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Terraces and landscape in Mixteca Alta, Oaxaca, Mexico: Micromorphological indicators

Terrazas y paisaje en la Mixteca Alta, Oaxaca, México: indicadores micromorfológicos
Terraços e paisagem em Mixteca Alta, Oaxaca, México: indicadores micromorfológicos

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ABSTRACT

In the semi-arid Mixteca Alta, Mexico, complex societies developed sophisticated terrace systems to control erosion and improve rain-fed agriculture. Knowledge regarding the agricultural systems has been crucial in understanding landscape construction through cultivation and social complexity. In this study six sequences on terrace systems were investigated. The samples were analyzed for bulk chemical, textural and micromorphological observations. Soils developed on terraces of the Yanhuitlán river (sequences Y04 and Y05) were dated, respectively, 5,300, 2,700 and 1,100 cal BP, suggesting a possible anthropic use since the early Formative period. These soils are composed of microstratified fine sediments of local origin, reflecting low energy during their deposition; they are weakly structured and developed in anoxic conditions due to saturation during terrace flooding. However, in these soils, a mixture of silt particles and charcoal fragments suggests the influence of anthropic use. On the other hand, sequences Y01 and Y02 are Pleistocene soils developed in an anoxic environment of a swampy landscape; their vertic properties may be related to dry seasonal periods. Knowledge of landscape genesis contributes to the assessment of anthropic impact in the area.

RESUMEN

En la Mixteca Alta, México, hubo sociedades complejas que desarrollaron sofisticados sistemas de terrazas para controlar la erosión y mejorar la escasez de agua durante las prácticas agrícolas. El conocimiento acerca de los sistemas agrícolas ha sido crucial para comprender la construcción del paisaje a través del cultivo y la complejidad social. En este estudio se investigaron seis secuencias pedoestratigráficas en un sistema de terrazas. Las muestras se analizaron para obtener datos químicos, físicos y observaciones micromorfológicas. Los suelo desarrollados en las terrazas del río Yanhuitlán (Y04 y Y05) fueron fechados, respectivamente, en 5300, 2700 y 1100 años cal AP, sugiriendo un posible uso antrópico desde el periodo Formativo inferior. Estos suelos se componen de sedimentos finos microestratificados de origen local, lo que refleja baja energía durante su depósito; están débilmente estructurados y se desarrollaron bajo condiciones anóxicas debido a la saturación durante la inundación de la terraza. Sin embargo, en estos suelos la mezcla de partículas de limo con fragmentos de carbón sugiere su uso antrópico. Por otro lado, las secuencias Y01 y Y02 son suelos pleistocénicos desarrollados en un ambiente anóxico de un paisaje pantanoso; sus propiedades vérticas se pueden relacionar con periodos secos. El conocimiento sobre la génesis del paisaje contribuye a evaluar el impacto antrópico en esta región.

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RESUMO

Na região semi-árida da Mixteca Alta, México, sociedades complexas desenvolveram sistemas de terraços sofisticados para controlo da erosão e melhorar as práticas de agricultura de sequeiro. O conhecimento dos sistemas agrícolas tem sido crucial para compreender a construção da paisagem através do cultivo e da complexidade social. Neste estudo foram investigadas seis sequências pedoestratigráficas num sistema de terraços. As amostras foram analisadas para obtenção de dados químicos, físicos e de micromorfologia. Os solos desenvolvidos nos terraços do rio Yanhuitlán (sequências Y04 e Y05) foram datadas, respetivamente de 5300, 2700 e 1100 anos BP, sugerindo um possível uso antrópico desde o período Formativo inferior. Estes solos são compostos por sedimentos finos microestratificados de origem local, refletindo baixa energia durante o seu depósito; estão fracamente estruturados e desenvolveram-se em ambiente anóxico devido às condições de saturação durante a inundação do terraço. Contudo, nestes solos, a mistura de partículas de limo com fragmentos de carvão sugere a influência do uso antrópico. Por outro lado, as sequências Y01 e Y02 correspondem a solos plistocénicos desenvolvidos em ambiente anóxico de uma paisagem pantanosa; as suas propriedades vérticas podem estar relacionadas com períodos secos sazonais. O conhecimento da génese da paisagem contribui para avaliar o impacto antrópico na área.

KEY WORDS
Paleoenvironments, soils, alluvial sediments, cultural landscape.

PALABRAS CLAVE
Paleoambientes, suelos, sedimentos aluviales, paisaje cultural.

PALAVRAS-CHAVE
Paleoambientes, solos, sedimentos aluvionares, paisagem cultural.

1. Introduction

Ancient agricultural terraces research, and its associated soils, suggests an understanding of anthropic environmental change at landscape level (Sandor 2006; Bal et al. 2010). Terrace agriculture is present in many elevated terrains; for millennia, terraces developed as cultural artefacts to capture water, soils and sediments along hillsides or across drainage channels (Donkin 1979).

Terracing has been studied from several perspectives, including geoarchaeological and sedimentary analyses (e.g. soils mineralogy, paleobotany and absolute dating methods). In Greece and southeastern France, Poupet (2000) and Harfouche (2007) developed pedological studies in an archeological context to characterize agricultural terrace systems. In the eastern French Pyrenees, Bal et al. (2010) and Rendu et al. (2015) studied terrace paleosols to reconstruct, through carbon dating, Neolithic agropastoral activities. In Italy, Nisbet (1983) studied terrace soils on the basis of micromorphology of paleosols, phytoliths and carbon dating. In Jawa, Jordan, Meister et al. (2017) used a multi-proxy approach to characterize Bronze-age agricultural systems.

In Latin America, in the Peruvian Andes, Sandor and Eash (1991, 1995) and Sandor (2006) reconstructed the agricultural history of the Colca valley using paleopedology and carbon dating. In the Peruvian Chicha-Soras valley, Kemp et al. (2006) studied a paleosol sequence to establish the succession of use, abandonment and reconstruction of terraces along time. In the Tafi valley, Argentina, Vattuone (2000) identified agricultural terrace systems that contributed to landscape stability and distribution of water resources. In Morelos, Mexico, Smith and Price (1994) developed stratigraphic and soil chemical analyses to understand agricultural intensification on valley-bottom terraces during the Aztec period.

In brief, it has been shown that anthropic transformations have significantly influenced the landscape in ancient agricultural regions. In this context, the Mixteca Alta, Mexico, is important, because its density of archaeological and current terrace systems allows the dynamics of such transformations to be reconstructed.

1.1. The Mexican Mixteca Alta

The Mexican Mixteca Alta is a crucial Mesoamerican region of high hills and semiarid landscapes, where complex societies developed large urban centers and intensive agricultural systems (Kirkby 1972; Mueller et al. 2012). Intensification of agriculture in the region has been of great research interest because of the relationship between societies and their environments, particularly the cultural and technological innovations that reflect a strong human adaptation to changing and variable environmental conditions (Mueller et al. 2012; Pérez-Rodríguez 2016).

1.1.1. Climatic history of the Mixteca Alta

The change to interglacial conditions (Late Pleistocene-Early Holocene transition) implicated an adjustment from arid to humid conditions and the subsequent increase in the streams' discharge (Borejsza and Frederick 2010). In Puebla and Tlaxcala, central Mexico, the transition involved the development of hydromorphic pedogenetic conditions and humus accumulation (Borejsza and Frederick 2010; Solis-Castillo et al. 2012), while in Oaxaca, the hydromorphic conditions were accompanied by secondary carbonate accumulation (Mueller et al. 2012). In both regions, strong valley incision was followed by rapid sedimentation.

During the Early and Middle Holocene (10,200-3,300 cal BP) there was a trend to more arid conditions; despite this, strong rainfall events occurred, triggering a high stream discharge around 5,000 cal BP, and instability of floodplains, particularly in Tlaxcala (Borejsza and Frederick 2010; Solis-Castillo et al. 2012) and Oaxaca (Mueller et al. 2012). Drier Holocene conditions occurred around 1,000 cal BP; here, the records of such conditions are modified by the increase of human activities, especially with the construction of urban areas and the onset of intensive agriculture.

1.1.2. Ancient settlements and agriculture

From Mid-Late Formative period (300 cal BP) until now, sophisticated agricultural valley-bottom terrace systems (*lama-bordos*) have contributed to efficient water management and erosion control (Muller at al. 2012; Pérez-Rodríguez and Anderson 2013; Leigh et al. 2013). Because of their long-standing operation according to the archaeological record (Pérez-Rodríguez 2016), the *lama-bordo* systems are regarded as effective agricultural technologies for people's livelihoods and soil conservation, closely embedded in the development of complex societies. Nonetheless, agricultural intensification has sometimes adversely affected the landscape (Kirkby 1972; Mueller et al. 2012; Pérez-Rodríguez and Anderson 2013).

The Verde River changed from a meandering to a braided stream, following an increase in sediment yield from the agricultural fields of the Verde River basin between 2,400 and 2,100 cal BP (Joyce and Mueller 1992; Mueller et al. 2012). Likewise, macroscopic determination of charcoal in sediments has been associated to change in the distribution of human settlements and their relation with land use along the Viejo River (Goman et al. 2010). The abandonment of locations during the late Postclassic along the Verde River plain is reflected in the absence of macroscopic concentrations of charcoal and the low enrichment of the carbon isotope values in the sediments of Pastoría Lagoon (Goman et al. 2005).

