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Paleosols in the Teotihuacan valley, Mexico: evidence for paleoenvironment and human impact

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ABSTRACT

The Teotihuacan valley, located in the northeastern sector of the basin of Mexico, was settled by approximately 1,100 BC. The first and largest prehistoric city in the Americas developed here in AD 350–550, reaching a population of around 125,000. The demise of the Teotihuacan state is now generally believed to have culminated between AD 600–650. Causes are attributed to global climate change, environmental degradation, economic and/or political upheaval, but no direct evidence has ever been presented to support these hypotheses. The study of paleosols contributes to the understanding of the environmental conditions that prevailed in the Teotihuacan region in order to better comprehend their potential relationship to cultural and economic events in the prehistoric past. The distribution of soils in the region is directly associated with relief. Profiles at Cerro Gordo (3,050 m a.s.l.) and Cerro Patlachique (2,700 m a.s.l.) are associated with forest conditions, where paleosols are characterized by polygenetic profiles with varying degrees of development. The older soils are represented by Luvisols. Soils in lower positions (Cerro Colorado, 2,390 m a.s.l.) are stratified and poorly developed, with evidence of colluvial deposition and erosion. Soils with fluvic properties in the alluvial plain (2,250–2,350 m a.s.l.) are also poorly developed and greatly influenced by erosive processes and intensive accumulation. Those corresponding to the Teotihuacan periods (2,000–1,350 yr BP) show multiple indicators of human impact. Micromorphological evidence indicates intensive agricultural activities (deforestation, burning, compaction, and erosion). The presence of carbonates in underlying strata is related to changes in humidity. Phytoliths identified from the same strata indicate alterations in vegetation through time that reflect variable conditions of temperature and humidity. The results clearly reflect environmental modification by human populations from the initial period of prehistoric settlement up to present. Furthermore, the evidence suggests that a major impact of the prehistoric city on the landscape resulted from unmanaged exploitation of forest resources that provoked intensive erosion and significant changes in the hydric conditions of the region.

Key words: Teotihuacan, paleosols, phytoliths, pollen, radiocarbon dating, human impact.

RESUMEN

El valle de Teotihuacan, localizado en el sector noreste de la Cuenca de México, fue colonizado en el año 1,100 AC. La primera y más grande ciudad prehispánica de las Américas se desarrolló aquí en los años 350–550 DC, alcanzando una población de 125,000 habitantes. Se considera que el decaimiento del estado teotihuacano tuvo lugar entre 600 y 650 DC. Las causas son atribuidas al cambio climático global, a la degradación del ambiente y a trastornos económicos y/o políticos, pero ninguna evidencia directa se ha presentado para apoyar estas hipótesis. El estudio de paleosuelos contribuye a un mejor *entendimiento sobre las condiciones ambientales que prevalecieron en Teotihuacan, con el fin de comprender mejor sus relaciones potenciales con los eventos culturales y económicos del pasado prehistórico. La distribución de los suelos se asocia directamente con el relieve. En los cerros Gordo (3,050 m s.n.m.) y Patlachique (2,700 m s.n.m.) se relacionan con condiciones forestales, donde los paleosuelos se caracterizan por tener perfiles poligenéticos con diferentes grados de desarrollo. Los suelos más antiguos son Luvisoles. A elevaciones menores (C. Colorado, 2390 m s.n.m.), los suelos están estratificados y pobremente desarrollados, con evidencias de coluvionamiento y erosión. Los suelos con propiedades flúvicas en la planicie aluvial (2,250–2,350 m s.n.m.) también tienen escaso desarrollo y están influenciados por procesos erosivos y una acumulación intensa. Aquellos suelos que corresponden con el periodo teotihuacano (2,000–1,350 años AP) muestran múltiples indicios de impacto humano. Las evidencias micromorfológicas indican actividades agrícolas intensivas (deforestación, quema, compactación, erosión). La presencia de carbonatos en los estratos subyacientes se relaciona con cambios en la humedad. Los fitolitos del mismo estrato indican alteraciones en la vegetación a través del tiempo, lo cual refleja condiciones variables de temperatura y humedad. Los resultados claramente reflejan modificaciones ambientales debidas a la influencia antrópica. Además, la evidencia sugiere que el mayor impacto de la ciudad prehistórica sobre el paisaje resultó por una inadecuada explotación de los recursos forestales que provocó erosión intensa y cambios significativos en el régimen hídrico de la región*

Palabras clave: Teotihuacan, paleosuelos, fitolitos, polen, fechamientos con radiocarbono, impacto

INTRODUCTION

Soils form an important part of the ecosystem and landscapes, modern and ancient. Landscapes developed long before the appearance of humans, but they were affected and altered by human occupation for the last two million years, with remarkable effects when agriculture began. Soil represents a surface that supports a culture, a source of food, reflects the environment, records the passage of time, and registers the impact of human activities, such as tillage, ploughing, application of chemicals, and irrigation (Holliday, 1989; Arnold *et al.*, 1990). Consequently, paleosols – soils formed in past landscapes and environments – are a valuable tool for archaeological studies, though they have been mainly considered as stratigraphic markers as well as age and paleoenvironmental indicators (Catt, 1991).

Some pedofeatures are diagnostic for agricultural practices and they are similar in modern soils and paleosols, as for example textural pedofeatures, agricutans–illuviation coatings made of sand, silt, clay, organic matter (one or more of these components) resulting from agricultural management (Jongerius, 1970); illuvial coatings (dusty clay coatings) often indicate deforestation, and poorly-sorted mineral coatings and infillings of charcoal and organic matter are evidence of agriculture (Courty and Nornberg, 1985). However, some works point out that the presence of such pedofeatures are not always related to agriculture but to unvegetated or irregularly protected soil surfaces (Macphail *et al.*, 1990; Usai, 2001).

The Teotihuacan valley, located in the northeastern sector of the basin of Mexico, was settled by permanent agriculturists by approximately 1,100 BC. The site of the urban center of Teotihuacan was initially occupied about 150 BC. The city began to develop around AD 1, and ultimately grew to cover an area of about 20 km^2. Between AD 350–550, the city was the center of a powerful state that had grown to dominate central Mexico and to have considerable influence in the rest of Mesoamerica, including Oaxaca and the highland and lowland Maya regions. Millon (1970, 1973) estimated a population for the city between 75,000 and 200,000 residents (125,000 as a probable mean estimate). The demise of the Teotihuacan state is now generally believed to have culminated between AD 600–650. The decline of the state and partial abandonment of the city have been attributed to diverse causes including global climate change, environmental degradation, economic and political upheaval, but no direct evidence has ever been presented to support these hypotheses. Insofar as the relationship between population size and resource potential is concerned, there are many indications that the prehispanic population of this city grew far beyond the capacity of the region to provide agricultural products, utilizing intensive cultivation techniques in all suitable areas.

A preliminary analysis of six soil profiles was undertaken in the Teotihuacan region. Pedological and botanical indicators from paleosols were examined to evaluate the potential role of climate change and human impact.

In this paper we present the results of the paleosol study, which contributes to an understanding of the environmental conditions that prevailed in the Teotihuacan region in order to better comprehend their potential relationship to cultural and economic events in the prehistoric past.

