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DURIPANS IN SUBTROPICAL AND TEMPERATE SUBHUMID CLIMATE OF THE TRANS-MEXICO VOLCANIC BELT

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ABSTRACT

The objectives of this work are: (1) to determine, by means of a basic investigation, the main properties of the soils and the duripans in the study area; and (2) to generate information about the genesis of both.

The main results are that: (a) the pedologic profiles are highly developed; (b) the silt and very fine sand particles have subangular roundness and low sphericity; (c) the duripans, contrary to the *solum*, have a lower number of pores, which have a lower diameter, are not continuous and are partially closed; (d) the duripans have a low resistance to single compression; and (e) there are high contents of Al_2O_3 in the duripan cementing matrix.

The principal conclusions are: (a) petrographically, the duripans are pyroclastic deposits of intermediate composition; (b) the clay-fraction mineralogy consists of kaolinite and metahalloysite; (c) the soils are considered paleosoils, formed as a consequence of a paleobioclimatic event (glaciation); and (d) the duripans have an igneous origin with secondary pedogenetic cementation.

Key words: Duripans of volcanic origin, duripan-tepetate, State of Morelos, Mexico.

RESUMEN

Los objetivos de este trabajo fueron: (1) determinar, mediante una investigación básica, las principales propiedades tipogenéticas de los suelos y los duripanes del área de estudio; y (2) generar información sobre la génesis de ambos.

Los principales resultados son: (a) los perfiles pedológicos manifiestan un desarrollo evolutivo alto; (b) en las fracciones de limo y arena muy fina, dominan las partículas de redondez subangular y esfericidad baja; (c) los duripanes, contrariamente al *solum*, presentan un menor número de poros, siendo éstos de menor diámetro, discontinuos y cerrados parcialmente; (d) en los duripanes, la resistencia a la compresión simple presenta valores bajos; y (e) fueron detectados contenidos altos de Al_2O_3 en la matriz cementante del duripán.

Las conclusiones más importantes son: (a) petrográficamente, los duripanes son depósitos de piroclastos de composición intermedia; (b) la mineralogía de la fracción arcillosa está dominada por caolinita y metahaloysita; (c) los suelos son considerados paleosuelos, resultantes de un evento paleobioclimático (glaciación); y (d) los duripanes son de origen ígneo, con aportes secundarios pedogenéticos.

Palabras clave: Duripanes de origen volcánico, tepetate-duripán, Estado de Morelos, México.

INTRODUCTION

According to the Soil Survey Staff (1990), duripan is a surficial soil horizon cemented by silica. In Mexico, it is known as "*tepetate*", a Náhuatl word that means compacted or cemented materials. About 30 percent of the Mexican republic has consolidated or cemented horizons (Flores-Román *et al.*, 1991).

The cemented volcanic soils exist in the majority of Latin American countries, and each country gives them its own name. Even though these soils with cemented horizons have been described for many years, their study is still limited and numerous problems remain to be resolved (Zebrowski, 1991).

The known processes that explain the dynamics of the cemented volcanic soils are: (1) the consolidation of the mineral particles that provoke compaction; (2) the hardening of pyroclastic material at the moment of its deposit (igneous origin); and (3) cementation by pedologic (sedimentary) processes that produce cements in solution. The cements can be: silica, iron and aluminum oxides, calcium carbonate and calcium sulfate (Miehlich, 1984; Nimlos, 1989; Dubroeucq *et al.*, 1989; Creutzberg *et al.*, 1990; Flores-Román *et al.*, 1991; Zebrowski, 1991).

The Transmexican Volcanic Belt constitutes the most characteristic physiographic element of the tectonics of Mexico (Demant, 1981). This study was undertaken in the central-southern part of the aforementioned belt, in the northern part of the State of Morelos, Mexico. The objectives were: (1) to determine, by means of a basic investigation, the main properties of the soils and duripans of the study area; and (2) to generate information about the origins of both. This investigation contributes to the knowledge of duripans.