In Nochixtlán valley, the construction of terraces to catch water and eroded soil increased during the Natividad period (1,620-900 cal BP). As a result, erosive events taking place approximately 1,000 yr BP associated to agricultural expansion during the Post-Classic period (Kirkby 1972; Mueller et. al. 2012). In the Verde River valley, agriculture began approximately 4,800 cal BP, and anthropic modifications to the alluvial plains took place as a result of agricultural intensification, 2,500 cal BP (Joyce and Goman 2012; Goman et al. 2010). The quick erosion that resulted from intensive agriculture is apparent in the alluvial deposits of the Nochixtlán Valley (Mueller et al. 2012) and in the drainage pattern of the Verde River (Joyce and Mueller 1992).

It has been suggested (Mueller et al. 2012) that landscape instability processes in the Nochixtlán valley have followed changes in environmental conditions some 10,300 cal BP, and that in response to a dry, warm and seasonal climate flood-plains became unstable. Despite this they afforded, from 4,000 cal BP onwards, a favorable niche for sedentary agriculturalists who built terraces to trap soils, sediments and humidity, and to develop agriculture (Mueller et al. 2012).

The above considerations suggest several questions: Which are the peculiar patterns of the soils developed in terraces? Under which environmental conditions are those soils developed? Is it possible to differentiate degrees of land use in the terraces? These questions have guided the course of this research.

2. Material and Methods

2.1. Study area

Paleopedology records were studied in agricultural terraces (*lama-bordos* and contour terraces) within the alluvial sedimentary sequences along the Yanhuitlán river (**Figure 1**), in Santo Domingo Yanhuitlán, Nochixtlán District, some 70 km NW of Oaxaca city. The area is covered by igneous and sedimentary rocks from the Paleozoic to the Quaternary (Ferrusquía 1970). Quaternary deposits influence relief development, particularly in the erosion cycle: the Yanhuitlán Basin is bounded at the west by the Cieneguillas fault system (that affects a plutonic rock group generating a tectonic block series), and at the east by the cuesta landscape of the Yanhuitlan Formation from the Tertiary (Ferrusquía 1970).

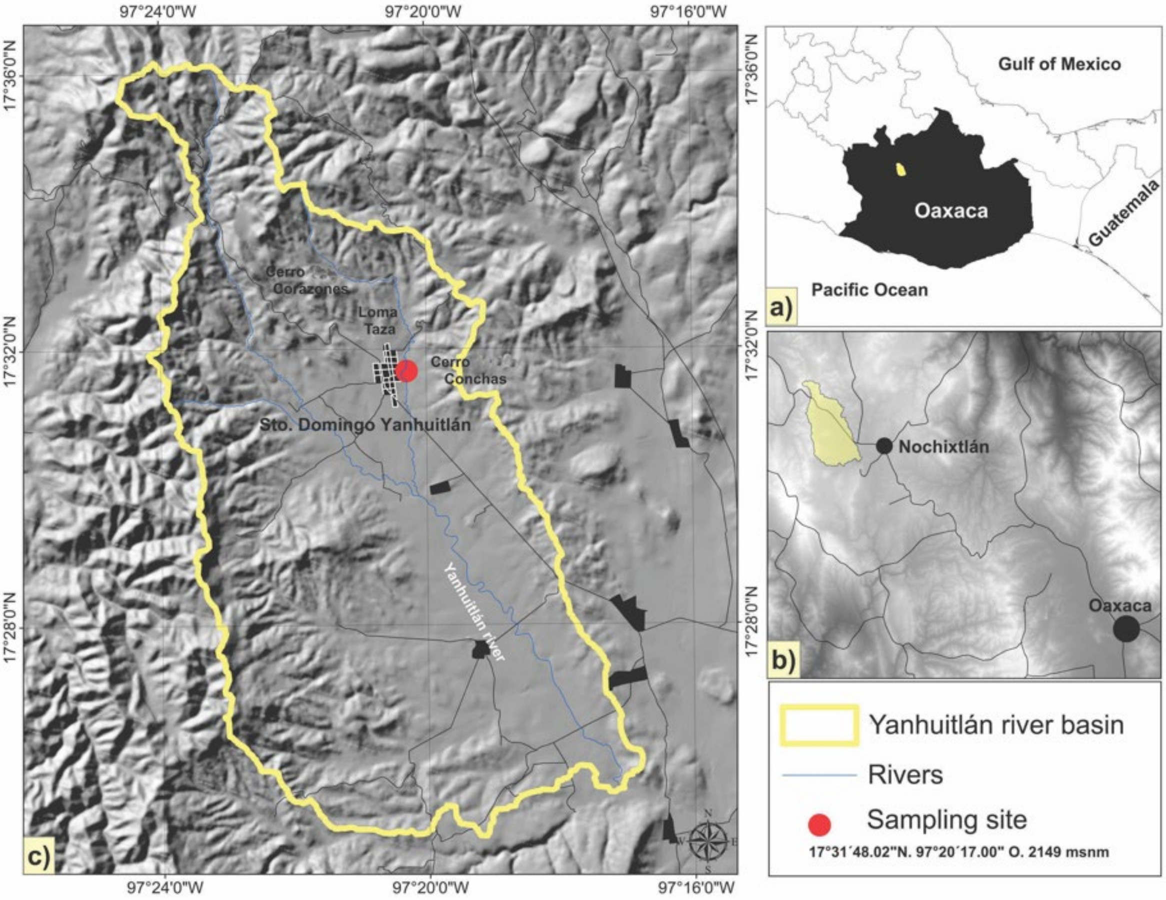


Figure 1. Study area within the Mixteca Alta, Mexico; a) Location Oaxaca on Mexico; b) Geographic location of Yanhuitlán river Basin with respect to Oaxaca and Nochixtlán cities; c) Yanhuitlán river Basin, location of Santo Domingo Yanhuitlán and sampling site.

Yanhuitlán relief is characterized by elongated and rounded hills with extensively dissected slopes. The streams form narrow valleys and deep canyons with headward erosion. The drainage pattern is controlled by the dip of the Yahuitlán Formation (basically horizontal strata); it is dendritic and occasionally radial, in this last case, surrounding plutonic bodies present in the area (Schlaepfer 1976). At the regional level, drainage is asymmetric.

The climate is subhumid temperate with summer rains (Cw) (García 2004), with an annual average temperature of 15 °C and an annual average (summer) precipitation of 650 mm (Yanhuitlán weather station). Land use is agricultural, including grazing for cattle and occasionally goats and rain-fed, subsistence crops.

Major vegetation types are scrubland and grassland, with some forest relicts on the lowlands. Pine-oak mixed forest of secondary origin is present in the highlands; primary relicts are rare. Soils reported for the area are Cambisols, Leptosols, Luvisols, Regosols and Vertisols (INEGI 2014). Ongoing soil erosion is severe; causes are the abandonment of terrace systems, overgrazing, and degradation of pasturelands (Contreras-Hinojosa et al. 2005).

2.2. Cultural landscapes

Lama-bordo systems in the Yanhuitlán valley are distributed along the drainage systems of El Jazmín, Los Corazones, Loma Taza, Las Canicas and Las Conchas hills (**Figure 1**). Geomorphologic survey helped identify four step-like W-SW anthropogenic terraces on the river margin (**Figure 2**). *Lama-bordos* capture slope-controlled overland flow and detritic sedimentation of loamy material. Their minimum age is 3,400-3,500 cal BP (Leigh et al. 2013) but their activity is ongoing. Terraces are delimited by stone walls perpendicular to the main drainage flow at Las Conchas hill (**Figure 2**), where pedostratigraphic analyses have been focused.

2.3. Analysis

The paleopedological records were studied for the agricultural terraces –*lama-bordos*– and contour terraces recognized in the alluvial sedimentary sequences of the Yanhuitlán river. A detailed survey of Holocene pedostratigraphy was carried out in six pedosedimentary sequences along the Yanhuitlán river: Y01, Y02, Y03, Y04, Y05 and Y06.

Terraces were labeled from older to younger as TL4 between 2,220 and 2,215 m a.s.l., TL3 between 2,215 and 2,210 m a.s.l., TL2 at 2,180 m a.s.l., and TL1 between 2,165 and 2,160 m a.s.l. (**Figure 2**). *Lama-bordos* are located across drainage channels, while contour terraces have been built across hillsides; all of them are perpendicular to the main drainage.

Soils and paleosols were described following the International Union of Soil Sciences (IUSS Working Group WRB 2015) and Retallack (1990). Twelve thin sections were obtained from undisturbed soil samples. Soil samples were collected following Stoops (2003), from exposed sequences following severe erosion. Sampling sites consider the association with archeological terraces and the detection of paleosols. Samples were collected from composed sequences; terrace TL4 corresponds to sequences Y01, Y02 and Y03; terrace TL3 corresponds to sequence Y04; terrace TL2 corresponds to sequences Y05 and Y06. Surficial soil was described in terrace TL1. Samples from genetic soil horizons were subjected to chemical and physical analyses. Laboratory analyses focused on properties associated with persistent soil characteristics.