MATERIALS AND METHODS

Site conditions

The Teotihuacan valley is located 50 km northeast of Mexico City, in the Basin of Mexico, between 2,970 and 2,250 m a.s.l. (Figure 1). Present day climate is a transition between the semiarid (BS) and sub-humid (C), with a mean annual temperature of 14.9°C and an annual precipitation of 563.3 mm (García, 1988), which are variable depending on altitude. At elevations lower than 2,800 m a.s.l., temperature is 12–18°C and rainfall is 500 mm, at higher altitudes, they are 5–12°C and 800 mm, respectively. Most of rainfall (80–94%) occurs in May to October.

The distribution of the vegetation in the northern Basin of Mexico in general and the Teotihucan valley in particular is affected more by rainfall patterns than temperature, although altitude affects the distribution of moisture, which in turns varies according to wind direction and topographical features. Cerro Gordo (3,050 m a.s.l.) in the north creates a partial shadow and average annual rainfall is between 600–800 mm.

Based on studies of the distribution of plant communities in the northern sector of the Basin of Mexico and Teotihuacan valley, four main zones can be distinguished (Rzedowski *et al.*, 1964; Castilla-Hernández and Tejero-Diez, 1983): 1) Forests situated on mountain ranges surrounding the Basin andn on higher slopes. Dominant genera include *Pinus* (2,500–2,900 m, annual rainfall *ca.* 800–1000 mm); *Quercus* (2,400–2,900 m, annual rainfall *ca.* 700-1000 mm); and *Juniperus* (2,500–2,800 m, annual rainfall *ca.* 600–800 mm). 2) Grasslands, secondary growth between 2,250–2,600 m, located principally in the western sector of the northern basin (annual rainfall averages between 600–800 mm). 3) Xerophytic scrub, generally situated below 2,600 m (*Opuntia*, *Zaluzania*, *Mimosa*, and *Hechtia*). 4) Halophytic vegetation, in salty alkaline soils of old lakebeds, below 2,250 m.

Modern soils are mainly Fluviosols, Phaeozems, Vertisols, Cambisols and Leptosols.

Field sampling

An extensive soil survey was conducted in the Teotihuacan valley in 1992, 1994, 1995 and 1999. During this survey, 33 soil profiles were described and sampled from pits. For this study we selected 5 soil profiles, located in different geomorphic positions and altitudes (Figure 1) to determine the general characteristics and perturbation related to human activities.

The studied profiles, from east to west, are the following: Zanja profile (92-5), 19°41’56’’N, 98°51’56’’W, at 2,317 m a.s.l., in talus of the volcanic cone Cerro Colorado; Chinampas profile (92-9), 19°40’55.2’’N, 98°52’21’’W, at 2,267 m a.s.l., near the archaeological zone; **S**an Lorenzo Tlamimilolpa profile (92-14), 19°40’25.2’’N, 98°52’1.2’’W, at 2,267 m a.s.l., at the center of the valley, where volcanogenic alluvium accumulates; Sierra Patlachique profile (92-11), 19°39’30.6’’N, 98°50’26.4’’W, at 2,304 m a.s.l., located at the slope of the Sierra Patlachique, constituted by different volcanic materials formed during the Miocene, but with additional

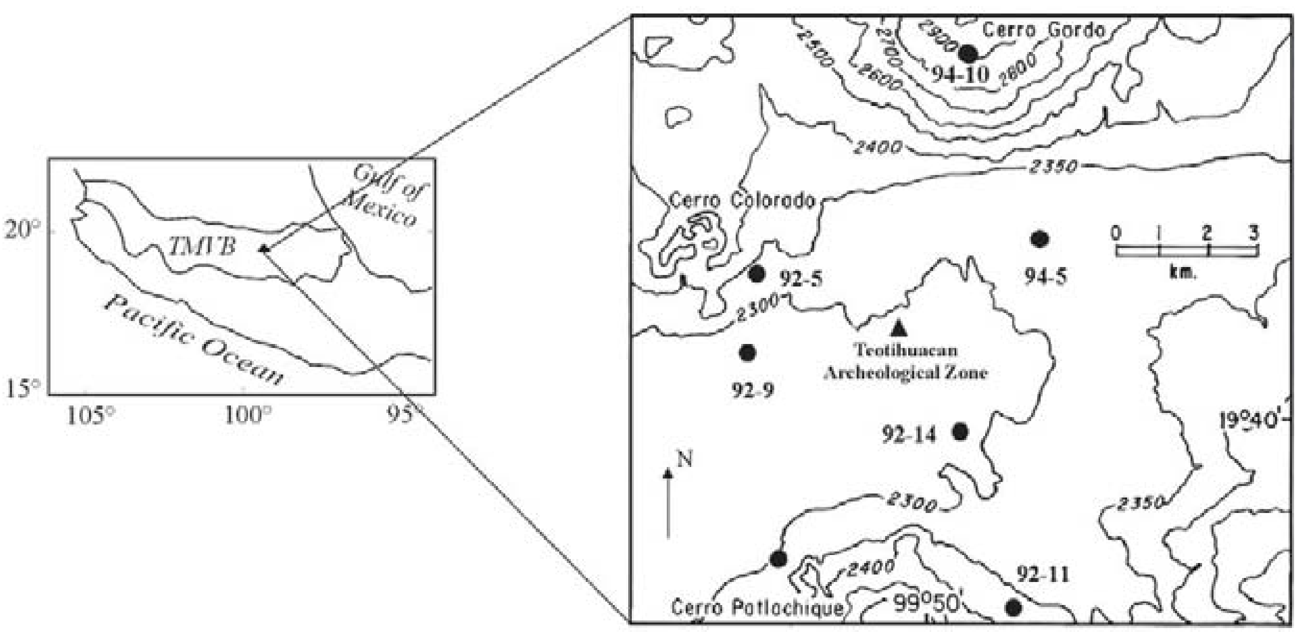


Figure 1. Location of studied area and paleosol profiles.

contributions during the Pliocene–Pleistocene; San Pablo Ixquitlan profile (94-5), 19°42’15.5’’N, 98°48’4.3’’W, at 2,300 m a.s.l., at the center of the valley, where volcanogenic alluvium accumulates; Cerro Gordo profile (94-10), 19°44’47’’N, 98°49’20.3’’W, at 2,900 m a.s.l., on the slope of a Pleistocene basaltic volcanic cone, approximately 6 km to the northeast of the archeological zone.

Bulk samples for physical and chemical analyses as well as undisturbed samples for preparation of thin sections were collected from genetic horizons of paleosols and modern soils.

Laboratory analyses

Soil colors were determined according to the Munsell Soil Color Charts (1975). Organic matter (OM) and cation exchange capacity (CEC) were evaluated according to USDA (1996). Particle size distribution was determined by separating quantitatively the sand fractions (2–0.05 mm) by sieving, and the silt and clay (<0.002 mm) fractions by gravity sedimentation with preliminary destruction of aggregating agents: 10% H_2O_2 was used for organic matter and dithionite–citrate–bicarbonate extraction for iron oxides. Thin sections were prepared from undisturbed soil samples impregnated at room temperature with the resin Cristal MC-40, studied under a petrographic microscope and described following the terminology of Bullock *et al.* (1985). Horizon designation was established mainly based on micro-morphological features because of difficulties in the recognition in alluvial soils of the Teotihuacan valley.