LOCATION OF THE STUDY AREA

The selection of the area was based on the genetic and morphological variety of duripans that exist in the north of the State of Morelos, as detected by teledetection techniques and verified by direct field techniques. The area extends between the 18°56'00"-19°00'00" N and 99°00'00"-99°17'00" W with an altitude between 1,600 to 1,900 m a.s.l. (Figure 1). Table 1 shows a synoptic vision of the environmental elements that characterize the area.

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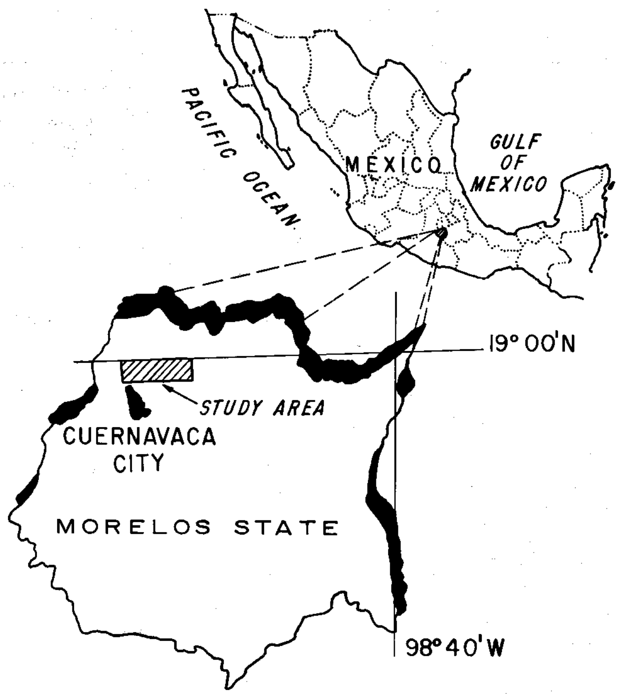

Figure 1. Location of the study area.

To locate the sample sites, a LANDSAT infrared color image, on a scale 1:250,000 and vertical black and white aerial photographs on a scale 1:30,000 were studied. Cartographic support material was collected and a reconnaissance of the land was undertaken. Finally, three typical profiles were selected.

METHODOLOGY

The analyses of color, texture (Boyoucous), structure, consistence, clay films and horizon separations, used for field morphological classification, were based on the Soil Survey Staff (1984). By means of the field morphology rating system (Bilzi and Ciolkosz, 1977), (1) the relative development of horizons (by the comparison of two adjacent horizons) and (2) the relative development of the profile (by the comparison of each horizon with the duripan of each profile) were determined.

The distribution of the size of the particles (pipette method) was accomplished by following Day's method (1965). The roundness and sphericity of these particles were studied according to Powers's scale (1953) and the porous space was characterized by various structure units representative of each horizon (Johnson *et al.*, 1960).

The bulk and particle densities, and percentage of the total porous space, were carried out according to the Soil Survey Staff (1984). The resistance to single compression was determined in carved nucleus, subject to increasing force, in an unconfined compression apparatus. The infiltration in soil and duripan, was measured by the concentric cylinders field technique. The weathering of the soils with duripans was studied by means of the total oxid test (Jackson, 1970).

To establish the losses or gains of total oxides between the parent rock and the weathered horizons, the Al_2O_3 constant was applied (Krauskopf, 1979). The test of free SiO_2, Al_2O_3 and Fe_2O_3 was undertaken according to Hashimoto and Jackson (1960). For the microanalysis of the cement agent, the samples were observed under a scanning electronic microscope JEOL, JSM-35c and the chemical analysis was performed with a Tracor X-ray dispersive energy equipment connected to the electronic microscope.The preparation of the samples consisted of making thin, polished sections, covered, previously, with a coat of ionized gold.

