2006, 2011; Rivera-Uria et al. 2007; Sedov et al. 2009, 2010; Sánchez-Pérez et al. 2013). Soil micromorphology is a useful tool for the study of pedogenesis and has been used previously in the study area (McClung de Tapia et al. 2003; Gama-Castro et al. 2005; Solleiro-Rebolledo et al. 2006; Sedov et al. 2009; Sánchez-Pérez et al. 2013).

Periods of geomorphological stability and pedogenesis, interrupted by stages of erosion, have been identified in connection with environmental changes, both natural and anthropogenic. However, the impact of these stages in the Teotihuacán "black soil" has not been clarified so far. Although previous studies showed that in upland areas the "black soil" is usually superposed on Luvisols, the exact relationships between the black soil and the Luvisol and their spatial variability along mountain hillslopes have not yet been studied.

The scenario in the Valley of Teotihuacán highlights soil erosion as one of the most enduring forms of alteration of the landscape, and this is also reflected in the soil memory and can be recognized through the study of soil micromorphology. The geomorphological position of the profiles in the landscape provides information on the dynamics of erosion/sedimentation of a site, in this case hydric erosion. Once the position in the landscape has been recognized, it is possible to look for signs of erosion, transport and deposition of materials in thin sections of soil, which appear as pedosediment features, such as rounded aggregates with abrupt contact, fragments of microlaminated clay coatings, microlamination of materials and crust fragments (Courty et al. 1989).

This work aims (a) to use micromorphological analysis to study pedogenesis of the Luvisol and the "black soil" of Valley of Teotihuacan, distinguishing between in situ or inherited; and (b) to establish spatial relationships of erosion and sedimentation along a toposequence of three soil profiles.

2. Study Area, Materials and Methods

2.1. Study area

The studied soils are located in the Valley of Teotihuacán, approximately 50 km NE of Mexico City, between 2 250 and 3 050 masl (**Figure 1**). The catena, named Zacatlán, is located between 2 465 and 2 575 masl at the foot of the Cerro Gordo, in the northern part of the region. The area consists of a floodplain comprised mainly of alluvial and laharic materials, surrounded by volcanic mountains including the Cerro Gordo, Chiconautla, the Sierra Patlachique and other small volcanic cones such as Cerro de San Lucas (Tapia-Valera and López-Blanco 2002; Rivera-Uria et al. 2007).

The geology of the area, predominantly of volcanic origin, consists of basaltic andesitic rocks located in the north (Cerro Gordo), basaltic lava flows in the southeast, and dacitic rocks in the south (Sierra Patlachique), whereas the central part is a floodplain of fluvial-lacustrine origin formed by unconsolidated clastic material (Hernández 2007). Modern climate is a transition between the semiarid (BS) and sub-humid (C) types, with a mean annual temperature of 14.9 ºC and an annual precipitation of 563.3 mm (García 1988). According to Rzedowski et al. (1964) and Castilla-Hernández and Tejero-Diez (1987) four main vegetation zones can be distinguished: forest situated on mountain slopes, secondary growth grasslands and xerophytic scrub in piedmonts, and halophytic vegetation in alluvial plain. Modern soils, according to CETENAL (1975), are Phaeozems, Vertisols, Cambisols and Leptosols. Phaeozems and Cambisols are generally found in middle and lower parts, Leptosols cover most of the mountain in the south (Sierra Patlachique) and Vertisols are present in the lower parts of the valley. Most of the area is characterized by urban and agricultural features; predominant crops are nopal (*Opuntia sp.*), beans, alfalfa and small grains (mostly barley and oats).

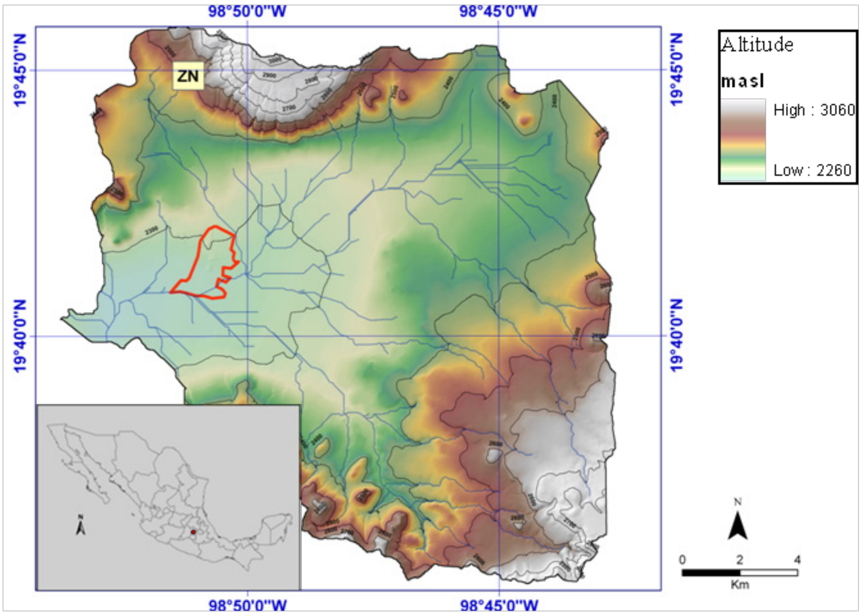

Figure 1. Valley of Teotihuacán hypsometric maps, indicating the location of the soil catena Zacatlán (ZN) and the archaeological site of Teotihuacán (in red).

2.2. Materials and methods

Photointerpretation of 1:40 000 aerial photographs and subsequent detailed fieldwork focused on geomorphological mapping allowed the selection of a catena including soil profiles, paleosols and sediments. The catena comprises denudation landforms, such as mountain hillslopes; and depositional landforms, such as colluvial piedmonts. We determined the stratigraphic relationships between profiles, using the "black soil" as a stratigraphic marker (Sánchez-Pérez et al. 2013).

Detailed descriptions of the observed horizons and layers were carried out in the studied profiles. Samples were taken for textural analysis, total organic carbon determination, and thin section micromorphology. The sampling and descriptions of soils and paleosols were made following the Soil Survey Manual (Soil Survey Division Staff 1993).

Soil samples were analyzed in the laboratory. Particle size distribution was determined by the pipette method (Rouiller and Jeanroy 1971; Avery and Bascomb 1974) in selected horizons; for the rest of the horizons the determination was made in the field by "textural feel". The amount of total organic carbon (TOC) was evaluated with a CHNS/O, Perkin Elmer 2400, series II analyzer, and then transformed to organic matter by means of the Duchaufour factor (1.72). Thin sections for micromorphological study were prepared from undisturbed samples, impregnated at room temperature with Cristal MC-40 resin, studied under a petrographic microscope, and described following the terminology of Bullock et al. (1985) and Stoops (2003).