Phytolith and pollen content

Phytoliths are silica particles produced by many plants but are particularly abundant among the Poaceae (grasses). However, while similar forms may be produced by many different grasses, some forms are diagnostic to the subfamily level which in turn represents generalized adaptations to certain temperature/humidity regimes (Gould and Shaw, 1983; Twiss, 1992; Dinan and Rowlett, 1993). For example, the Pooideae (F) are C3 plants are generally associated with high latitude/high elevation regions characterized by cool temperatures and relatively localized moisture (short-grass savanna). The Panicoideae (P), on the other hand, include both C3 and C4 genera which are situated at lower altitudes in warmer more humid latitudes. The Chlorideae (C) are C4 plants well-adapted to semi-arid environmental conditions in low–intermediate elevations (tall-grass savanna), characterized by relatively high temperatures and low humidity. The relative abundance of the different types of grasses, and associated conditions of temperature and moisture, can be estimated by taking the ratio of the total of each type with respect to the sum of pooid, panicoid, and chloridoid phytoliths (FPC) (Twiss, 1992; Fredlund, 1993).

Radiocarbon dating

Radiocarbon dating of selected horizons was performed by Beta Analytic, Inc. (Miami, Florida, USA). All dates were obtained from paleosol organic matter in the absence of charcoal. Unfortunately, in some cases insufficient carbon was recovered for dating via conventional means and financial resources for AMS dating were not available.

RESULTS

In general, the studied soils clearly show stratification in the major part of the profile, so stratification is the main characteristic used to distinguish these soils from others. Modern soil formation has affected the upper part of the profile. Dark colored surface horizons, rich in organic matter, originated in comparatively short time are common.

Morphological properties

Macropedological morphology of the studied soils is contrasting, but all of them are constituted by complex profiles with different buried Ah horizons, sometimes separated by fresh volcanogenic alluvial material. Surface epipedons are very dark gray (moist), strongly modified by present day agriculture, and formed in the last 1,000 yr BP (Figure 2).

Deeper profiles are 92-14 (San Lorenzo) and 94-5 (San Pablo), located in the center of the valley. They are more than 3 m thick and it is possible to recognize at least three soil-forming cycles (Figure 2). Radiocarbon dating allows the correlation between these profiles (Table 1). Younger paleosols in both profiles were dated at 670±70 yr BP and 840±80 yr BP, respectively, and are buried by Ap horizons (Table 1). In the case of 92-14, it exhibits an 2Ah/2AB/2B profile, very dark grayish brown (moist), while in the 94-5 profile, the paleosol can be regarded as pedocomplex according to the concept of Smolikova (1967) with two Ah horizons formed during different pedogenetic cycles (2Ah, 2´Ah). The oldest paleosols have a well expressed, dark–very dark gray (moist) Bt horizon (3Bt1-3Bt2) in the 92-14 profile, and a very dark gray (moist) B horizon (3B1-3B2) with some evidence of clay illuviation in 94-5.

Located in the piedmont of Sierra Patlachique, the 92-11 profile has a less profound, 26 cm thick Ap horizon dated at 380±70 yr BP, which overlies a very dark gray (moist) 2AB horizon dated at 2,370±70 yr BP (Table 1). The contact with the underlying horizon (3Bt horizon) is abrupt and irregular, and the 2AB penetrates into the 3Bt for 12 cm providing evidence of strong erosion processes. Colors vary from very dark gray in the upper horizon to dark brown in the lower. Underlying 3Bt, a compact 4Bt

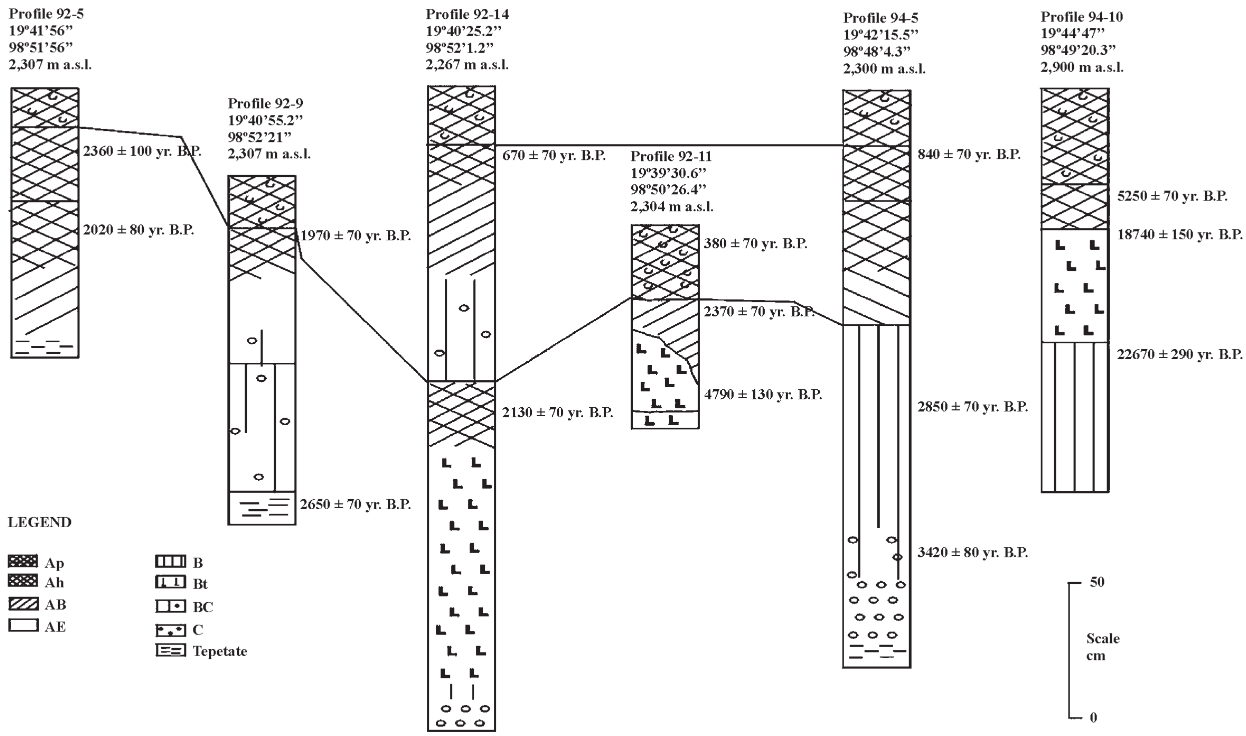


Figure 2. Pedostratigraphic columns of paleosol profiles.

horizon with a morphology similar to a tepetate occurs.

Profile 92-9 (Chinampas) is located in the area surrounding the Teotihuacan archaeological site. The surface horizon Ap is 18 cm thick. It overlies a paleosol dated at 1,970±70 yr BP (Figure 2). This paleosol is constituted by a 2Ah/2AE/2BC profile. Color ranges from brown in the upper horizons (Ah/AE) to dark brown in the 2BC. Beneath, a second paleosol with a dark brown, truncated profile (3B/3BC) was recognized.