Particle size distribution was determined by measuring the differences in the sedimentation rate of the particles and by pipette (Rouiller and Jeanroy 1971; Avery and Bascomb 1974). Each soil subsample (30 gr) was saturated with sodium hexametaphosphate $(NaPO_3)_6$. The sands were determined by wet sieving, and the clay and silt fractions were separated by sedimentation.

Carbonate contents were determined by weight difference after dissolution with HCl. Samples were oven-dried at 105 °C for 72 h, weighed and treated with 25 ml HCl to decompose carbonates.

Organic matter content and percentage of organic carbon were determined following the

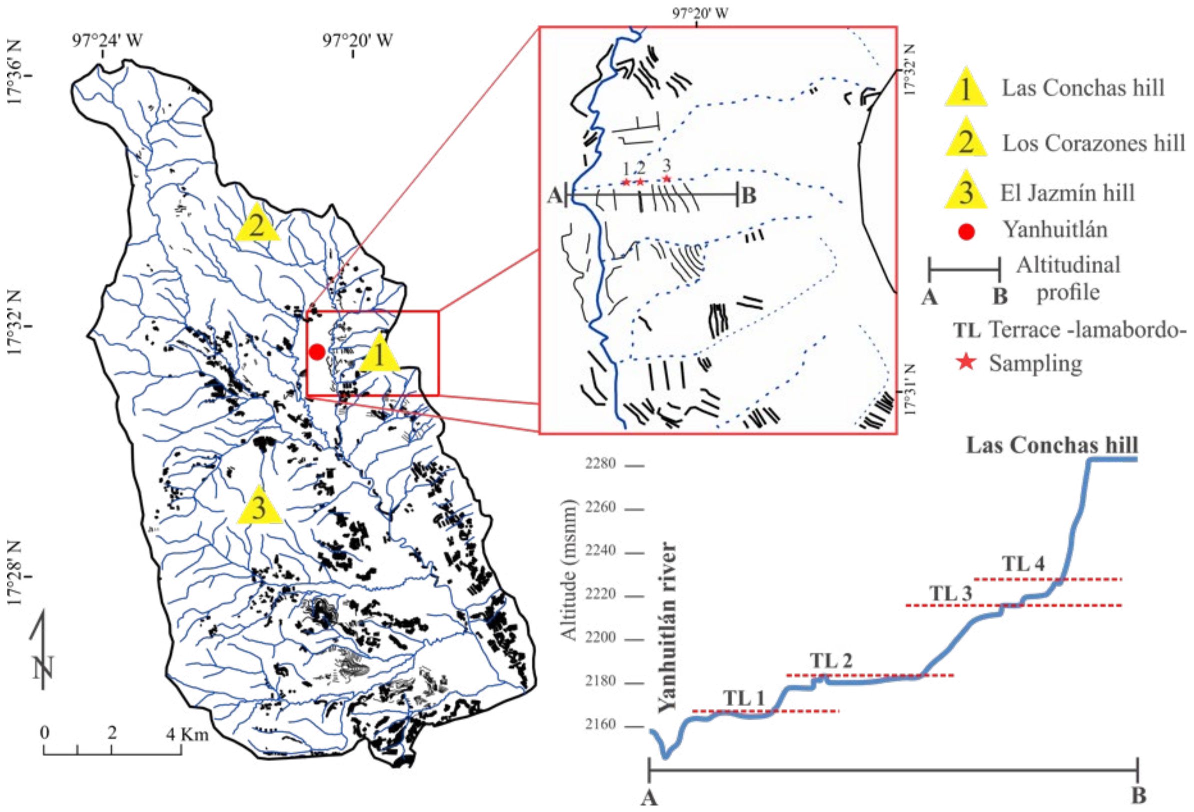


Figure 2. Sampling points: a) Yanhuitlán river Basin; distribution of *lama-bordos* and terraces associated with secondary streams; b) Sequences Y01–Y06 as related to the terrace systems at valley bottoms.

Walkley and Black method (Nelson and Sommers 1982). To measure pH, a 10 g soil sample was added to distilled water at 1:2.5 and agitated for 30 minutes; after sedimentation, pH was measured with a potentiometer Conductronic pH120.

Thin sections for determination of micromorphology were prepared from undisturbed samples impregnated with epoxy resin Crystal MC40 with a 1.65 refraction index; air was extracted in a vacuum chamber at 24 bar for 15 minutes. Once solid state was obtained (using an electric grill Termoline), sections of 5 x 4 x 1 cm were cut and polished (abrasive 100, 200, 400 y 1000) to a thickness of 30 micrometers. Sections were further studied under petrographic microscope following Bullock et al. (1985) and Stoops (2003).

Radiocarbon dating of the charcoal fragments extracted from A horizons was carried out at ICA Laboratories in Miami, Florida, and is reported as calibrated ages following CALIBRadiocarbon Calibration 7.0 (Stuiver and Reimer 1993; Stuvier et al. 2014).

3. Results

3.1. Morphology and selected analytical properties of the soils

The Yanhuitlán pedostratigraphic section is characterized by six profiles (**Figures 3 and 4**); the most representative morphological characteristics are mentioned following in stratigraphic order (for details see **Table 1**).

Profile Y01 is composed of 17Bw/17Bwg horizons; both horizons have a 7.5YR 4/6 color in the matrix, carbonate concretions, vertic properties and 7.5YR 3/6 mottles. No A horizons were found, probably removed by erosive processes.

Sequence Y02 (**Figure 4**) is formed by 16Ass/16Bw/16Bk horizons. 16Ass has a 10YR 4/1 color, presents gradual limits with 16Bw, an angular blocky structure, evidence of roots, vertic features, carbonate concretions, and is hard

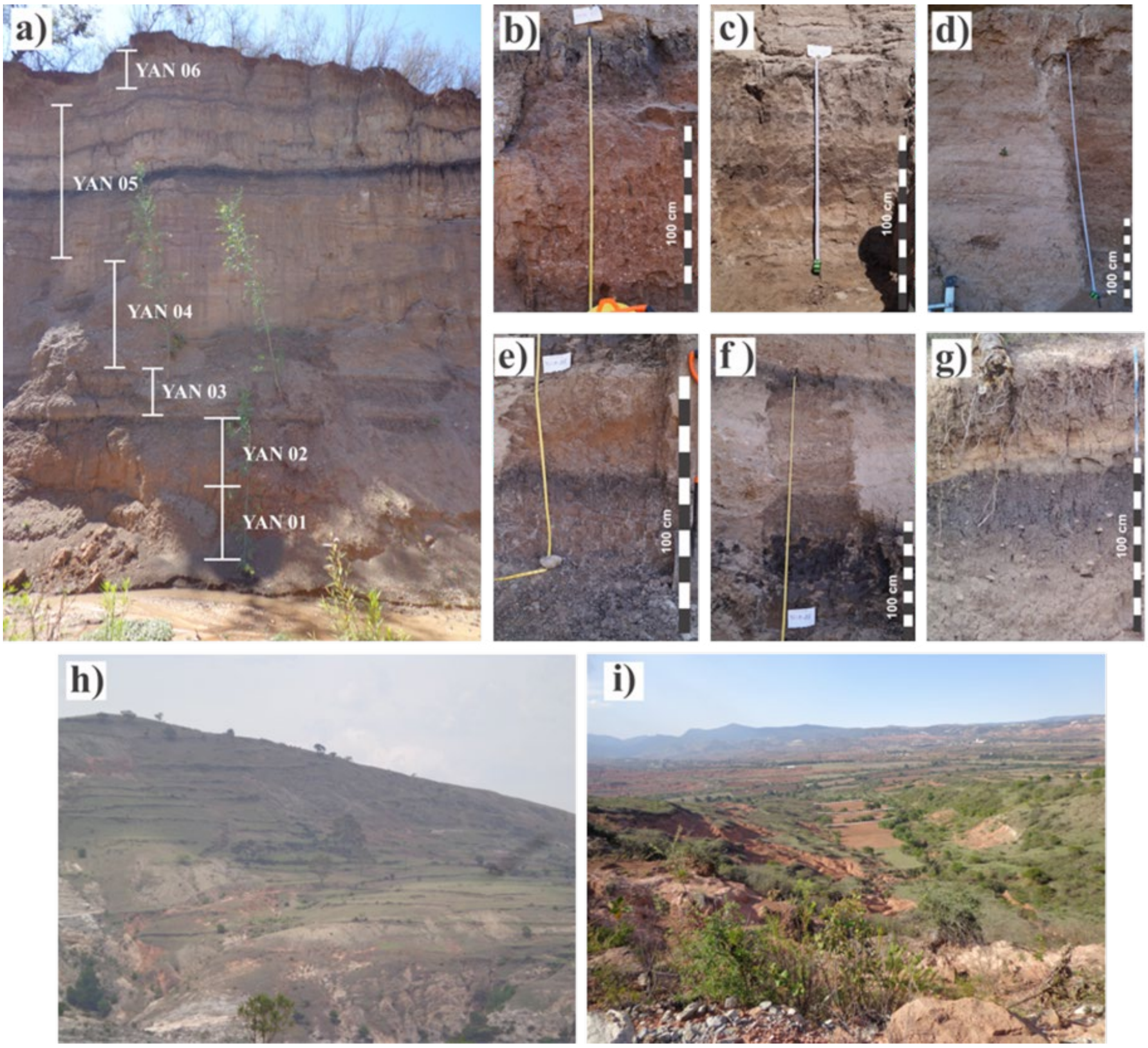


Figure 3. Paleosols in agricultural terraces. (a) Alluvial sequences of Yanhuitlán River; (b) Pleistocene paleosols; (c) Early Holocene paleosols; (d) Alluvial sediments; (e) Middle Holocene paleosols; (f) Soil development 5,000 cal BP (in the lower part); (g) Late Holocene paleosols; (h) Countour terraces in cerro Las Conchas. Valley bottom terraces; (i) View of soils from Corazones hill.

and compact. 16Bw has a 7.5YR 5/3 color with columnar structure, is more clayey and has a higher carbonate concentration. Horizon 16Bk has a 7.5YR 5/2 color, is angular blocky and clayey with prismatic structure and carbonate concretions (ca. 3 cm).