3. Results

3.1. Geomorphology

Based on geomorphological mapping, some interesting localities were identified and type profiles were selected (**Table 1**, **Figure 2**) at the base of Cerro Gordo, a large domic complex located on the north side of the Valley of Teotihuacán, with basaltic-andesitic parental material (Hernández 2007). The main characteristics of the selected profiles are presented in **Table 2**.

Table 1. General characteristics of the studied profiles. Detrital terrigenous sediments (DTS). Lithology according to Hernández (2007). Zacatlán 7 (ZN7), Zacatlán 5 (ZN5), Zacatlán 3 (ZN3)

Profile	Geographic location (UTM 14N)	Landform	Altitude (masl)	Slope (%)	Lithology	Current use
ZN7	X515330 Y2184400	Middle hillslope	2575	12	Basalt-Andesite	Forest
ZN5	X514000 Y2184010	Low hillslope	2501	8	Basalt-Andesite	Forest
ZN3	X514700 Y2183530	Colluvial piedmont	2465	1-7	Basalt-Andesite and DTS	Rainfed agriculure

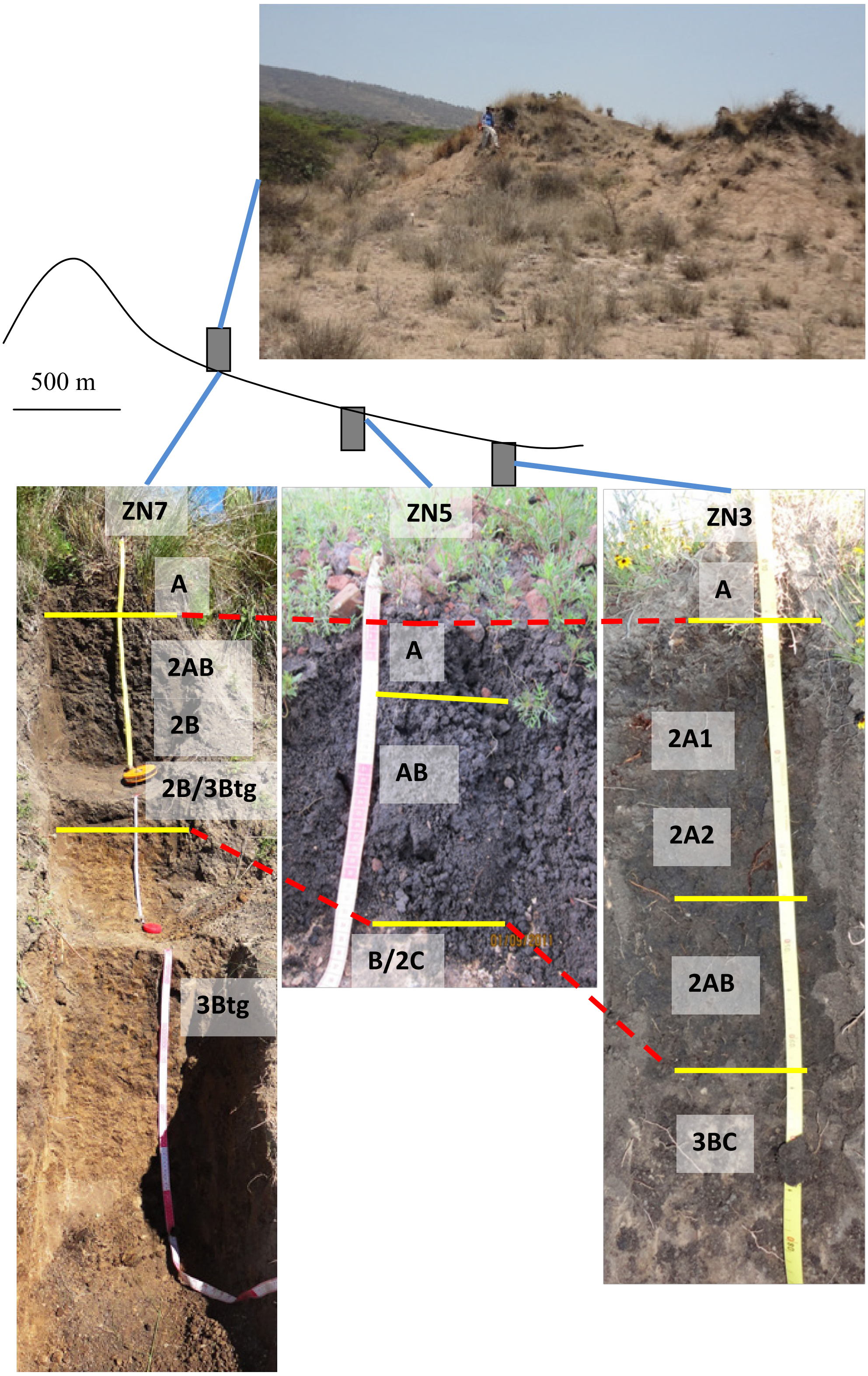

Figure 2. Schematic representation of the Zacatlán catena. Top photo: relict pedestal area in the middle hillslope. The red dotted line indicates correlated soil sequences.

Profiles ZN7 and ZN5 are located on hillslope units, at 2 575 and 2 501 masl respectively. ZN7 is on the middle hillslope and shows differences with respect to ZN5, located on the low hillslope. Both profiles are located in an area of disturbed vegetation (scrub) subject to grazing. In many places these landforms are terraced, indicating ancient cultivation. Both units are highly susceptible to accelerated soil erosion. They represent 12% of the total study area. From a regional standpoint, they are important sources of sediments for the lowland areas.

Profile ZN7 was described on an erosional pedestal, i.e. a small relict promontory, the surface of which represents the ancient ground level. The entire sequence was probably removed from most of the site during a recent catastrophic erosion period, leaving only a few pedestals as relicts of the original surface. Radiocarbon dating suggests that the erosional event took place during the early Colonial Period (early 16th century) (González-Arqueros et al., manuscript in preparation).

Profile ZN5 is located on a low slope. This position in the landscape with respect to groundwater flow enhances certain pedogenic processes such as the accumulation of secondary carbonates. In many places the erosion of these relatively shallow soils has exposed caliche (calcrete) on the surface. Around ZN5 signs of moderate sheet erosion and incipient gullies are present.

Profile ZN3 is located in the colluvial piedmont unit, at 2465 masl. This mapping unit is in the middle parts of the study area at the foot of mountain. Its primary use is agricultural. The material is lava and pyroclastic deposits reworked by colluvial processes. It is a relatively stable unit with colluvial sedimentation processes, although human disturbance has led to severe erosion in many places. The unit covers 14% of the total study area.

On the colluvial piedmont (ZN3), due to an intense erosion history, “tepetate” (indurated volcanic tuff, normally classified as a fragipan or duripan horizon) occupies most of the surface, but at some points there is a shallow modern soil at the surface, underlain by the so-called “black soil”, followed by the “tepetate", less than 1 m below the surface.