Profiles 92-5 (Zanja) and 94-10 (Cerro Gordo) are located in the talus of Cerro Colorado (Zanja profile) and Cerro Gordo, respectively, with the latter in the highest position. They exhibit complex profiles with 3–4 different stages of soil formation, although they are not correlative, because, as indicated by radiocarbon dating, pedogenesis in Cerro Gordo is older (Figure 2). The Zanja profile has three Ah horizons. The Ah surface is affected by modern agriculture. The second and the third Ah horizons were dated at 2,360±100 yr BP and 2,020±80 yr BP respectively (Table 1). We consider that this paleosol is a pedocomplex, with a 2Ah/2´Ah/2´AC/2´C profile. Cerro Gordo profile has two Ah horizons. The second Ah is 5,250 yr BP, however as it has a mixture of different kind of sediments, its age could be younger. The third paleosol is 18,740 yr BP old and is constituted by a truncated profile with no Ah horizon, but with a well developed, very dark grayish brown Bt horizon (Table 2). The lower paleosol is also truncated, and has a grayish brown B horizon, dated at 22,670 yr BP.

Micromorphological features

All soil horizons and layers are composed of volcanic minerals such as pyroxene, amphibol, plagioclase, glass, and rock fragments in different proportions.

Patlachique profile (92-11).

The surface horizon (Ap) has a granular structure and contains a mixture of coarse volcanic material partially weathered and reworked by cultivation. The 2AB also has granular and angular blocky structure, poorly developed, with abundant, colored volcanic glass. The underlying horizon corresponds with a 3Bt where clay illuviation is the prominent feature. 3Bt2 has abundant clay cutans and subangular blocky structure. However, it is possible to distinguish the presence of a granular structure in the soil matrix, which evidences the evolution of this Bt horizon from an Ah horizon with a granular structure (Figure 3). Iron nodules are abundant.

Zanja profile (92-5)

The upper layer (Ap) is poorly structured. 2Ah1 has a granular and subangular blocky structure, very porous, and moderately weathered. 2Ah2 is more compact; it has a subangular blocky structure with some areas where a granular structure is observed; in the matrix, organic matter mixed with fine material is found. It shows some reworked features as clay cutans. The 2AC horizon is similar to 2Ah.

Table 1. Selected conventional radiocarbon age determinations on bulk sediment from soil profiles in the Teotihuacan Valley.

Profile	Horizon	Depth (cm)	Laboratory No.	Age (years B.P.)
92-5	2Ah	14-30	Beta 68333	2360 ± 100
	2´Ah	30-64	Beta 60626	2020 ± 80
92-9	2Ah	18-40	Beta 68353	1970 ± 70
	2BC	60-80	Beta 60627	1380 ± 80
	3C	143-150	Beta 68354	2650 ± 70
92-14	2Ah	34-47	Beta 68328	670 ± 70
	2B	86-132	Beta 60632	2290 ± 90
	3Ah	132-154	Beta 68340	2130 ± 70
	3C	>291	Beta 68341	Insufficient carbon
92-11	Ap	0-26	Beta 68336	380 ± 70
	2AB	26-38/48	Beta 60629	2370 ± 70
	3Bt	48-66	Beta 68337	4790 ± 130
	4Bt	>66	Beta 68338	Insufficient carbon
94-5	2Ah1	20-38	Beta 73315	840 ± 80
	2Ah2	38-69	Beta 73316	3290 ± 80
	2B	69-83	Beta 73317	2030 ± 60
	3B1	83-118	Beta 73318	1540 ± 70
	3B2	118-155	Beta 73319	2850 ± 70
	3BC	155-189	Beta 73320	3420 ± 80
	3C	189-240	Beta 73321	3210 ± 60
94-10	2Ah	30-50	Beta 73336	5250 ± 70
	3Bt	50-90	Beta 73337	18740 ± 150
	4B	90-143	Beta 73338	22670 ± 290

It has a subangular blocky structure, compact with very porous areas, and small granular aggregates. Bioturbation is evident (channels, tubules). Fine material shows signs of transportation for short distances. The lower horizon (C) contains a mixture of fresh volcanic minerals and reworked clay fragments with stress cutans that resemble a Vertisol ped. This horizon looks like the tepetate layers found in Glacis de Buenavista, Morelos (Solleiro *et al.*, 2003). Some neoformed carbonates were observed in voids and channels.

San Lorenzo profile (92-14)

The upper horizon, Ap, is very porous (30–40% porosity), rich in organic matter, with a subangular blocky structure; primary minerals are fresh. 2Ah and 2AB have well developed granular and subangular blocky structures, respectively; 2B is more compact. Volcanic glass is highly weathered, having a porous structure (voids and cracks) filled with fine material. Fe nodules are present in this paleosol, especially in 2B. A common feature observed in this horizon is the presence of redeposited desiccation crusts. Some dusty clay or clay with silt coatings are observed in cavities (Figure 4a). 3Ah has a well developed granular structure, showing spongy fabric. The lower horizon (3Bt) has a subangular blocky structure, with some areas where granular aggregates appear. Thin, clean, and pure clay cutans are common. Volcanic minerals are weathered, and iron mottles and concretions are observed. In the lower part of this horizon, some neoformed carbonates are found over the clay cutans (Figure 4b).

Chinampa profile (92-9)

The most prominent feature in this profile is the presence of limestone fragments rich in fossils mixed with volcanic material and clay. The 2Ah horizon is compact and contains primary carbonates (micrite) in the soil matrix and neoformed carbonates in pores and channels. The lower horizons are also compacted and have also carbonates in the matrix but not as rock fragments. Remains of charcoal, phytoliths, and redeposited clay cutans are common in the profile. Some mottles and Fe–Mn nodules are present.

Cerro Gordo profile (94-10)

The upper Ah horizon has a well developed granular structure that is strongly bioturbated: channels and coprolites are observed. Organic materials with different degrees of decomposition are present. Primary minerals are fresh with no signs of intense weathering. The underlying 2Ah has also granular structure, but some granules appear to be redeposited, and contains clay and cutan fragments. The sample shows a laminated structure. Parent material of this horizon seems to be part of Ah and Bt horizons redeposited from an eroded soil. Some areas show impure, thin clay cutans. Channels are filled by fine material. 3Bt has two kinds of clay cutans formed during two different stages (Figure 5). The first ones, clean and yellowish, are partially destroyed. The second generation of cutans are reddish and better preserved. The soil matrix has abundant phytoliths and humus, which indicates that this horizon could be an Ah that evolved into a Bt horizon.

Physical and chemical properties

The modern soils (Ap horizons) show some differences in clay content. In the deeper profiles (92-14 and 94-5) they reach 36–42% while in the others, clay proportions are lower (18–28%). The percentage of organic matter is between 2.4 and 2.7% in 92-5, 92-9, 92-14 and 94-10 profiles; Cation Exchange Capacity (CEC) in such profiles is 17–25 cmol/mg. The profiles 92-11 and 94-5 have the lowest (1.3%) and the highest (4.9%) organic matter contents, respectively, that correspond to the lowest (16 cmol/mg) and the highest (32 cmol/mg) CEC (Figure 6).

The first paleosol in 92-14 and 94-5 profiles have similar contents of clay (34–44%) and organic matter (0.8–1.1%) though in the first Ah of 94-5, the latter is higher

Table 2. Moist color, date, and phytolith content in studied paleosols.