Profile Y03 (Figure 4) is the sequence with the largest number of paleosols, and has been interpreted as several pedogenetic phases interrupted by alluvial sedimentation. This profile is made up of several soil development cycles with a succession of A/AC horizons; it has large numbers of charcoal fragments and high content of carbonates. The phase of human occupation as depicted in the paleosols is separated from the soils formed during the Pleistocene-Holocene by a 230 cm accumulation of alluvial sediments.

Sequence Y04 is formed of alluvial strata; it has a massive sandy texture with a high content of carbonates in the soil matrix. The sediments between 684 and 784 cm have a laminar structure; the sediments between 784-824 cm present a cross-bedding structure. Mainly composed by fine sand.

Table 1. Morphological descriptions and selected chemical properties of the studied paleosols in Yanhuitlán

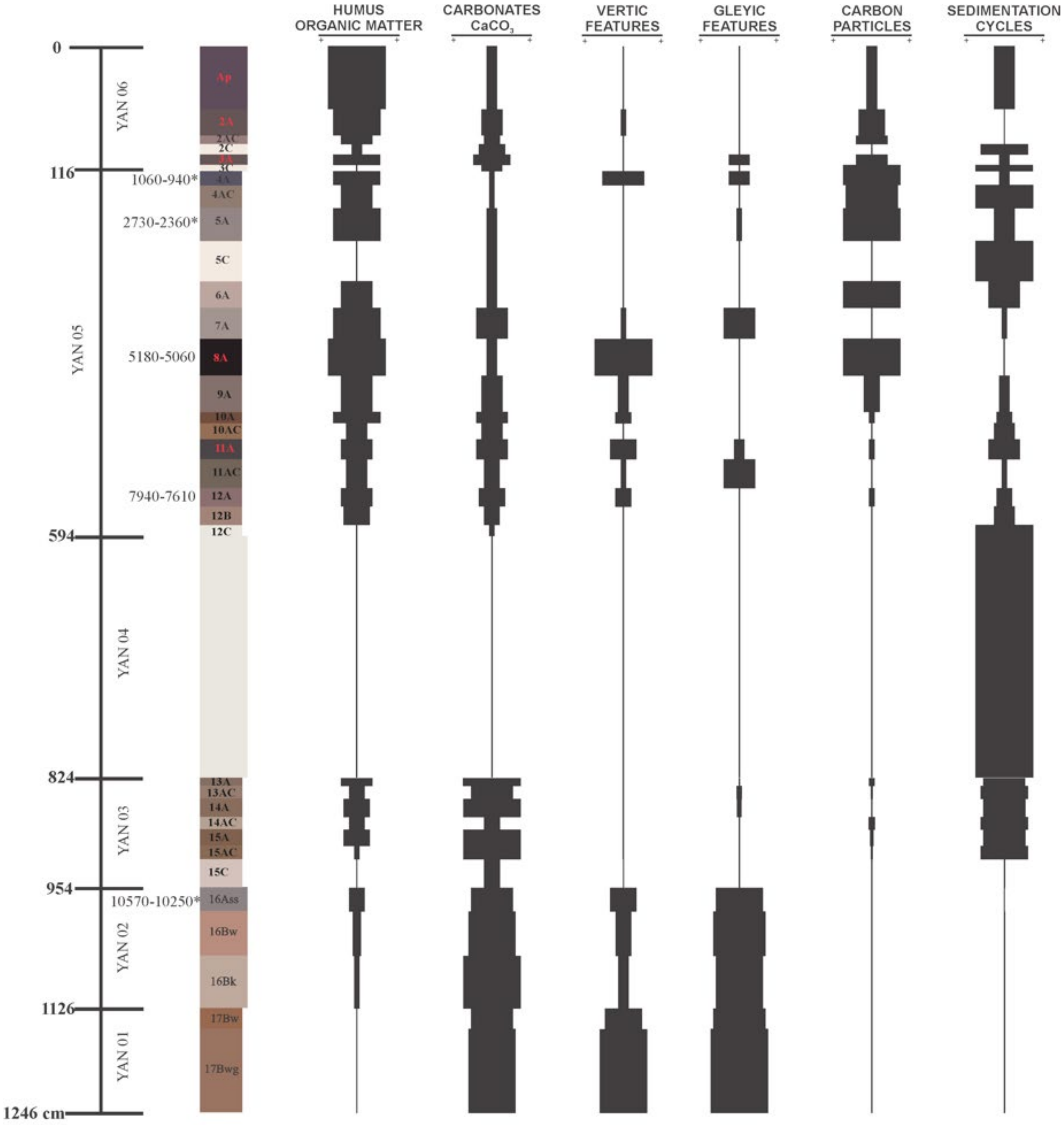
Sequence	Profile/ Horizon	Depth (cm)	Color	pH	Carbonate (%)	Organic Carbon (%)	Age/Cultural period	Features
Y06	Ap	0-6	7.5YR 5/4	8.11		0.12	Recent	Subangular structure, aggregates of fine to medium size, friable, large amount of biopores and carbonate in the matrix, the limit with the lower horizon is diffuse and has a clayey texture.
	2A	60-85	10YR 5/1	8.40	18.05	0.79		Columnar structure that breaks to subangular blocky and carbonate concretions, most aggregate stability from thickness to moderates, bipores, root traces and carbonate in matrix.
	2AC	85-93	10YR 4/3	8.49	19.30	0.67		Columnar structure that is broken to subangular blocky and carbonate concretions.
	2C	93-103	2.5Y 5/2	8.50	27.25	0.53		Pedosediment with soil fragments and rock fragments, carbonate concretions and slickensides.
	3A	103-113	10YR 6/2	8.69	29.00	0.79		Without structure, brown, low in organic matter and carbonate.
	3C	113-116	10YR 6/2	8.56	23.60	0.53		Alluvial sediments with carbonate concretions.
Y05	4A	116-151	10YR 4/3	8.10	15.20	0.46	**1060-940* Classic "Late Las Flores"**	Dark brown, gray spots, root traces, biopores, rock fragments (3 mm), a lot of carbon particles, some thin argillans and an angular almost columnar structure.
	4AC	51-170	10YR 5/2	8.32	15.25	0.46		Alluvial sediments composed of sands and pebbles; brown.
	5A	170-208	10YR 6/2	8.31	16.35	0.46	**2730-2360* Formative "Early Ramos"**	Sand texture, black carbon particles, root traces, pore filling with red clays, subangular structure and friable. Black carbon particles.
	5C	208-256	10YR 6/2	8.51	16.25	0.31		Alluvial sediments composed of pebbles.
	6A	256-286	10YR 6/2	8.50	16.20	0.39		Sand texture, black carbon particles, pores, black carbon fragments, small blocky structure, brown.
	7A	286-316	10YR 6/1	8.48	25.90	0.39		Subangular blocky structure, silty clay texture, gray spots, root traces.
	8Ass	316-356	10YR 4/1	8.09	13.30	0.39	**5300-5190 (43.1%) 5180-5060 (52.3%) "Archaic"**	Dark color, angular blocky almost columnar structure, clayey, black carbon particles, carbonate concretions, root traces and pores.
	9A	356-400	10YR 6/2	8.31	20.00	0.70		Angular blocky structure, black carbon particles, carbonate concretions, root traces and pores.
	10A	400-415	10YR 6/2	8.23	24.10	0.60		Subangular blocky structure, sandy texture, black carbon particles, slickensides, root traces and pores.
	10AC	415-440	10YR 6/1	8.19	22.00	0.70		Rock fragments (4 cm), root traces, carbonate concretions, black carbon particles and light brown.
	11A	440-466	10YR 5/2	8.42	24.75	0.31		Angular blocky structure, few black carbon particles, carbonate on surface peds and voids. Black carbon particles.
	11AC	466-433	10YR 6/3	8.2	20.08	0.312		Carbonate on biopores, gray mottles, black brown matrix color, subangular blocky structure.
	12A	433-456	10YR 5/2	8.45	17.20	0.23	**7940-7610 "Archaic"**	Blocky angular structure, root traces with red clayey filling, carbonate on ped surfaces, gray reddish spots and carbonate concretions (4 cm).
	12B	456-492	10YR 4/3	8.35	17.09	0.07		Blocky angular structure, root traces, carbonate, sand texture and light brown.
	12C	492-594	10YR 4/2	8.56	17.21	0.39		Sediments with scant soil development.