3.2. Soil profiles along Zacatlán catena

Regardless of the profile in which it is described, the “black soil” stratigraphic marker (Solleiro-Rebolledo et al. 2011; Sánchez-Pérez et al. 2013) shows similar characteristics. The colour is black (moist). Particle size is clayey in low hillslope positions, and silty clay in middle hillslope and piedmont positions. It displays cracks of different sizes depending on the profile.

ZN7 (A-2AB-2B-2B/3Btg-3Btg1-3Btg2) is a polycyclic profile. It shows a colluvial soil on the surface with strong subangular blocky structure. It represents clear material lamination at macroscopic scale. The colour is very dark brown (moist). Particle size is silty clay loam and organic matter content is 2.94%. Below, with a gradual contact, black and dark brown (moist) horizons follow, “the black soil”. It has moderate to strong angular and subangular blocky structure and shows characteristic vertic features. Particle size is silty clay and the organic matter content varies between 0.78 and 2.22%. The horizons at the base of the sequence are a Luvisol (3Btg1 and 3Btg2 horizons), which is considered similar to other dated soils reported on the upper part of Cerro Gordo by McClung de Tapia et al. (2003) and Solleiro-Rebolledo et al. (2006).

In contrast to profile ZN7, profile ZN5 (A-AB-B/2C) shows the “black soil” on the surface, with moderate to strong granular structure in the A horizon, and moderate to strong angular blocky structure in the AB horizon. Both horizons are black (moist), clayey and the content of organic matter varies between 2.52 and 2.77%. Unlike other sites, the “black soil” of profile ZN5 contains nodules of secondary carbonates, which is probably due to its position in the landscape. Below the “black soil” a layer of calcrete is described.

Table 2. Morphological, physical and chemical characteristics of soil profiles. Horizons belonging to the "black soil" stratigraphic marker appear in grey

Profile	Horizon	Depth (cm)	Contact	Structure	Particle size	Colour (moist)	Organic matter (%)
ZN7	A	0-25	G – F	BSA, F, 2	SiCL	10YR 2/2	2.94
	2AB	25-50	G – F	BSA, F-M, 2	SiC	10YR 2/1	2.22
	2B	50-85	D – F	BSA, M, 2-3	SiC	10YR 2/1	2.53
	2B/3Bt	85-130	D – F	BA, F, 2-3	SiC	10YR 3/3	0.78
	3Btg1	130-155	D – F	BA, F-M, 2	SiC	7.5YR 3/2	0.79
	3Btg2	155-185	nd	BA, F-M, 1-2	CL	10YR 3/3	0.95
ZN5	A	0-10	D – F	GR, F-M, 2-3	C	10YR 2/1	2.77
	AB	10-35	A – F	BSA, M, 2	C	10YR 2/1	2.52
	B/2C	>35	nd	Caliche	nd	nd	nd
ZN3	A	0-15	C – F	GR, M, 2	SiC	10YR 2/2	2.89
	2A1	15-34	G – F	BSA, G, 2	SiC	10YR 2/1	1.94
	2A2	34-47	G – F	BSA, M, 2	SiC	10YR 2/1	2.18
	2AB	47-62	D – O	BSA, M-G, 2	SiC	10YR 2/1	1.69
	3BC	62-73	nd	BSA, M, 2/Tepetate	nd	nd	nd

Abbreviations: Contact: transition: A-abrupt, C-clear, G-gradual, D-diffuse; topography: F-flat, O-ondulated. Structure: shape: GR-granular, BA-angular blocky, BSA-subangular blocky; size: F-fine, M-medium, C-coarse; development: 1-weak, 2-moderate, 3-strong. Particle size: C-clayey, SiC-silty clay, L-loam, CL-clay loam, SiCL-silty clay loam. nd-not determined.

Profile ZN3 (A-2A1-2A2-2AB-3BC) is a polygenetic profile. It presents a colluvial soil on the surface with moderate granular structure. The colour is very dark brown (moist). The particle size is silty clay and organic matter content is 2.89%. Below, with clear contact, horizons with black colour (moist) are observed. The structure is moderate subangular blocky. Particle size is silty clay and organic matter content varies between 1.69 and 2.18%. Below the "black soil", a 3BC horizon is found and underneath the "tepetate".

3.3. Micromorphology

For better comprehension, descriptions of similar horizons are grouped. In general, coarse mineral components in all the profiles are mostly pyroxenes, feldspars (plagioclase) and amphiboles. Volcanic glass, pumice and basaltic rock fragments with inclusions of volcanic glass are also present. They are inherited from the parent material and they show different degrees of weathering.

In thin sections, coarse organic components are basically composed of organic residues such as roots and tissue residues. They are found mostly in the upper horizons. Fine amorphous organic material is also present, as well as punctuations and concentrations of organic pigment in specific areas of the groundmass. Charcoal fragments are found throughout the "black soil" horizons (**Figures 3c** and **6f**). The c/f related distribution is open porphyric in all horizons. Groundmass colour varies from reddish-brown/very dark reddish-brown to grey-brown.