The exchangeable cations, organic matter, pH, cationic exchangeable capacity, organic carbon and total nitrogen were determined by the Soil Survey Staff (1984). The exchangeable aluminum was measured by the Coleman and coworkers' (1959) and Pratt and Bair's (1961) methods. The petrographic study was carried out on thin sections, examined under the petrographic microscope with magnifications up to x125. For the mineralogical analysis, an X-ray diffraction, a Philips PW 1130/96 generator, with filtered copper Kα radiation, graphite monochromator, and excitation conditions of 30kV-20 mA, were used.

To carry out this investigation, a methodological design similar to that which was successfully applied in the study of the fragipans (Flores-Román *et al.*, 1992), was used.

RESULTS AND DISCUSSION

TELEDETECTION

The analysis and interpretation of the LANDSAT 3 images and the aerial photographs led to the establishment of very

Table 1. Environmental elements of the studied area

Profiles	Geology	Climatic classification*	Altitude [m a.s.l.]	Temperature yearly average [°C]	Rain yearly total [mm]	Soil use
II-1	It is represented by the Chichinautzin Group of the Quaternary period. It is composed of basaltic and rhyodacitic lava overflows, with volcaniclastic material and some alluvium (Fries, 1965)	(A) Ca (w2) (w) (i') g Subtropical subhumid	1680	19.9	1463	Induced grassland
II-2		A (c) w2 (w) ig Subtropical subhumid	1600	20.7	1146	Altered dry deciduous forest
II-3		Cb (w2) (w) ig Temperate subhumid	1830	17.0	1511	Altered pine-oak forest

* According to Köppen modified by García (1988).

diagnostic spectral patterns for the cemented layers (duripans) that are abundant in the area.

The limits of spacial distribution of the aforementioned materials appeared in the false color image as well as the MSS6 and MSS7 bands. The confrontation between the field truth and its spectral image showed that the presence of the duripan through this technique, with a certainty percentage of more than 85, could be deduced.

MORPHOLOGICAL FIELD CLASSIFICATION

Table 2 shows the morphological properties of the studied soils that acted as a base to estimate the relative horizon development (RHD) and the relative profile development (RPD).

These developments were used as a quality measure to estimate the pedologic changes that have taken place among the horizons, and among these and the parent material (Table 3). It was considered necessary to evaluate other areas that, without being morphological, demonstrated the evolution of these soils. Therefore, certain weathering products such as Al^{3+} exchangeable, and free SiO_2, Al_2O_3 and Fe_2O_3 were included (Table 4 and Figures 2 and 3).

The highest value of the RHD of the II-1 profile was obtained by comparing the B3/Cqm horizons and by the determination of color, structure, clay films, lower boundaries and the products of weathering already mentioned. The highest value of RHD of profile II-2 was reached in the same horizons and was due to the same characteristics. For the II-3 profile, the biggest number of points was obtained by comparing the A12/E horizons. The properties that must have influenced these were color and weathering products(Table 3).

The RPD of profile II-1 reached its highest value by the comparison of the duripan with horizon B3, which coincided with the highest information of the RHD in the same profile. For the RPD of the II-2 profile, the highest numbering was obtained by the comparison of the characteristics of the A/Cqm horizons and was due to color, structure and the products of weathering. In the II-3 profile, the horizons that gave the highest values were B21t/Cqm and B22t/Cqm; the more influencing characteristics were color, structure, clay films and the products of weathering (Table 3).

Table 2. Morphological properties of the studied soils.