Sequence	Profile/ Horizon	Depth (cm)	Color	pH	Carbonate (%)	Organic Carbon (%)	Age/Cultural period	Features
Y04	S1	594-684		8.37	11.45	0.46		Alluvial sand sediment without stratification structure and with high cabonate content.
	S2	684-784		8.67	19.05	0.42		Alluvial sediment with laminar stratification.
	S3	784-824		8.57	16.35	0.42		Alluvial sand sediment with cross stratification and redeposited soil.
Y03	13A	824-845	10YR 5/2	8.15	9.90	0.62	**10570-10250* "Early Holocene"**	Organic matter increase, subangular blocky structure, light brown spots, roots traces, dark brown matrix and silty clayey texture.
	13AC	845-857	10YR 5/2	8.25	18.04	0.46		Light brown, diminished roots, fine sand and silt fractions, subangular blocky structure and carbonate.
	14A	857-874	10YR 5/2	8.21	19.05	0.78		Higher content of organic matter, some very thin thin argillans are observed, roots traces, particles of black carbon, subangular blocky structure, more clayey, carbonate present.
	14AC	874-885	10YR 6/3	8.34	11.45	0.62		Increased sand content, few roots traces, few carbonate in the matrix, subangular blocky structure.
	15A	885-910	10YR 5/2	8.29	16.25	0.54		Darker than the upper one, clayey, better structure, angular blocks, roots traces with gray mottles, concretions of carbonate, some thin argillans, carbonate associated with the root traces.
	15AC	910-925	10YR 6/2	8.36	17.90	0.78		Sediment with sandy texture and small rocks, few roots traces, without structure, with carbonate and enriched with organic matter.
	15C	925-954	10YR 5/2	8.46	15.70	0.70		Alluvial sediment with crossed stratification and carbonate.
Y02	16Ass	954-989	10YR 4/1	8.04	11.70	2.24		Angular blocky structure, traces of roots, dark brown black, hard, compact, some friction facets, angled structure, specks of reddish brown, concretions of carbonate.
	16Bw	989-1040	7.5YR 5/3	8.16	25.90	0.53		Gradual change from dark brown to light brown, mottled reddish, concretions of carbonate, clay texture, traces of roots.
	16Bk	1040-1126	7.5YR 5/6	8.33	29.30	1.03		Carbonaceous concretions, darker color than the upper one, with presence of roots, friction facets, clayey texture, angular blocky and prismatic structure.
Y01	17Bw	1126-1156	7.5YR 4/4	8.29	26.90	0.46		Angular blocky, clayey, presence of roots, carbonate concretions, friction facets on the surface of the aggregates, carbonate in the soil matrix, light brown mottles, presence of carbonate in the pores and in the matrix.
	17Bwg	1156-1246	7.5YR 4/4	8.27	23.20	0.31		Yellowish mottles, some pores, carbonaceous concretions, root traces, friction facets, roots filled with soil material, mottling increases with depth, structure in reddish angular blocks (7.5YR 4/6).

* Dating reported by Mueller et al. 2012.

Sequence Y05 is composed of eight phases of soil development (labeled 4 to 12) (Figure 4). Paleosol 12 is made up of horizons 12A/12B/12C; 12A has a 10YR 5/2 matrix color, with mottles and carbonate concretions (4 cm). Horizon 12B has an angular blocky structure, contains fewer carbonate concretions and is more clayey; horizon 12C is a loamy strata. Paleosol 4 is conformed by 11A/11AC horizons, and a high concentration of carbon fragments in 11A; carbonates increase in 11AC (Figure 4). The soils formed by horizons 10A/10AC; 10A has a subangular blocky structure with carbonate concretions and charcoal; 10AC has rock fragments.

Soil 9A has a large quantity of carbon, an angular blocky structure and carbonates in the soil matrix. Paleosol 8A is the most representative of Y05, is black, with an angular blocky nearly columnar structure, with carbonate concretions, traces of roots and charcoal.



*Mueller et al., 2012

Figure 4. Stratigraphic scheme of Yanhuitlán paleosols sedimentary sequences and pedogenic features scheme.

Paleosols 6A and 7A are sandy, with a subangular blocky structure. In soil 5A/5C, the horizon 5A has a 10YR 6/2 matrix color, sandy texture with a subangular structure, is friable and contains charcoal particles. In soil 4A/4C, horizon 4A has a 7.5YR 4/1 matrix color, an angular blocky structure, and is compact and hard, with charcoal particles. The Y06 Profile is the Modern soil, Ap/AB/Bwk and paleosols 2A/2AC/2C/3A/3C. These horizons show charcoal and coarse sand of up to 0.5 cm thickness in their C horizons.

Laboratory analyses (**Table 1 and Figure 5**) indicate that paleosol Y01 is loamy with a limited amount of clay (4.7%); carbonate content increases in Bwg (23.2%). Y02 shows an increase in clay at Ass (5.6%) and organic carbon (2.24%). Y02 shows an increase in clay (5.6%) and organic carbon (2.24%) at Ass; in Bk there is an increase in sand (4.2%) and carbonates (29.3%), which coincides with a slightly alkaline pH (8.29) in spite of the increase in organic carbon (2.24-0.53%).

In the sequence Y03 there is an increase in the carbonate content, particularly in horizon 14A (19.05%); the proportion of sands increases in 15A, and also in soils 13 and 14 of the same sequence. Charcoal fragments are oriented following the laminar structure, with a maximum concentration in horizon 5C (1.8%) and 13AC (4.8%); organic carbon content varies between 0.7% and 0.46%. pH values are alkaline, a range of 8.15-8.46.

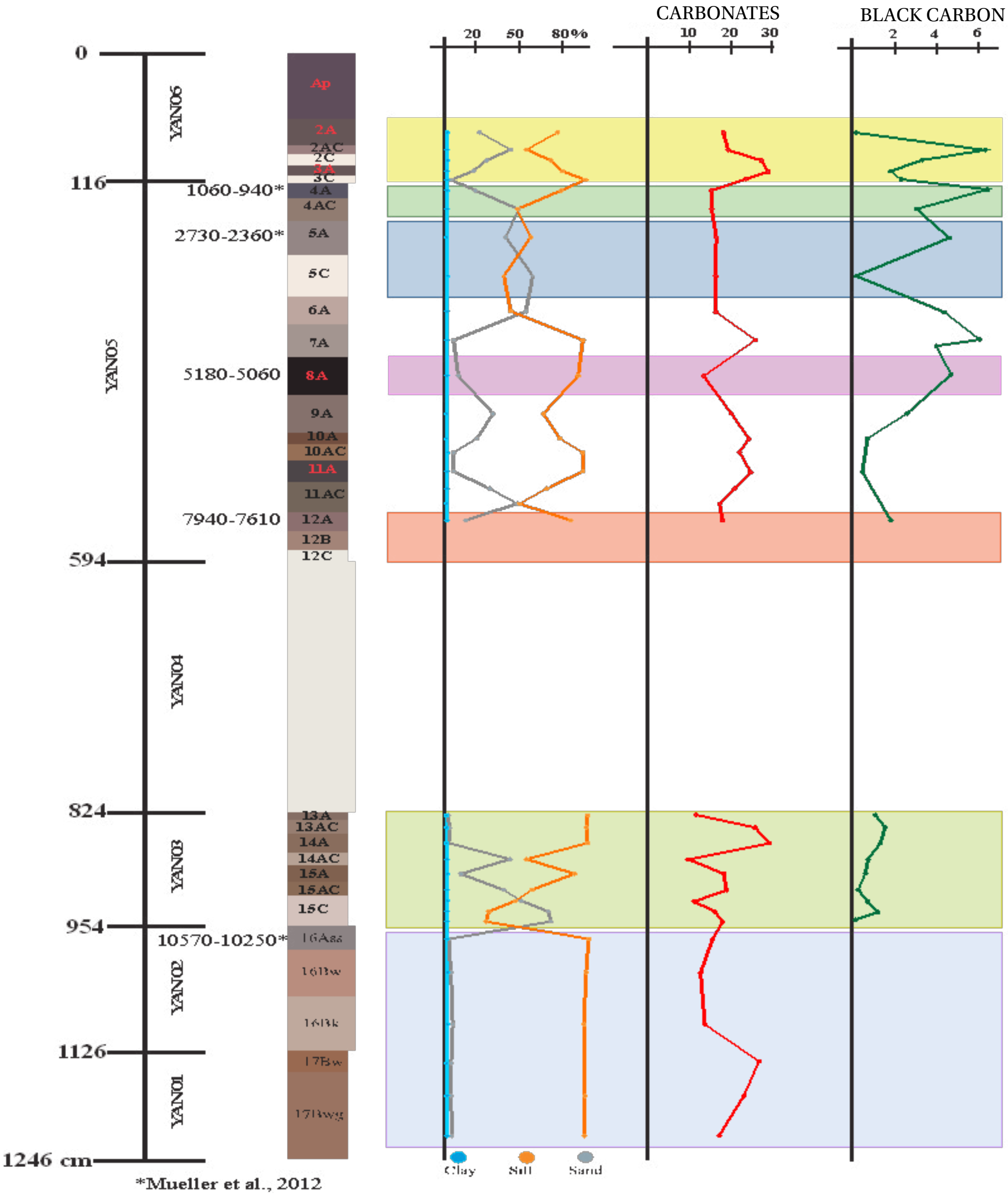


Figure 5. Stratigraphic scheme of Yanhuitlán paleosols sedimentary sequences. Different colors indicate the pedostratigraphic units identified in this study.