Profile	Horizon	Depth	Moist color	^{14}C (yr BP)	Total Phytoliths	Total FPC	F/FPC %	P/FPC %	C/FPC %
92-5	Ap	0-14	10YR 3/1		200	152	25.66	25.66	48.68
	2Ah	14-30	10YR 3/1	2360 ± 100	66	48	0	100.00	0
	2´Ah	30-64	10YR 3/1	2020 ± 80	83	45	0	0	100.00
	2´AC	64-94	10YR 3/1		78	53	0	0	100.00
	2´C	>94	10YR 5/3						
92-9	Ap	0-18	10YR 3/2		200	57	12.28	87.72	0
	2Ah	18-40	10YR 4/3	1970 ± 70	234	12	0	100.00	0
	2AE	40-60	10YR 4/3		117	45	8.89	91.11	0
	2BC	60-80	10YR 3/2	1380 ± 80	151	61	19.67	80.33	0
	3B	80-103	10YR 3/2		148	74	41.89	58.11	0
	3BC	103-143	10YR 3/2		187	98	18.37	62.24	19.39
	3C	143-150	7.5YR 3/2	2650 ± 70	118	25	0	100.00	0
92-14	Ap	0-34	10YR 3/2		188	100	37.00	33.00	30.00
	2Ah	34-47	10YR 3/2	670 ± 70	200	148	0	84.46	15.54
	2AB	47-86	10YR 3/2		64	5	20.00	80.00	0
	2B	86-132	10YR 3/2	2290 ± 90	49	17	0	70.59	29.41
	3Ah	132-154	10YR 3/1	2130 ± 70	206	110	34.55	53.64	11.82
	3Bt1	154-212	10YR 2/1		61	32	0.00	100.00	0
	3Bt2	212-266	10YR 3/1		200	171	29.24	48.53	22.22
	3BtC	266-291	10YR 4/2		138	80	0	0	100.00
	3C	>291	10YR 5/3		183	116	6.90	4.31	88.79
92-11	Ap	0-26	10YR 3/1	380 ± 70	200	82	19.51	51.22	29.27
	2AB	26-36/48	10YR 2/1	2370 ± 70	202	90	3.33	5.55	91.11
	3Bt	36/48-66	10YR 3/3	4790 ± 130	191	104	6.73	18.27	75.00
	4Bt	>66			171	52	0	100.00	0

(1.5%). CEC is 21–23 cmol/mg and 35–28 cmol/mg in 92-14 and 94-5, respectively. The second paleosol of 92-14 profile (3Ah-3Bt-3BtC) shows some dissimilarity as they have higher clay (44–50%) and organic matter (0.7–1.5%) contents, as well as higher CEC (26–31 cmol/mg). At the same stratigraphic level, 92-11 (2AB) and 92-9 profiles (2Ah to 2BC) have similar quantities of clay (28–42%), organic matter (1.3–0.5%, higher in 92-11), and CEC (18–33 cmol/mg). Profiles 92-5 (2Ah-2BC) and 94-10 (2Ah) show lower values in the mentioned properties (Figure 6). The older paleosols found in 92-11 and 94-10 profiles (Bt horizons of different ages) have 42 and 28% clay, 0.11 and 0.67% organic matter, 33 and 68 cmol/mg CEC, respectively

Phytoliths and pollen

Pollen preservation is generally poor in the alluvial soils of the Teotihuacan region and thus does not provide a firm basis for vegetation reconstruction. Phytoliths, on the other hand, are quite well preserved and are used here as potential indicators, albeit unspecific, of generalized conditions. In the Teotihuacan Valley, numerous genera of the subfamilies Pooideae, Panicoideae, and Chlorideae have been reported as components of the local flora, whereas other subfamilies of the Poaceae do not appear to be represented (Rzedowski *et al.*, 1964; Castilla-Hernández and Tejero-Diez, 1983).

The predominance of C4 genera pertaining to the Chlorideae subfamily reflect the semi-arid conditions that characterize the region today. Both *Zea mays* (maize), a C4 plant in the Panicoideae subfamily, and *Hordeum* sp. (barley), a C3 plant in the Pooid subfamily are cultivated in the region today.

The Ap horizons of five soil profiles have a mixture of C4 grasses of the Chlorideae (C) subfamily, C3 and C4 grasses of the Panicoideae (P) and C3 plants of the Pooideae (F). The 92-9 profile is only represented by members of the Panicoidaeae (more than 80%) and Pooideae subfamilies (Table 2).

Zanja profile (92-5)

Phytoliths representing C3 grasses of the Chlorideae subfamily are predominant in the 2Ah2 and 2AC horizons, however, in the first centimeters (2Ah1) there is a high proportion of C3 and C4 grasses of the Panicoideae subfamily. Pollen frequencies are quite low but the predominant families represented throughout the profile include Asteraceae, Chenopodium–Amaranthus, Cheno-ams, Poaceae, and *Alnus*. *Alnus* does not appear until 2Ah and neither Asteraceae nor Poaceae are reported from 2AC. A single grain of *Zea mays* was recovered from 2Ah2. Pollen from all of the predominant types mentioned above was also recovered from 2AC at a depth of 78 cm (not represented by phytoliths).

Chinampas profile (92-9)

This profile has a high proportion of phytoliths representing grasses of the Panicoideae and Pooideae subfamily throughout the profile. Pollen was exceptionally well represented in this profile in comparison with other profiles studied, probably due to anaerobic conditions resulting from the high water table over a considerable period of time. Predominant pollen types include Poaceae, Asteraceae, Cheno-ams, Equisitaceae, Cyperaceae, *Alnus*, *Pinus*, *Cupressus*, *Quercus* and, to a lesser extent, Fabaceae, and Malvaceae. *Zea mays* is minimally present in Ap, 2Ah and 2B horizons. *Populus* appears in 2Ah2.

Sierra Patlachique profile (92-11)

Grasses of the Panicoideae are predominant on the surface of this profile, whereas in the 2AB horizon, Chloridoid phytoliths are more abundant. The lowest horizon (3Bt2) has 100% of phytoliths of Panicoideae subfamily. Pollen is very poorly represented. However, Asteraceae and Poaceae predominate throughout the profile. *Quercus* and *Pinus* appear in Ap, and *Pinus* also occurs in 2AB.

San Lorenzo Tlamimilolpa profile (92-14)

This profile is characterized by the overall predominance of grass phytoliths associated with the subfamily Panicoideae, with the exception of the surface horizon in which all three types of regular grass phytoliths are present in similar proportions, and the two lowest horizons (3BtC-3C). Pollen represented in this profile is similar to those of 92-9 but with lower frequencies. Predominant types throughout the profile include *Alnus*, Cheno-ams, Poaceae, *Pinus*. *Alnus* is absent from layer Ap, 3Bt1, and 3C horizons. *Pinus* is present in Ap, 2Ah, and 2B horizons. *Cupressus* appears in 2Ah horizon. Asteraceae occurs in Ap, 2B, 3Ah, 3Bt, and 3BtC, although it is most frequent in 3Bt.

San Pablo Ixquitlan profile (94-5)

Dominant phytoliths recovered from this profile are chloridoid grass types. An exception is 3B horizon where the proportion of pooid phytolith types is greater than the chloridoids, and panicoid types are completely absent. Among the pollen samples, *Pinus*, Asteraceae, Cheno-ams, Poaceae, and Malvaceae appear consistently throughout most of the profile. However, all are represented by very low frequencies (often only 1–2 grains), with slightly better representation of Asteraceae in Ap horizon and *Pinus* in 2Ah. *Alnus* is present only in 2B. Pollen content is congruent with disturbance caused by agricultural activities in the zone.