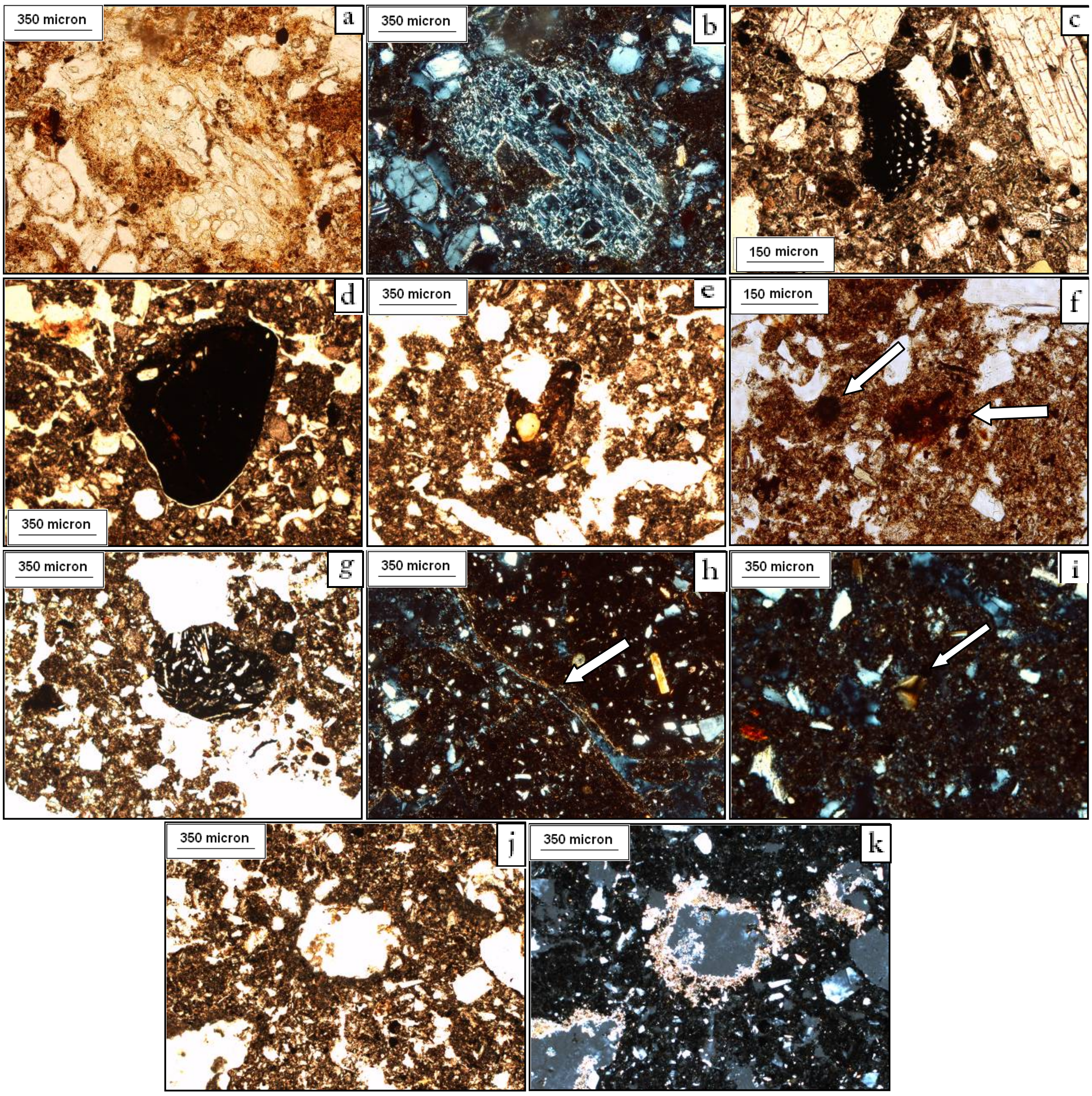

Figure 3. Micromorphology of ZN7 profile. (PPL, plane polarized light; XLP, cross-polarized light). **(a)** Pumice fragment strongly weathered (PPL, in 2AB horizon). **(b)** Same field in XLP. **(c)** Charcoal fragment. Note the cell structure (PPL, in 2AB hor.). **(d)** Typic ferruginous disorthic nodule, with strong impregnation and clear boundary (PPL, in 2AB hor.). **(e)** Nucleic ferruginous disorthic nodule, fragmented (PPL, in 2B hor.). **(f)** Ferruginous hypocoating with strong impregnation. Note open porphyric c/f related distribution (PPL, in 2B hor.). **(g)** Fresh volcanic rock fragment with inclusions (PPL, in 2B hor.). **(h)** Weakly-developed porostriated b-fabric along a planar void (XLP, in 2B hor.). **(i)** Fragment of microlaminated clay coating well oriented in an undifferentiated b-fabric (XLP, in 2B hor.). **(j)** Micritic hypocoating in voids with an associated coating, in a non-calcareous groundmass (PPL, in 2B hor.). **(k)** Same field in XLP.

In profile ZN7, soil thin sections of 2AB and 2B horizons show an undifferentiated b-fabric (Figures 3h, i and k) although incipient porostriation is evident (Figure 3h). Rock fragments with differential development of weathering are also present (Figures 3a, b and g).

In the 2AB horizon, the groundmass is broken by vughs, but not interconnected, with some channels and chambers. Therefore, the predominant microstructure is vughy and in channels, the presence of unseparated aggregates is apparent. In 2B, aggregates are unaccommodated-partially accommodated showing granular and sub-angular blocky microstructure, weakly developed. In the 2B horizon voids are more frequent than in 2AB; and channels with chambers and planar voids are connected (Figure 3h).

In both horizons frequent typic and spheroidal ferruginous disorthic nodules, sometimes broken, with strong impregnation and clear boundaries are present (Figures 3d and e); Also evident are frequent impregnative ferruginous hypocoatings (Figure 3f); frequent impregnative micritic typic coatings and hypocoating in voids (Figures 3j and k); very little dense incomplete micritic orthic infillings; and very frequent fragmented microlaminated clay coatings (Figure 3i).

The 3Btg horizons in the ZN7 profile show a porostriated b-fabric in some parts (Figure 4b) and an undifferentiated b-fabric in the rest (Figure 4e). Rock fragments are strongly weathered (Figure 4c). Planar voids are predominant (Figures 4a, b and c), but also channels and chambers are found. Aggregates are accommodated sub-angular blocks (Figures 4a and b) with moderate developed microstructure.

Pedofeatures are abundant illuvial clay coatings. In some planar voids limpid oriented clay is found (Figures 4a and b), but voids are also found with partly microlaminated limpid yellow-brown clay coating (older phase 1 of clay illuviation), partly reoriented dusty yellow-brown sand size grains-clay coatings (younger phase 2) (Figures 4d and e); dense incomplete illuvial clay infillings; very abundant typic ferruginous orthic nodules with strong impregnation and diffuse boundaries; and dendritic Fe/Mn oxide orthic nodules.