In sequence Y04 the sand content increases, the carbonates decrease; at 654 cm macroscopic carbon follows laminar orientation. Carbonate concentrations (19-11%) and pH values (8.37-8.57) are very similar to those of other sequences. In sequence Y05 four zones are easily distinguished. The first, paleosol 12, is characterized by an increase in sand content in horizon 12AB (49.13%) and an increase in carbon particles (0.5%) in the soil matrix in 12A. In the paleosols 10AC and 9A organic carbon content is high (0.7%). Soil 8A of Y05 exhibits a decrease in carbonate content (13.3%). The carbonate content in soil 5 is constant.

3.2. Micromorphological observations

The organic mineral horizons 17Bw and 17Bwg of sequence Y01 have a sandy-loam texture, concentration of sparite carbonate nodules (**Figure 6a**), with organic pigment sand and an incomplete irregular blocky structure that includes sapric organic material (**Figure 6b**) and shells (**Figure 6c**). Also present are calcic hypocoatings of micritic carbonates related to the sinuous pores and channels forming relatively thick coatings that become massive in most of the area. Fe/Mn oxide nodules are abundant (**Figure 6e**). The clayey component includes random striated b-fabric (**Figure 6c**); pyrite framboidal structures are characteristic (**Figure 6f**).

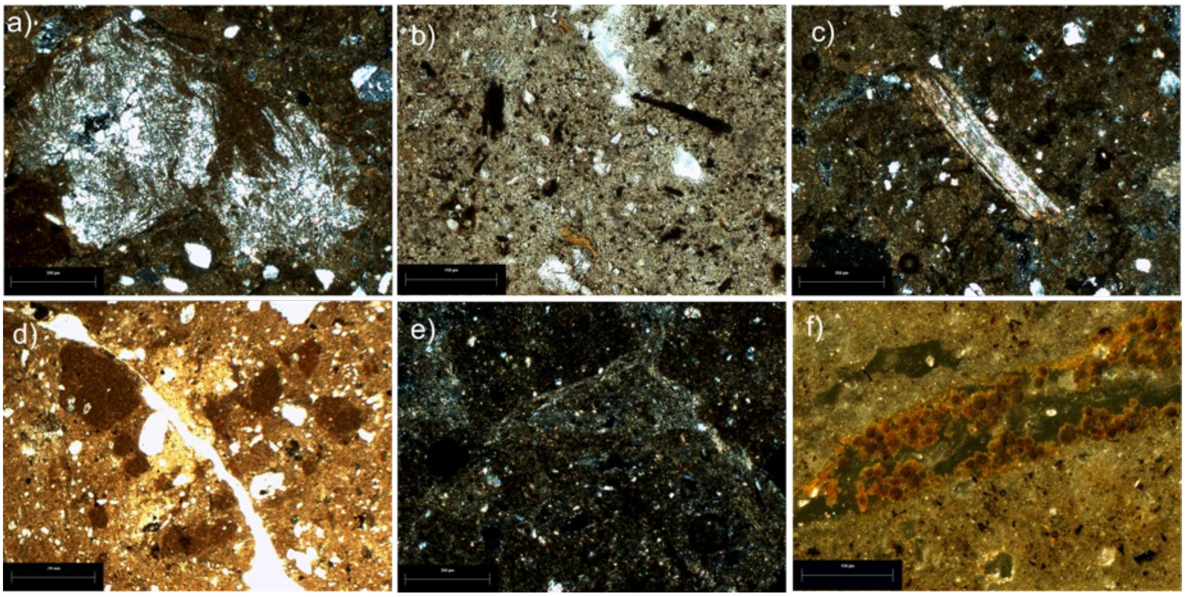


Figure 6. Micromorphology of sections (PPL, plane polarized light; XPL, cross polarized light). (a) Sparite carbonate nodules (XLP in 17Bw horizon); (b) Sapric organic material (PPL in 17Bwg horizon); (c) Fragment of a mollusc shell (XLP in 17Bwg horizon); (d) Fe/Mn oxides nodules with regular outline (PPL in 17Bw horizon); (e) Fractures due to contraction, vertic features (XLP in 17Bw horizon); (f) Pyrite framboidal structures (PPL in 17Bwg horizon).

Micromorphology of the Y02 paleosol section shows a brownish-reddish matrix and irregular Fe/Mn oxide nodules. The structure is irregular blocky; lithogenic carbonates are present in the coarse fraction (**Figure 7a**). Organic horizon 16Ass has sapric organic materials and colloidal material. There is an increase in the neoformation of carbonates on groundmass, as sparite carbonate nodules, and opaline silica-bodies as elongated cells (**Figure 7f**).

The A horizons of sequence Y03 are more sandy, particularly composed of volcanic glass (fragments of weathered pumice) (**Figure 7b**), quartz, fragments of granite; primary carbonates (dolomite) and phytoliths are also present (**Figure 7c**). These soils have a poorly biogenic structure with a composite granular and laminar microstructure (**Figure 7d**), sand lenses and fine material (loams), aggregates of reworked soil fragments, charcoal fragments and bone particles (**Figures 7e, f**).

Sequences Y05 and Y06 have a heterogeneous groundmass. The organic soil 8Ass is a pedal or has a weakly developed laminar microstructure. Clayey components are sometimes oriented but clay accumulation is due to sedimentation. In the 8Ass horizon, strongly decomposed organic material, fine charcoal fragments with sharp boundaries (**Figure 7f**) and coatings of impure clay with null to poor orientation (**Figure 7g**) are observed. Calcitic hypocoatings occur on surfaces of peds and pore systems. In the 5A horizon there are impregnative redox pedofeatures in some zones where oxidized Fe/Mn has accumulated in the matrix as mottling (**Figure 7h**). The Ap horizons are characterized by silty clay groundmass with material rich in organic matter and random striated b-fabric; an angular blocky structure; redox features such as Fe oxide hypocoatings; lithogenic calcite grains can be distinguished in the groundmass and fragments of reworked soils (pedosediment) (**Figure 7i**).