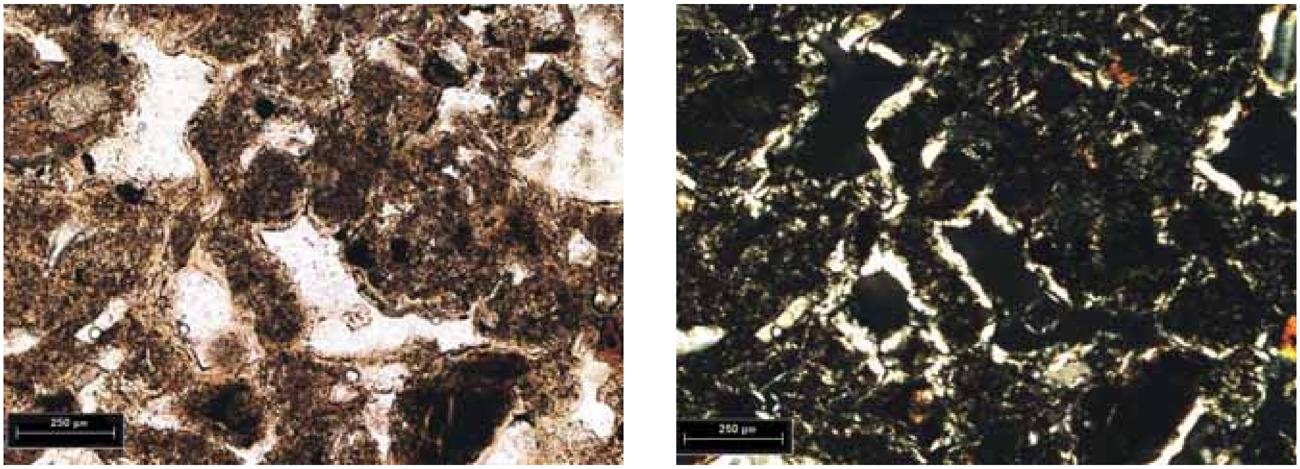
Cerro Gordo profile (94-10)

Throughout the profile, phytoliths pertaining to the Chlorideae subfamily predominate. Only a single grain of *Pinus* and an unidentified spore were recovered from the pollen sample corresponding to Ap horizon All other samples were devoid of pollen.

Table 2. Continued.

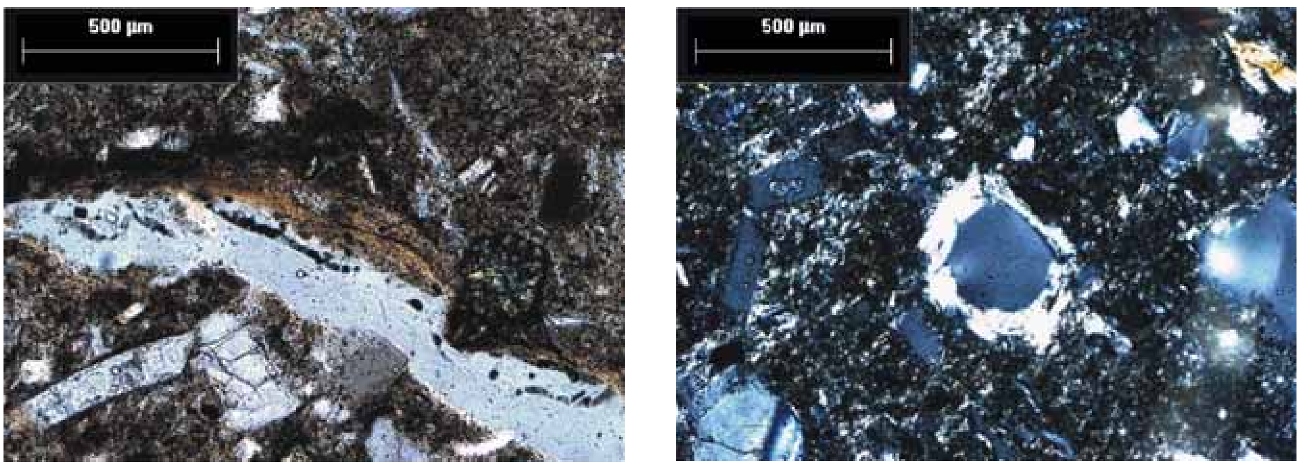
Profile	**Horizon**	**Depth**	**Moist color**	**^{14}C (yr BP)**	**Total Phytoliths**	**Total FPC**	**F/FPC %**	**P/FPC %**	**C/FPC %**
94-5	Ap	0-20	10YR 3/2		168	97	5.15	11.34	83.51
	2Ah	20-38	10YR 3/2	840 ± 80	177	117	32.48	24.79	42.73
	2´Ah	38-69	10YR 2/2	3290 ± 80	242	124	16.13	23.39	60.48
	2B	69-83	10YR 2/2	2030 ± 60	193	105	19.04	24.76	56.19
	3B1	83-118	10YR 3/1	1540 ± 70	200	111	51.35	0	48.65
	3B2	118-155	10YR 3/1	2850 ± 70	200	93	32.26	0	67.74
	3BC	155-189	10YR 3/1	3420 ± 80	778	291	24.74	17.53	57.73
	3C	189-240	10YR 3/1	3210 ± 60	627	272	26.10	19.85	54.04
94-10	Ap	0-30	10YR 3/2		176	76	1.31	6.58	92.11
	2Ah	30-50	10YR 3/2	5250 ± 70	193	92	0	15.21	84.78
	3Bt	50-90	10YR 3/2	18740 ± 150	195	96	0	21.87	78.13
	4B	90-143	10YR 5/2	22670 ± 290	200	75	0	6.67	93.33

Note: F: Pooideae; P: Panicoideae; C: Chlorideae



a) b)

Figure 3. Micromorphological features of 3Bt horizon in Patlachique paleosol, showing granular structure with clay cutans. a) Natural light; b) polarized light.



a) b)

Figure 4. Micromorphological features of paleosol San Lorenzo. a) A dusty clay coating in a cavity of 2B horizon; b) neoformed carbonate of 3Bt horizon.

DISCUSSION

Radiocarbon ages of the paleosols are strongly contradictory. Younger ages often underlie older ones, likely because of their alluvial origin. However, we propose a correlation between paleosols of the Teotihuacan valley, based on selected radiocarbon dates, macro- and micromorphological features, and physical and chemical properties.

We consider different phases of soil formation, associated with the occupation history of the valley. The modern pedogenesis occurs in periods younger than 950 yr BP (Post-classic and colonial-modern period); a second phase was recorded between approximately 950 and 1,950 yr BP (Epiclassic and Classic period); and a third, between 1,950 and 3,000 yr BP, corresponding to the initial

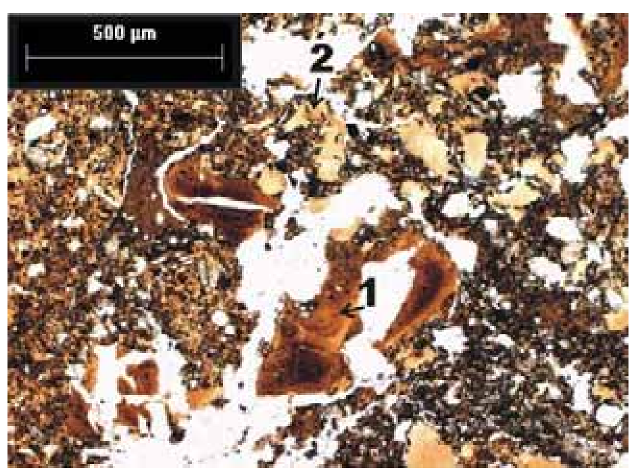


Figure 5. Micromorphological features of paleosol Cerro Gordo. Two different stages of cutan generation are showed.