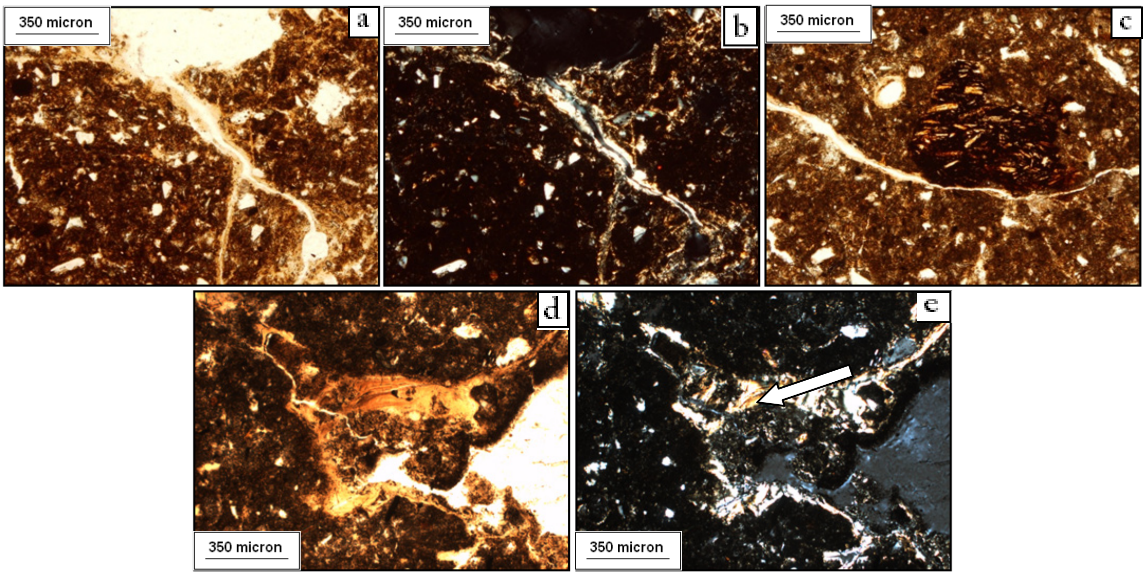

Figure 4. ZN7 profile. **(a)** Subangular blocky microstructure, with open porphyric c/f related distribution and illuvial clay coatings (PPL, in 3Btg1 hor.). **(b)** Same field in XLP. Note planar voids and porostriation. **(c)** Basaltic rock fragment, with inclusions, strongly weathered; note Fe/Mn substitution (PPL, in 3Btg2). **(d)** Microlaminated limpid yellow-brown clay coating (older phase 1 of clay illuviation), partly reoriented dusty yellow-brown coatings with material coarser than clay (younger phase 2), fragmented by pressure (PPL, in 3Btg2). **(e)** Same field in XLP, white arrow points to the boundary of phases 1 and 2.

The AB horizon in ZN5 shows granostriated b-fabric (**Figures 5b** and **e**). Rock fragments with differential development of weathering are also evident, although most of the fragments are strongly weathered; they are often surrounded by a clay coating (**Figure 5a**). The quantity of minerals is lower than in ZN7, and they are concentrated in some zones.

Planar voids are abundant, as are channels with chambers (**Figure 5**). Aggregates are sub-angular blocks (**Figure 5g**) in a weak to moderately developed microstructure. This thin section exhibits a compound microstructure, as it also present fissured and cracked (**Figures 5f** and **g**). Most common features are abundant typic spheroidal ferruginous disorthic nodules, with strong impregnation and a clear boundary. Numerous fragmented microlaminated clay coatings are present (**Figure 5a**).

In the B/2C horizon of ZN5, the notable differences with respect to the overlying horizon include the absence of fragmented clay coatings and the presence of impregnative ferruginous hypocoatings (**Figure 5c**). The Fe/Mn nodules are typic, concentric and nucleic (**Figure 5f**). Rock fragments are absent.

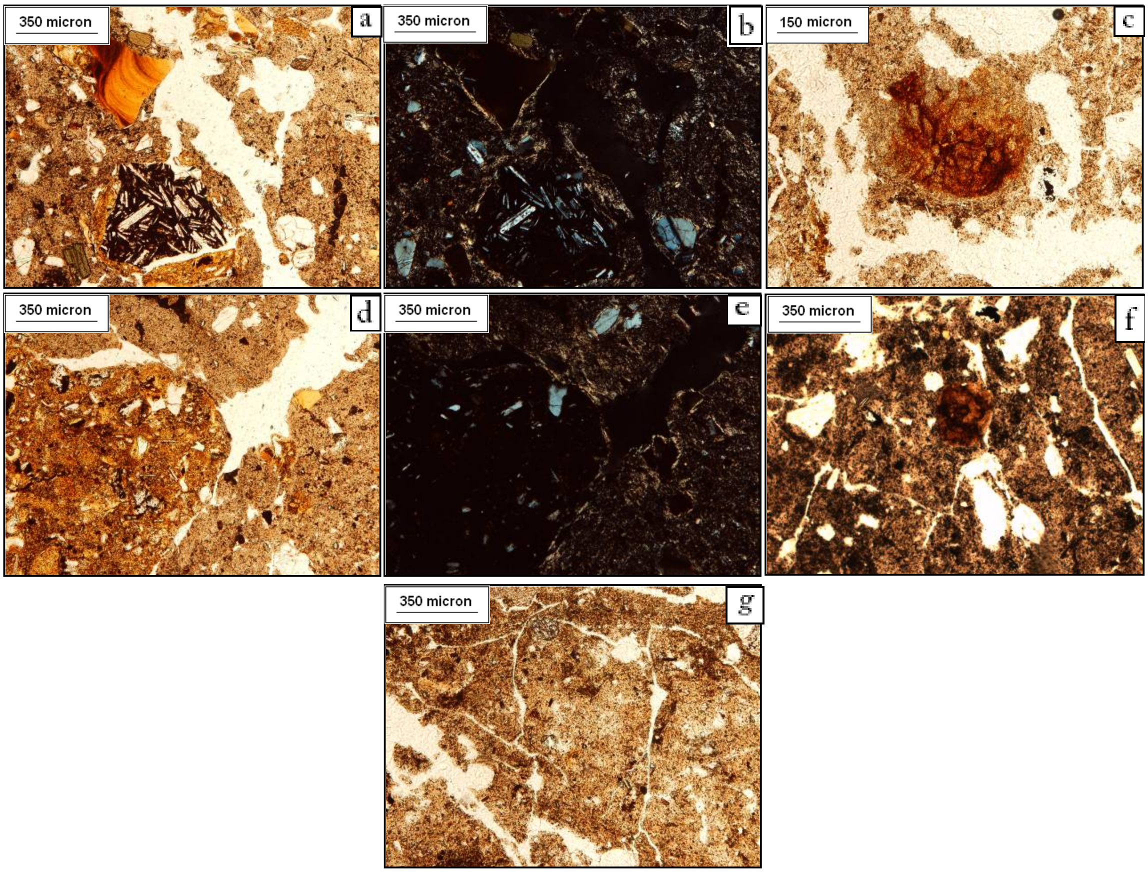

Figure 5. ZN5 profile. Dense groundmass with low content of mineral clasts. **(a)** Microlaminated clay fragment in the upper part; an aggregate with a fresh rock fragment inside and illuvial clay around is visible in the bottom (PPL, in AB hor.). **(b)** Same field in XLP; note moderate granostriated b-fabric. **(c)** Ferruginous hypocoating with moderate impregnation (PPL, in B/2C hor.). **(d)** Disorthic soil aggregate with different groundmass (PPL, in AB hor.). **(e)** Same field in XLP; Note porostriation and the undifferentiated b-fabric of the aggregate. **(f)** Concentric ferruginous nodule, with strong impregnation and sharp boundary. Note fissures (PPL, in B/2C hor). **(g)** Planar voids and fissures typical for vertic material (PPL, in B/2C hor.).