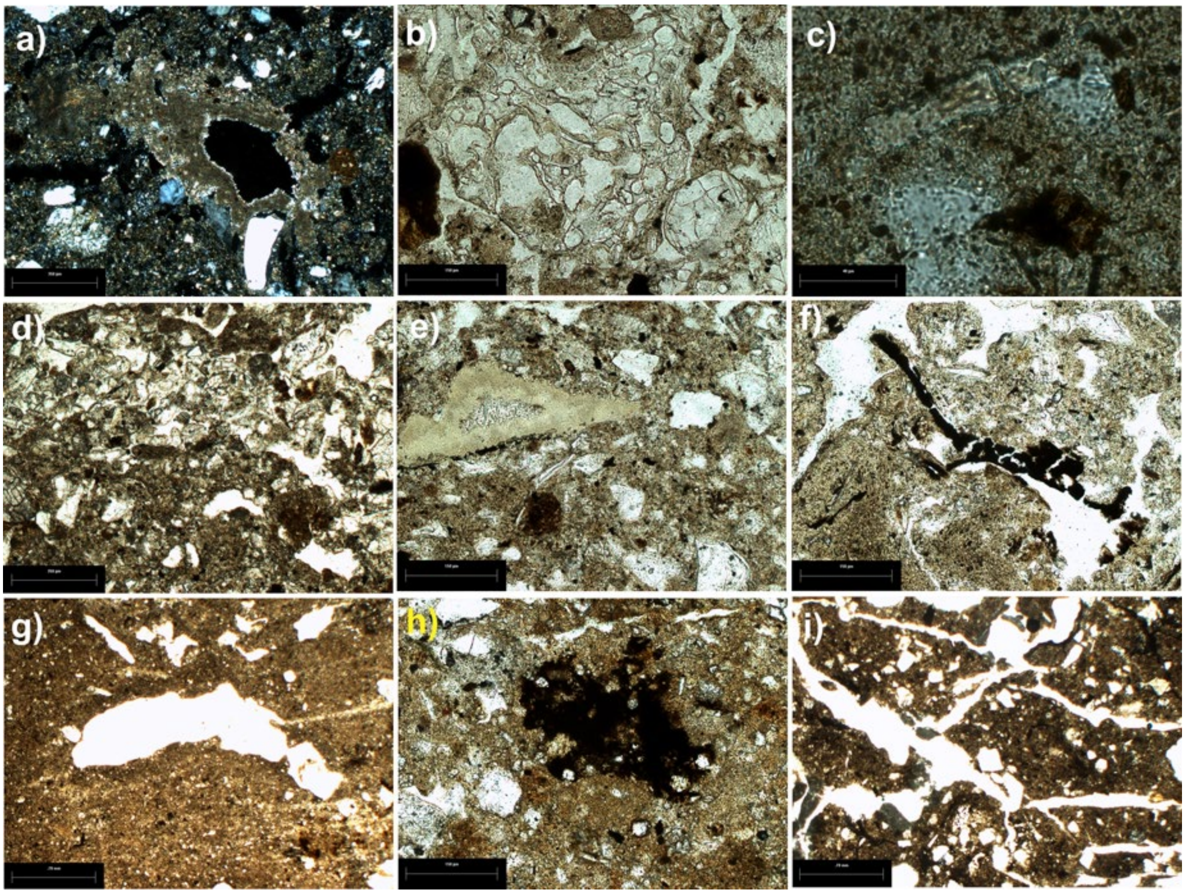


Figure 7. Micromorphology of sections (PPL, plane polarized light; XPL, cross-polarized light). (a) Calcitic hypocoatings (XPL in 15A horizon); (b) Weathered pumice fragment (PPL in 15A horizon); (c) Elongated phytoliths (PPL in 16Ass horizon); (d) Sedimentary features, laminations (PPL in 14A horizon); (e) Fragment of a bone (PPL in 14A horizon); (f) Charcoal fragments (PPL in 8Ass); (g) Impure clay hypocoatings (PPL in 8Ass); (h) Fe/Mn oxide hypocoating (PPL in 5A horizon); (i) planar voids as limits of angular blocky microstructures (PPL in modern soil).

4. Discussion

4.1. Pedostratigraphic correlation

We propose a correlation between the six sections based on the radiocarbon dating and paleosol morphology (**Figure 5**). The red-brown paleosols, which appear welded, (Y01- 02) are the oldest of the study site. The age for these units is estimated on the basis of correlating the alluvial sequences studied by Mueller et al. (2012).

Red-brown soils with dark-brown to black A horizons, with secondary carbonates and prismatic wedge structure, clayey with slickensides, have been dated at the Yanhuitlán river, in the sequence Y077 in 12,400 cal BP. We have found evidence of similar soils in other riverbanks: in the Yuzanu river, in Yuz12, 13,970, in Yuz7 13,300 and in Yuz9 13,270 cal BP; and in the Yutztoton river, 13,990 cal BP (Mueller et al. 2012). They are old paleosols formed under a climate different from that of the last glacial-interglacial cycle.

At a regional scale, paleosols in Axamilpa and Santa Cruz Nuevo, Puebla, have pedogenic characteristics similar to those in Nochixtlán and Yanhuitlán. Clayey soils with slickensides and angular blocky structures in Axamilpa developed between 42,735 ± 475 and 25,965 ± 527 cal BP. In Santa Cruz, gley properties and humus accumulation are common in soils dated as 34,512 ± 191 cal BP (Tovar et al. 2013).

In Huexoyucan, Tlaxcala, paleosols classified as Histic Fluvisols have been recorded with accumulation of dark humus, clay and detrital organic matter, strong redoximorphic features and a series of iron oxide laminations following the slope orientation. The characteristics of these soils, formed 49,724 ± 2,074 cal BP (Solís-Castillo et al. 2012; Tovar et al. 2013), suggest characteristics similar to those found at the lower Yanhuitlán river.

By Late Holocene, soil morphologies change; in all sequences, soils with a strong humus accumulation are found. In Yanhuitlán, wide floodplains are formed (Mueller et al. 2012), with an accumulation of fine-grain sediments at a moderate pace, allowing the development of A horizons dated as 13,990 (Yuz4), 13,970 (Yuz12), 13,300 (Yuz7), 13,270 (Yuz9), 12,400 (Yan7), and 10,410 cal BP (Yan2), and perhaps also as 11,870 (Yan 8) and 10,160 cal BP (Yan4). In Puebla and Tlaxcala, soils with accumulation of organic matter and thick A horizons, dated 16,402 ± 412 to 10,426 ± 88 cal BP, suggest similar late-Holocene environments (Borejsza and Frederick 2010; Solís-Castillo et al. 2012; Tovar et al. 2013).

Another soil marker, a dark A horizon dated as 4,500 cal BP in Yutz4 at Yutzatoto stream, and in sequences Yuzt8, Yutz9 and Yutz15, in Yazanu and Yanhuitlán streams, has a sandy-loam texture with a large number of carbon particles, also observed in the sequence Y05.

Finally, as suggested by Mueller et al. (2012) at the contact of alluvial and cultural stratigraphy there is an almost pitch-black paleosol, modified by human activity and dated to 2,540 cal BP. On top of this there is sandy alluvial material that formed a moderately developed A horizon and dated 1,000 cal BP. The two paleosols form the base of the sequence Y06, where an event of quick deposition is recorded later than 800 cal BP, forming the upper portion of the sequence.

4.2. Micromorphology, genesis and landscape evolution

Time has been crucial in the transformation of the cultural landscape of the Yanhuitlán valley. The time frame has been established on the basis of radiocarbon dating, as well as on the morphology and micromorphology of paleosols.

Microscopic observation of thin sections revealed discrepancies with field observations. These observations together with the physical and chemical paleosol data modified our earlier impressions about the type of pedogenesis, particularly the parent material of soils and their clayey composition. In the alluvial sequences, the parent material determines the pedologic features of paleosols; for example, in the sequences at Axamilpa and Santa Cruz Nuevo in Puebla, and in the pedostratigraphic sequences at Huexoyucan in Tlaxcala, micromorphology modified the previous assessments about the grade of paleosols development and its interaction with the sedimentation processes (Solís-Castillo et al. 2012; Tovar et al. 2013; Tovar et al. 2014).

The older soils, described in the sequences Y01 and Y02, correspond to the distal flood-plain of the Yanhuitlán river. The microscopic analysis of paleosol Y01 revealed hydromorphic conditions suggested by the presence of neoformation of iron (pyrite), humus, fragments of vegetable material and mineral-organic horizons typical of anoxic environments. All these features are characteristic of saturation environments suggesting a reductomorphic origin in a swampy landscape, because of proximity to the flood-plain, and the clayey composition of sediments derived from the Yanhuitlán formation, with low permeability and high saturation. The later vertic characteristics could be related to episodes of drying or to the abandonment of the flood-plain. Another important pedofeature is the abundant precipitation of secondary carbonates; it is assumed that most of the carbonates are hydrogenic in origin and are precipitated from groundwater (Durand et al. 2010). Following this assumption, the carbonates are attributed to a position in the valley or close to a channel, allowing groundwater accumulation.

The Y02 soil, in spite of the similarities with Y01, has a major accumulation of humus and evidence of biogenic aggregation, abundance of phytoliths -short cellular and conical-, partly decomposed plant fragments and matrix-enriching colloidal humus. These characteristics suggest anoxic conditions in a swampy environment, supported by the highest organic carbon values on the 16Ass horizon (2.24%). The reductomorphic pedofeatures, abundance of iron (pyrite) and manganese concentrations support this idea. However, these features also demonstrate less water saturation, due to granular microstructure and porosity; together with the lack of evidence of sedimentary structures this suggests that these soils are formed far from the river influence where land stability persisted for longer. The abundant evidences of reworked of a poorly developed soil suggest the alluvial origin of the soil; it is proposed here that an old alluvial process eroded Y01 soil and allowed the development of Y02; in fact, the high organic content in 16Bk (1.03%) horizon may be the result of A horizon reworked.

The upper Y03 paleosols correspond to an incision period, with coarse-grained deposits, interrupted by few episodes of soil development and floodplain stability. Their granular biogenic structures reflect pedogenesis under good soil drainage and sufficient aeration. Also, loamy hypocoatings indicate a free drainage that afforded percolation of suspensions. Redoximorphic features, iron nodules and manganese mottling indicate temporal water saturation. The presence of pumice fragments, and of sandy lenses intercalated with finer material on the Ah horizon, suggests an increase in the river discharge and alluvial sedimentation.

In sequence Y05, bottom paleosols from 7,940 cal BP have similar characteristics, with the soil-forming processes being largely limited to humus accumulation and development of a dark A horizon. Their vertic properties could be related to fast desiccation very similar to that occurring in the 16Ass horizon; carbonate contents also are associated with parental material, since their values (8.45%) approximate those of alluvial sediments (8.33%). We suggest that this change is related to a period of stability at the onset of the Middle Holocene.

Micromorphologic observations suggest an incipient development of the paleosol; pedogenic processes such as gleyzation, humus accumulation and vertic features developed as rapid soil processes; these combined with the depositional features allow a limited interpretation of past bioclimatic conditions. Nonetheless, as indicated by Tovar et al. (2014) for the Axamilpa sequences, rapid pedogenetic features, combined with sedimentary characteristics, show superficial processes in the fluvial valley and the landscape conditions. It is suggested here that this interpretation could be extrapolated to the regional scale.