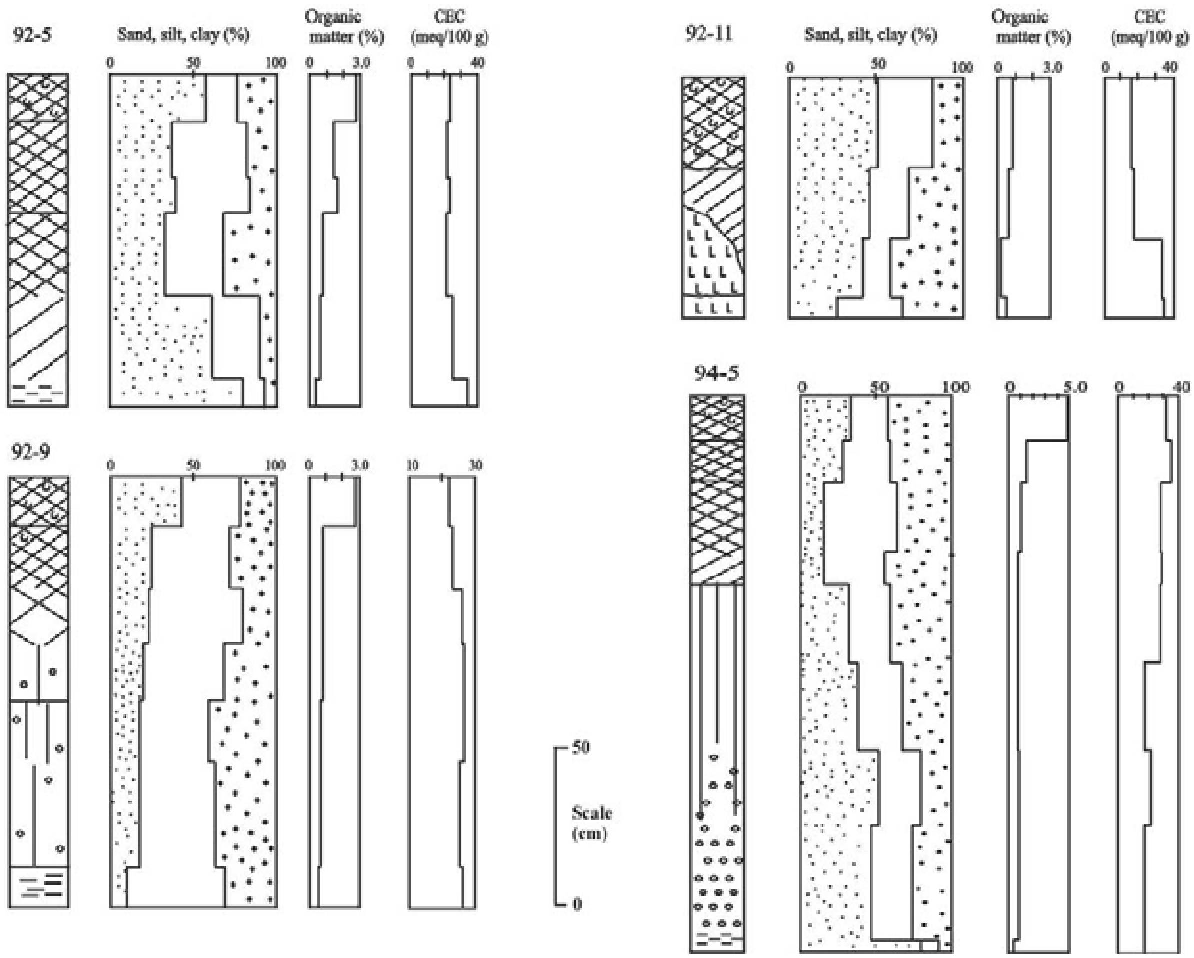


Figure 6. Selected analytical propertties of studied paleosols.

settlements and growth of agricultural communities on the alluvial plain in Teotihuacan (1,100 BC–AD100). The oldest cycles dated at 4,790, 18,740, and 22,670 yr BP are registered in the piedmonts of Cerro Gordo and Sierra Patlachique.

The 22,670 yr BP (4Bt) and 18,740 yr BP (3Bt) paleosols in Cerro Gordo can not be easily correlated with any other paleosol in the valley. However, 4Bt in Patlachique profile has similar characteristics to those observed in Cerro Gordo 3Bt: similar clay (26%) and organic matter (0.9%) contents, and a soil matrix with abundant phytoliths in a granular structure. Concerning the 3Bt in 92-11 and 2Ah in 94-10, they have been dated at 4,790 yr BP and 5,250 yr BP, respectively. We consider that 2Ah is younger than the reported age because it has materials originating from a soil that was eroded and redeposited; we observed evidence of such processes in thin sections (reworked granular aggregates and fragments of clay cutans).

Paleosols formed around 3,000–1,950 yr BP are present in all profiles except for Cerro Gordo. Profiles 92-5, 92-9, and 92-14 exhibit the most developed paleosols during this period. In fact, 92-14 has a Bt horizon, which is generally believed to require several thousand years to form (Birkeland, 1999). Profile 92-11 is less developed and exhibits a truncated soil with a single AC horizon. Profile 92-5 has two different stages of soil formation not separated by parent material, while 92-9 shows a more complete profile, but not as well developed as 92-14 and 94-5. We consider that the AE horizon originated due to lateral drainage and eluvial development.

Paleosols formed around 1,950 to 950 yr BP are only present in the most complete sequences: 92-14 and 94-5 in the center of the valley. Both sequences have moderately developed soils, and in the case of 94-5 contain a complex profile involving two cycles of soil formation.