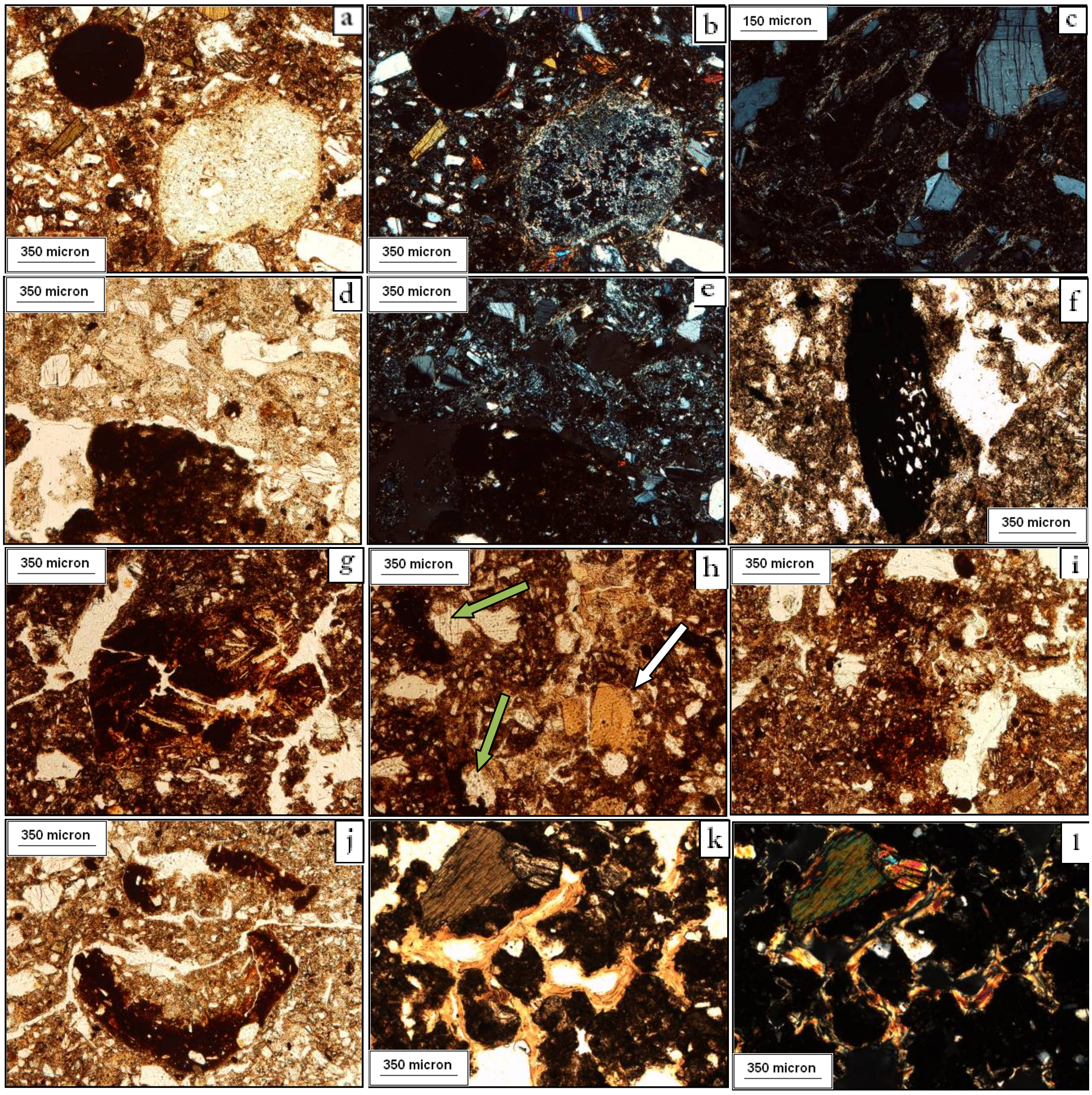

Figure 6. ZN3 profile. **(a)** Top: Typic spheroidal ferruginous nodule with strong impregnation; Bottom: Weathered pumice fragment (PPL in 2A1). **(b)** Same field in XLP. **(c)** Moderate-developed granostriated b-fabric; note plagioclases (XLP, in 2A1). **(d)** Heterogeneous groundmass with material rich in organic matter with undifferentiated b-fabric occurring next to clayey material with random striated b-fabric (PPL, in 2A1). **(e)** Same field in XLP. **(f)** Charcoal fragment. Note the cell structure (PPL, in 2A2). **(g)** Fragmented and highly weathered rock fragment, showing Fe/Mn and clay substitution (PPL, in 2A2). **(h)** Green arrows: Fe/Mn oxides hypocoating; White arrow: fragmented clay coatings (PPL, in 2AB). **(i)** Ferruginous hypocoating (PPL, in 2AB). **(j)** Ferruginous geodic nodule fragmented and displaced by swell-shrink behaviour (PPL, in 2AB). **(k)** Strong illuviation with limpid and oriented clay coatings; amphibole in the top left corner (PPL, in 3BC). **(l)** Same field in XLP, note sharp extinction bands that indicate good orientation of the clay particles.

In the 2A and 2AB horizons of ZN3, striated b-fabric with incipient grano- and porostriation are apparent (Figure 6c). Some spheroidal aggregates with undifferentiated b-fabric are usual as well (Figures 6d and e). Rock fragments with differential weathering are also found (Figures 6a, b and g). Minerals are abundant, similar to ZN7. Channels with chambers are predominant, but also planar voids are also found. Aggregates are partially accommodated granular and sub-angular blocks with weak to moderately developed microstructure, along with some fissures and cracks. Also, some ferruginous geodic nodules were observed in the groundmass (Figure 6j).

We observe the presence of very frequent typic spheroidal ferruginous nodules (**Figures 6a** and **b**), also nucleic and concentric nodules, mostly with strong impregnation and a clear boundary (disorthic); frequent impregnative ferruginous hypocoatings (orthic) (**Figure 6i**); and fragmented microlaminated clay coatings (only in 2AB horizon) (**Figure 6h**).

The 3BC horizon in ZN3 shows two different zones in the thin section. The first is an undifferentiated b-fabric with channels and chambers (**Figure 6l**) in which aggregates are unaccommodated granular, with a moderate to strongly developed microstructure. Few strongly weathered rock fragments are found. The pedofeatures found are typic and nucleic ferruginous orthic nodules, mostly with strong impregnation and a diffuse boundary; impregnative ferruginous hypocoatings; and microlaminated clay coating illuviation (**Figures 6k** and **l**).

The other zone shows monostriated b-fabric, planar voids, channels and chambers. Aggregates are sub-angular blocks with moderately developed microstructure. Almost no mineral clasts or rock fragments are found. Illuvial clay coatings have high birefringence and abundant ferruginous nodules are present. Rock fragments are not present.

4. Discussion

Pedogenic processes are inferred from the features observed in the thin sections. On this basis it is possible to make inferences about landscape dynamics, and to reconstruct the environmental conditions during pedogenesis.

Correlations between soil sequences of the different profiles are possible by the identification of macro and micromorphological features of the "black soil", notwithstanding the spatial variability of this stratigraphic marker along the toposequence.

In the "black soil", the vertic features of shrink-swell, pedoturbation and lateral shearing are present in different stages of development. The relevant characteristics are clayey texture, blocky structure, open porphyric c/f related distribution, deep wide cracks, monotonous colour, pedogenic carbonate and impregnative ferruginous oxides.