In Axamilpa sequences, the synsedimentary character of the paleosols has been interpreted as a deposition type varying from slow fluvial to lacustrine and palustrine deposits. Soil profiles at Huexoyucan show a dramatic change from a palustrine to a flood-plain landscape (Tovar et al. 2013; Solís-Castillo et al. 2012).

In Yanhuitlán, flooding is a regular process, periodically saturating the soils of flood-plains corresponding to the lower river portion; stability periods are interrupted by cut and fill cycles.

The transition from Pleistocene to Holocene is well represented in the Yanhuitlán river sequences. The large sediment discharge in sequence Y04, the incipient soils in sequence Y03, with three stratification phases (massive, laminar, and crossed) and a composition of fine to coarse sand, suggest events of high precipitation and a complex sedimentation.

The transition described above has been recorded in Puebla (Tovar et al. 2014), Tlaxcala (Solís-Castillo et al. 2012; Tovar et al. 2013; Borejsza et al. 2008), Guanajuato (Borejsza et al. 2008) and in the Nochixtlán valley (Mueller et al. 2012), as a change from dry to wet conditions. These deposits of alluvial sediments are a product of an erosional dynamic following a change in vegetation cover at 9,000 cal BP that has been recorded at Guilá Naquitz (Pérez-Crespo et al. 2013), in turn related to a change to more humid conditions in the Early Holocene (Mueller et al. 2012).

4.3. Micromorphology, human impact inferences and cultural landscape

Terrace systems TL1 and TL2 are located on the hillsides of cerro Las Conchas; the poor conservation of the rock walls precludes establishment of a relationship between these systems and the lama-bordos. Micromorphologic observations suggest a close relation. In terrace TL2, captured sediments are fine textured in soils dated to 5,300 cal BP, and micromorphology features laminated silty-clayed components, sometimes oriented, implying a constant sedimentation; the poorly decomposed organic tissues and the reductomorphic microfeatures (iron nodules and manganese impregnations) indicate that sediment capture is a result of water accumulation. Since this is a constant process, it is possible that anoxic conditions were the result of a quick accumulation of fine sediments. Field observations of this buried soil, a dark color, an angular blocky structure, and charcoal particles, suggest a shift to a widespread land surface; this was recognized in the Yutzatoto stream, dated 5,520 cal BP; in the Yuzanu river it has been related to Archaic archaeological settlements (Mueller et al. 2012).

The soil developed 2,700 cal BP in terrace TL2 is similar to the above-described soils. A poorly developed structure due to a continuous clayey sediment deposition is evidence of its sedimentary origin. The presence of nodules and mottles of iron and manganese derives from anoxic conditions during the capture of sediments in the terraces; however, in this soil, saturation is not a long-term process because the rock walls allow drainage to move outside the terrace. This soil has been reported for the archaeological site of Etlaltongo, dated as 3,800 cal BP (Mueller et al. 2012), for Coixtlahuaca, dated at least 3,500 cal BP (Leigh et al. 2013), and in the Yutzatoto stream, dated 2,990 cal BP; these similarities suggest a similar origin, controlled by the terrace wall.

There is nonetheless one difference; in these soils there is an impure clay fraction that occurs both within the groundmass as an integral part of the soil fabric and in the interpedal void space. "Dusty" or impure clay (**Figure 7g**) is composed of a mixture of silt particles and minute fragments of organic matter (Macphail 1987). This type of feature is characteristic of soils disturbed by turbid water; this suggests an agricultural use of the soil, or the development of soil on the terrace (Slager and Van de Wetering 1977; French and Whitelaw 1999).

The paleosols developed 1,060-940 cal BP are found on TL2 and clearly reflect a shift to widespread land surface stability and pedogenesis under periodic alluvial events: their dark brown color is related to organic carbon content (0.46%), similar to the 5A horizon, and the high presence of charcoal fragments (6%) is evidence of intensive anthropic use. A rapid increase in charcoal in the A horizons perhaps follows human activity, with peak values obtained within a few centuries. In sequence Y03 and soils developed between 7,000 and 5,000 cal BP at the base of sequence Y05, values of charcoal may be associated with fire; however, starting in 5,180 BP the values increase to about 75%. In the NW Iberian Peninsula, the increase in charcoal fragments is associated with an increase in grazing between 1,700 and 400 cal BP (Gil-Romera et al. 2010). In micromorphologic observations of A horizons of Amazonian Terra Preta soils, large quantities of microscopic inclusions of charcoal fragments and bones are mixed to sand and silt-sized fractions (Arroyo-Kalin 2010).

Hypocoating of calcic micrite may be related to flooding episodes, and their crystalline nature could then be explained by the fairly constant supply of bicarbonate subsurface water (Poch et al. 2013). However terrace TL2 is located between 15 m and 45 m of the current fluvial terrace, suggesting that surficial water flowing through the coarse fraction of these soils, is enriched with bicarbonate derived from geologic deposits (caliche) in the river basin; a similar carbonate content between soils (8.31%) and alluvial sediments exposed in Y03 (8.15-8.46%) suggests that the recrystallization of carbonates can be inheritance of parental material.

The modern soil is dominated by one fabric composed of organic sandy clay loam with poor soil structure. This is a mixture of soil material derived from very fast erosion responsible for the incorporation of fine materials (lama sedimentation) and illuviation of silt and clay. The amorphous pedofeatures and cryptocrystalline nodules of iron and manganese could be the result of terrace flooding. These soils show evidence of vertic properties such as soil cracks that may be attributable to dessication of surficial water on the terrace or to limited infiltration capacity and low physical and hydrological qualities in abandoned terraces (Stanchi et al. 2012).

4.4. Human activities at Yanhuitlán and their implication for local landscape and soil development

The set of samples discussed above, deriving from different contexts and resulting from different events and processes, can be tied only loosely to each other. The red-brown soils at the base of the Y01 and Y02 profiles underlie terraces that appear to be part of the same system as those retaining the deposits of sequences Y05 and Y06, which integrate the Formative, Classic and Postclassic periods. Although there is no direct evidence to relate soils to the archaeological context, a close correspondence can be argued between the archaeological reconstruction of the pattern of occupation and activity on the region, and the soil genesis and sedimentation processes documented through micromorphological analysis.

Soil erosion cannot always be attributed to anthropogenic processes in Yanhuitlán, in contrast to the Nochixtlán areas. Important erosion-sedimentation processes occur at the transition from Pleistocene to Holocene (Mueller et al. 2012). Sediments derived from cut-and-fill cycles of the Early Holocene are reworked in terraces located in TL2 and TL1. In the Early Formative, there was an intensification of agriculture following a population increase (Spores 1972). Etlatongo archaeological site has been occupied since 3,600 cal BP (Spores 1972; Zárate 1987; Blomster 2004). It is on a fluvial terrace created by the incision of the Yanhuitlán river about 5,250 cal BP (Mueller et al. 2012), which corresponds to terrace TL2 and the formation of soil 8A of Y05 (**Figure 7f**). In TL2, soils exhibit a sedimentary nature (**Figure 4**) that is associated with accumulative phases recorded for the Formative (Mueller et al. 2012). Also in 8A impure clay hypocoatings (**Figure 7g**) were observed; they can be evidence of disturbance by turbid water due to agricultural use, or they may be evidence of the sedimentary phases during soil development.

Soils 5A and 4A in TL2 have been correlated to those developed approximately 3,000 cal BP in Yanhuitlán (Mueller et al. 2012) and Coixtlahuaca (Leigh et al. 2013). These soils are poorly developed, a product of sediment accumulation phases recorded regionally during the Late Holocene.

Potentially, soils dated 1,060 cal BP corresponding to the Natividad phase, a period of strong landscape modification following intensified agriculture, are characterized by their poor development with sedimentary features (**Figure 4**). The final period of human transformation following terrace construction suggests an intensification of land use, as evidenced by the increase in the presence of charcoal particles, a fact that implies soil erosion due to the loss of fine material; desiccation periods can be related to lack of use of the terrace.

5. Conclusions

Micromorphologic observations of the six sequences have shown processes and characteristics that depend on the one hand upon environmental conditions during late Pleistocene-early Holocene; on the other hand, they depend on the anthropic use of soils during middle-late Holocene.

Soils developed during the late Pleistocene-Holocene exhibit hydromorphic features (organic-mineral horizons, colloidal humus and neoformation of iron), carbonate precipitation and clay-silty texture. These characteristics point to a paludal environment, where the presence of carbonates in the soil follows the saturation in carbonate-enriched water, in turn suggesting a low elevation in the landscape. Early Holocene soils have features that contrast with those of older soils. They have a well developed granular structure with sedimentary patterns of alluvial origin; this points to less saturated conditions. From 7,940 cal BP, vertic soils with neoformation of carbonates suggest a transition to drier conditions and strongly seasonal environments. On soils formed from 5,300 cal BP the sedimentation of laminated and oriented clayey components is associated with the accumulation of sediments under saturated conditions. This soil developed on terrace TL2 has been associated with human occupation at the Etlatongo site. Late Holocene soils are characterized by an increase in carbon particles suggesting anthropic use.

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