We interpret this behavior as the result of varying dynamics of geomorphic processes. During the late Pleistocene, the landscape was more stable and allowed the formation of well developed soils, however soil erosion occurred, maybe associated with volcanic activity in the Basin of Mexico. Cores obtained from Lake Chalco, south of the Teotihuacan valley, registered two important tephra layers: Tlapacoya 1 and Tlapacoya 2, dated between 15,020

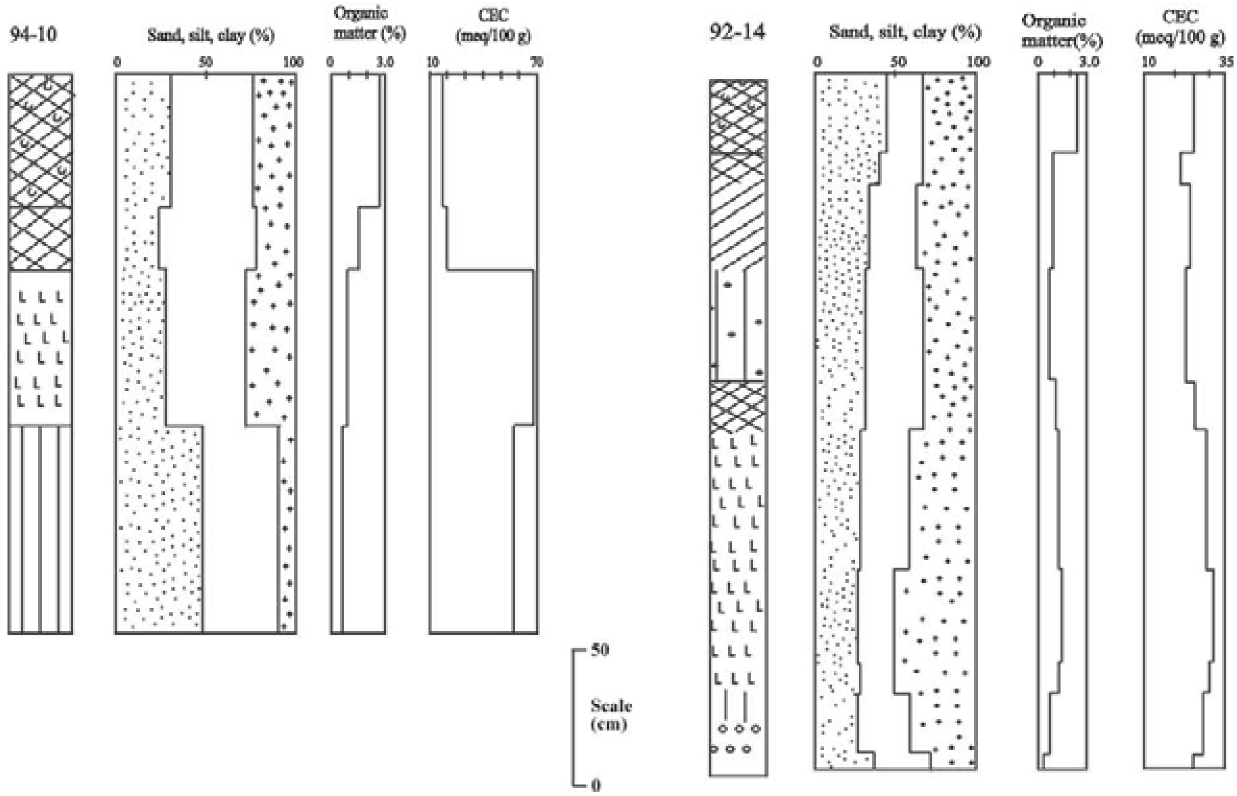


Figure 6. Continued.

and 14,430 yr BP (Ortega-Guerrero *et al.*, 2000). During the period from *ca.* 16,500 to 14,000 yr BP high rates of erosion and intense volcanism were recorded (Lozano-García and Xelhuantzi-López, 1997). An important hiatus in the sedimentation of Lake Tococomulco, located to the north-east, was inferred between 14,000 to 3,300 yr, B.P. (Caballero-Miranda *et al.*, 1999). However no soils of this age were recovered in the study area. After 3,300 yr BP in lakes Texcoco, Chalco, and Tecocomulco, a trend toward high lake levels and reduction of arboreal vegetation are recognized and interpreted as the result of human impact (Caballero-Miranda *et al.*, 1999). Volcanic activity is also registered. A tephra layer, Huitzilzingo, dated at 2,645 yr BP appears in cores from Lake Chalco. In the Teotihuacan valley during this time, erosion was strong as it is noticed in paleosols. They have complex profiles in which the parent material is reworked volcanogenic alluvium. Some horizons are enriched with residues of previously formed soils, for instance 2Ah of 94-10 and 2´Ah of 92-5. This reworking is most likely responsible for the contradictory radiocarbon ages.

Paleoenvironmental interpretation

We consider that environmental conditions prevailing between 22,000 and 18,000 yr BP were more humid than present, as indicated by the formation of Bt horizons (94-10 profile), which require high humidity in order to transform primary minerals into clay which is then translocated through the profile. However, the relatively low proportion of panicoid phytolith types, together with the absence of most pooid types, indicates semi-arid conditions dominated by warm temperatures and low humidity. Limnological records in Lake Tecocomulco indicate that between 25,700 and 15,000 yr BP the climate was drier than at present (Caballero-Miranda *et al.*, 1999); however, during the same time in Lake Texcoco, a dominance of pine pollen with lower proportion of oak and Tsuga was interpreted as indicator of subhumid–cooler climate with drier periods (Lozano-García and Xelhuantzi-López, 1997). The presence of a hard calcareous layer (caliche) at the top of a sediment dated at 16,350 yr BP is taken as an indicator of intermittent aridity by 16,000–15,000 yr BP (Caballero-Miranda *et al.*, 1999).

During the middle Holocene, environmental conditions were humid and warm as indicated by the presence of Bt horizons (92-11 profile), and the complete absence of diagnostic phytoliths other than the Panicoideae subfamily in 3Bt1 of 92-14. However, the presence of carbonates over clay cutans indicates a drier phase. Not enough information for lake sediments is available to be correlated.

Between 3,000 and 1,950 yr BP, the climate was warmer and humid, but the alternation of pooid phytoliths suggests a considerable fluctuation in temperature. The presence of Bt horizons in profile 92-14 supports this hypothesis. Particularly low phytolith counts in 2AB, 2B and 3Bt1 hinder interpretation. In general terms, the presence of plants associated with high moisture (such as Equisitaceae, Cyperaceae, *Populus* and, possibly, *Alnus*) in some profiles (92-14 and 92-9) complements the pattern of high humidity indicated by phytoliths. In fact, in profile 92-9, the high proportion of phytoliths representing grasses of the Panicoideae subfamily throughout the profile, together with relatively high proportions of Pooideae phytoliths, reflect the degree of humidity that is characteristic of this profile, which is located in an area of high water table and drained-field agriculture. The predominance of high humidity is slightly offset by fluctuations in overall warm temperature, indicated by the variation in the relative proportions of both phytolith classes. The high content of Chorideae phytoliths in 92-5, 94-5, 92-11, and 92-14 reflects the variation in climate conditions. Between 1,900 and 950 yr BP, the predominance of phytoliths of chloridoid grass types indicate semi-arid (warm temperatures and low humidity)environmental conditions.

The apparent inversion of radiocarbon dates (Table 1) as well as the presence of limestone in some horizons of 92-9 profile may partially reflect the practice of placing older sediments dredged from adjacent canals on the surface to increase nutrients available to cultivated plants. However, possible contamination by roots or younger dissolved C may be feasible. Poaceae, Cheno-ams, Asteraceae, and Malvaceae suggest perturbation associated with agricultural activities. Micromorphological features such as dusty clay or clay with silt coatings and the strong bioturbation observed in thin sections are also evidence of agriculture activities. It is feasible to suppose that such practices strongly modified the environment. However, soil erosion was present during the late Pleistocene and early Holocene but not with the same intensity as was observed during the last 3,000 yr BP.

Physical and morphological properties of studied paleosols suggest that a major impact of the prehistoric city on the landscape resulted from intensive agriculture with unmanaged exploitation of forest resources that provoked intensive erosion and significant changes in the hydric conditions of the region.

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