The degree of pedality and ped separation can vary depending on the field conditions. Peds falling down cracks lead to a heterogeneous groundmass, as shown by darker zones in the groundmass due to humus accumulation. Dense groundmass, as is shown in some micromorphological figures, open porphyric c/f related distribution and planar voids are typical in vertic soils. Otherwise, coarse material or nodules are fragmented by swell-shrink behaviour of the soil with decreasing depth.

Colours are macro-morphologically different between the Luvisol and the soil with vertic features. However, in thin sections the colour of the groundmass of both soils is similar, in general reddish-brown, which could result from the semi-arid climate and parent material (Kovda and Mermut 2010).

Reorientation and alignment of clay domains result in a striated b-fabric, and are signs of vertic features. The expression of striation differs from profile to profile and could be associated with a low degree of development, a high organic matter content which darkens the micromass, a marked seasonality in rainfall, or basaltic parent material (Kovda and Mermut 2010). Shrink-swell processes are less evident in the presence of micritic calcite, which could explain the weak striated b-fabric found in ZN7, where the micritic coatings are described.

Pedofeatures such as Fe/Mn impregnative nodules are typical for this type of soil; concentric nodules in particular are reported in moisture regimes with repeated seasonal wet/dry cycles (Kovda and Mermut 2010).

In the Luvisol, pedofeatures include clay illuviation coatings and abundant ferruginous orthic nodules. Some of the clay coatings are limpid with strong extinction bands that indicate a strong pure illuviation process. Dusty clay coatings are also present, with material coarser than clay, moderately sorted and usually with weak parallel orientation. The observed coatings reflect different phases of formation: an initial phase with the limpid clay and a second phase with the dusty material or material coarser than clay. The latter are related to turbulent overland flow, with high concentration of suspended matter. All these coatings cover planar voids and channels. Some clay infillings are also found.

The two soil types (the Luvisol and the “black soil”) indicate pedogenesis under different environmental conditions. The Luvisol initially developed under humid climatic conditions, and the subsequent “black soil” under a seasonal semiarid climate.

Similar to microfeatures identified in sediments by Courty et al. (1989), general features found in the “black soil” indicate translocated material on the slope, namely: fragments of clay coatings; disorthic and fractured ferruginous nodules; disorthic typic ferruginous nodules with sharp boundaries; rounded aggregates composed of material derived from other soil horizons or with strong differences in the groundmass; fresh rock fragments coexisting with strongly weathered rock fragments or pumice showing weathering rims and clay-Fe/Mn substitution; and heterogeneous distribution of charcoal fragments.

The Bt horizons of the Luvisol are associated with an advanced degree of weathering, where the grains and rock fragments are usually highly altered. In the vertic horizons, the presence of strongly weathered pumice fragments and less weathered coarse components in the same groundmass are evidence for the transport event.

Many of the fragmented coatings found in the groundmass have weak birefringence. On the one hand Gutiérrez-Castorena and Effland (2010) argue that such features are made of opal, occurring as microlaminated coatings in duripans, in volcanic materials. In contrast, Sedov et al. (2003) support the idea that the coatings are made of clay, in particular halloysite, which has weak birefringence and does not orientate properly during illuviation. Regardless of the origin, these fragments indicate erosion.

Although we recognize that impregnative nodules can acquire sharp boundaries in soils with vertic features, the presence of the variety of features mentioned above indicate the translocation of material with evidence for prior pedogenesis.

According to the study of the stages of Late Quaternary landscape development in the Valley of Teotihuacán (Solleiro-Rebolledo et al. 2011), erosion and deposition in the upper parts, associated with a substantial increase in sedimentation in lowland areas, might have occurred near the Pleistocene-Holocene transition (16 000 - 9 000 years BP), as result of climate change and increased volcanic activity. The landscape became unstable promoting sedimentation over pedogenesis, whereby Luvisols were partially eroded and their material deposited on low mountain slopes.

5. Conclusions

To summarize, the Zacatlán catena developed on the lower gently sloping sector of Cerro Gordo. The profiles described along the middle hillslope –low hillslope– piedmont landforms reflect a history marked by episodes of intense erosion in the middle and low hillslope, but also by the local accumulation of colluvial sediments eroded from the upper parts of Cerro Gordo.

The overall appearance of the catena area and its surroundings is that of a heavily eroded landscape. Middle hillslopes show the strongest signs of erosion; relict pedestals (ZN7) in some cases exceed 2 m in height, exposing the “black soil” on the surface or under a thin horizon of colluvial origin with little soil development. In areas of the low hillslope (ZN5) erosion is also evident; sheet erosion has produced 35-50% of surface stoniness, small gullies are active, and the “black soil” remains in patches, where the “tepetate” has not yet been exposed.

A tentative reconstruction of the sequence of events, based on the hierarchy of attributes, could be the following: (i) an initial pedogenesis phase during the late Pleistocene, associated with long period of stability and humid climate, led to the formation of a Luvisol characterized by abundant illuvial clay and redoximorphic features; (ii) a period of instability resulted in the partial erosion of the Pleistocene Luvisol from upland to mid-low lands, indicated by rounded aggregates of different groundmass, rounded ferruginous nodules with sharp boundaries and an heterogeneous distribution of charcoal fragments; (iii) a period of stability and pedogenesis acting on the pedosediment of the Luvisol during the Holocene under a semi-arid climate, resulting in the soils with vertic features (blocky structure, planar voids, striated b-fabric indicative of shrink-swell processes) and inheriting some of the Luvisol pedofeatures; (iv) a phase of accelerated anthropogenic soil erosion, producing relict soil pedestals in the middle slopes and sedimentation in the lowlands.

Soil micromorphology confirms the differences described macromorphologically between the “black soil” and the Luvisol. The soil with vertic features, the so-called “black soil”, developed from the pedosediment of a Luvisol as inferred from the observed micromorphological features of three profiles of a catena.

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REFERENCES

- Avery BW, Bascomb CL. 1974. Soil survey Laboratory Methods. Harpenden, Hertfordshire (United Kingdom): Rochamsted Experimental Station.
- Bullock P, Federoff N, Jongerius A, Stoops G, Tursina T, Babel U. 1985. Handbook for Soil Thins Section Description. Wolverhampton (United Kingdom): Wayne Research Publications.
- Castilla-Hernández ME, Tejero-Diez JD. 1987. Flora y vegetación del Cerro Gordo (San Juan Teotihuacan) y regiones aledañas, Valle de México, México. Biótica 12:231-255.
- CETENAL. Comisión de Estudios del Territorio Nacional. 1975. Clasificación de Suelos FAO-UNESCO (1970) modificado por CETENAL 1975. México, DF: Secretaría de la Presidencia.
- Courty MA, Goldberg P, McPhail R. 1989. Soils and Micromorphology in Archaeology. Cambridge (Great Britain): Cambridge University Press.
- Dregne HE. 1976. Soils of Arid Regions. Netherlands: Elsevier Scientific Publishing Company.
- Gama-Castro JE, Solleiro-Rebolledo E, McClung E, Villalpando JL, Sedov S, Jasso-Castañeda C, Palacios-Mayorga S, Hernández D. 2005. Contribuciones de la Ciencia del Suelo a la investigación arqueológica: el caso de Teotihuacán. Terra Lat. 23(1):1-11.
- García E. 1988. Modificaciones al sistema de clasificación climática de Köeppen. México: Offset Larios.
- Gutiérrez-Castorena MdC, Effland WR. 2010. Pedogenic and Biogenic Siliceous Features. In: Stoops G, Marcelino V, Mees F, editors. Interpretation of Micromorphological Features of Soils and Regoliths. Amsterdam: Elseiver. p. 109-127.
- Heine K. 2003. Paleopedological evidence of human-induced environmental change in the Puebla-Tlaxcala area (Mexico) during the last 3500 years. Rev Mex Cienc Geol. 20:235-244.
- Hernández JI. 2007. Geología y geomorfología volcánica de la región de los yacimientos de obsidiana de Otumba en el sector norte de la Sierra Nevada de México: México D.F. Universidad Nacional Autónoma de México. Facultad de Filosofía y Letras. Tesis de Licenciatura en Geografía.
- IUSS Working Group. 2006. World Reference Base for Soil Resources 2006. World Soil Resources Reports No. 103. Rome: FAO.
- Kovda I, Mermut AR. 2010. Vertic features. In: Stoops G, Marcelino V, Mees F, editors. Interpretation of Micromorphological Features of Soils and Regoliths. Amsterdam: Elseiver. p. 109-127.

- León-Portilla M. 2005. Aztecas-Mexicas, Desarrollo de una civilización originaria. México: Algaba Ediciones.

- Lounejeva Baturina E, Morales Puente P, Cabadas Báez HV, Cienfuegos Alvarado E, Sedov S, Vallejo Gómez E, Solleiro Rebolledo E. 2006. Late Pleistocene to Holocene environmental changes from $_{13}$C determinations in soils at Teotihuacán, Mexico. Geofís Int. 45(2):85-98.

- Lozano-García S, Ortega-Guerrero B, Caballero-Miranda M, Urrutia-Fucugauchi J. 1993. Late Pleistocene and Holocene paleoenvironments of Chalco lake, central Mexico. Quaternary Res. 40:332-42.

- Lozano-García S, Vázquez-Selem L. 2005. A high-elevation Holocene pollen record from Iztaccíhuatl volcano, central Mexico. Holocene 15(3):329-338.

- McClung de Tapia E, Solleiro-Rebolledo E, Gama-Castro JE, Villalpando JL, Sedov S. 2003. Paleosols in the Teotihuacán Valley, Mexico: Evidence for paleoenvironment and human impact. Rev Mex Cienc Geol. 20:270-282.

- McClung de Tapia E, Domínguez Rubio I, Gama Castro J, Solleiro E, Sedov S. 2005. Radiocarbon dates from soil profiles in the Teotihuacán Valley, Mexico: indicators of geomorphological processes. Radiocarbon 47(1):159-175.

- Ortega-Guerrero B, Thompson R, Urrutia Fucugauchi J. 2000. Magnetic properties of lake sediments from Lake Chalco, central Mexico, and their palaeoenvironmental implications. J Quaternary Sci. 15:127-140.

- Rivera-Uria MY, Sedov S, Solleiro-Rebolledo E, Pérez-Pérez J, McClung E, González A, Gama-Castro J. 2007. Degradación ambiental en el Valle Teotihuacán: evidencias geológicas y paleopedológicas. Bol Soc Geol Mex. 59(2):203-217.

- Rouiller J, Jeanroy E. 1971. Resumé de quelques techniques de Pédologie Generale. Nancy: Centre de Pédologie Biologique du C.N.R.S.

- Rzedowski JG, Guzmán A, Hernández Muñiz C. 1964. Cartografía de la vegetación de la parte norte del Valle de México. Anales de la Escuela Nacional de Ciencias Biológicas 13:31-57.

- Sánchez-Pérez S, Solleiro-Rebolledo E, Sedov S, McClung de Tapia E, Golyeva A, Prado B, Ibarra-Morales E. 2013. The Black San Pablo paleosol of the Teotihuacán Valley, Mexico: pedogenesis, fertility, and use in ancient agricultural and urban systems. Geoarchaeology 28:249-267.

- Sanders WT, Parsons JR, Santley RS. 1979. The basin of Mexico. Ecological processes in the evolution of a civilization. New York: Academic Press Inc.

- Sedov S, Solleiro-Rebolledo E, Gama-Castro JE. 2003. Andosol to Luvisol evolution in Central Mexico: timing, mechanisms and environmental setting. Catena 54(3):495-513.

- Sedov S, Rivera Y, Solleiro E. 2009. Holocene paleoecology of Teotihuacán, Mexico: Micromorphological evidences from alluvial paleosols and pedosediments. Frankfurter Geowissenschaftliche Arbeiten Serie D Physische Geographie 30:123-131.

- Sedov S, Lozano-García S, Solleiro-Rebolledo E, McClung de Tapia E, Ortega-Guerrero B, Sosa-Nájera S. 2010. Tepexpan revisited: A multiple proxy of local environmental changes in relation to human occupation from a paleolake shore section in Central Mexico. Geomorphology 122(3-4):309-322.

- Soil Survey Division Staff. 1993. Soil Survey Manual. Soil Conservation Service. U.S. Department of Agriculture Handbook 18.

- Solleiro-Rebolledo E, Sedov S, McClung de Tapia E, Cabadas H, Gama-Castro J, Vallejo-Gómez E. 2006. Spatial variability of environment change in the Teotihuacán Valley during the Late Quaternary: Paleopedological inferences. Quatern Int. 156-157:13-31.

- Solleiro-Rebolledo E, Sycheva S, Sedov S, McClung de Tapia E, Rivera-Uria Y, Salcido-Berkovich C, Kuznetsova A. 2011. Fluvial processes and paleopedogenesis in Teotihuacán Valley, Mexico: Responses to the late Quaternary environmental changes. Quatern Int. 233:40-52.

- Stoops G. 2003. Guidelines for the Analysis and Description of Soil and Regolith Thin Sections. Madison, Wisconsin: Soil Science Society of America Inc.

- Tapia-Varela G, López-Blanco J. 2002. Mapeo geomorfológico analítico de la porción central de la cuenca de México: unidades morfogenéticas a escala 1:100 000. Rev Mex Cienc Geol. 19(1):50-65.

- Watts WA, Bradbury JP. 1982. Paleoecological studies at Lake Patzcuaro on the West-Central Mexican Plateau and at Chalco in the Basin of Mexico. Quaternary Res. 17:56-70.