Horizons	Color[a]	Texture	Structure	Consistency[a]	Clay films	Lower boundaries
P II-1						
A	10YR5/4	L	ab, f, mo	so	b	clear
	5YR3/5			fr		
B	10YR5/6	Cl	p, f, mo	lh	z, mt, if	gradual
	5YR4/3			fm		
B3	10YR6/4	Cl	p, f, mo	lh	z, mt, if	clear
	5YR4/6			fr		
Cqm	10YR7/6	Sl	m	vh		diffuse
	10YR5/6			fm		
P II-2						
A	5YR4/4	L	ab, f, st	lh		gradual
	5YR3/3			fr		
B21t	5YR4/6	C	sab, f, st	lh	cn, mt, hv	gradual
	5YR3/4			fr		
B22t	7.5YR5/6	C	ab, f, st	lh	cn, th, hv	gradual
	5YR5/6			fr		
B3	7.5YR6/6	C	sab, me, st	lh	ds, mt, hv	gradual
	5YR3/4			fr		
Cqm	10YR7/6	Cl	m	vh		diffuse
	5YR4/6			fm		
P II-3						
A11	10YR4/3	L	sab, f, mo	so		gradual
	7.5YR3/2			fr		
A12	10YR4/4	L	ab, me, mo	lh		gradual
	5YR3/3			fr		
E	5YR5/6	L	ab, me, mo	so		gradual
	5YR5/8			fr		
B21t	7.5YR5/6	CL	ab, me, st	lh	ds, ti, hv	gradual
	2.5YR4/6			fr		
B22t	7.5YR5/6	C	ab, me, st	h	cn, mt, hv	gradual
	5YR4/4			fm		
B31	7.5YR5/6	CL	ab, me, mo	lh	z, mt, if	gradual
	5YR4/4			fr		
B32	7.5YR5/6	SL	sab, f, w	lh		gradual
	5YR3/3			fr		
Cqm	10YR6/4	SL	m	vh		diffuse
	10YR5/6			fm		

a = First entry, dry; second, moist. b = Not present. L = loam; Cl = clay loam; Sl = silt loam; C = clay; ab = angular blocks; F = fine; mo = moderate; p = prismatic; m = massive; so = soft; fr = friable; lh = lightly hard; hv = horizontal and vertical; th = thick; ds = discontinuous; w = weak; h = hard; ti = thin; fm = firm; vh = very hard; z = zonate; mt = moderately thick; if = in fissures; st = strong; me = medium; cm = continuous; sab = subangular blocks.

PHYSICAL PROPERTIES

Particle size distribution. In Table 5, the particle-size distribution is presented. The percentage of clay content in the II-1 profile increases with depth, reaching its highest value in the duripan. It can be explained that, first, the illuviation horizon was formed and, then, a cementation process finished with the duripan formation. On the II-2 and II-3 profiles, the highest contents of clay were obtained on the B21t and B22t horizons, which typify them as accumulation horizons.

The greatest percentages of total silt were present in the three profiles in the duripan. This is interpreted as one of the principal causes of the lessening of the values of porosity and infiltration. In all the values of total silt, the greatest proportion corresponded to medium and fine silt (0.020-0.002 mm).

The highest values of total sand were found in the upper horizons, which showed strong lixiviation, where the medium and fine particles were transported towards the depth of the profile.

Table 3. Morphometric classification and products of weathering of the studied profiles.

Profile	Horizons	RHD	Horizons	RPD
II-1	A/B	43	A/Cqm	47
	B/B3	53	B/Cqm	57
	B3/Cqm	99	B3/Cqm	99
II-2	A/B21t	39	A/Cqm	117
	B21t/B22t	55	B21t(Cqm	109
	B22t/B3	43	B22t/Cqm	90
	B3/Cqm	57	B3/Cqm	57
II-3	A11/A12	51	A11/Cqm	61
	A12/E	54	A12/Cqm	65
	E/B21t	37	E/Cqm	76
	B21t/B22t	49	B21t/Cqm	82
	B22t/B31	51	B22t/Cqm	83
	B31/B32	29	B31/Cqm	38
	B32/Cqm	42	B32/Cqm	42

Within the total sand, the greatest proportions corresponded to fine and very fine sand (0.25-0.05 mm).

Roundness and sphericity of the mineral particles. This investigation was carried out in the fractions of silt and very fine sand, to which a pretreatment to eliminate aggregates was previously applied. In the three profiles, the greatest percentage of the mineral particles showed subangular roundness and low sphericity (Table 5). These materials owe their form to its *in situ* deposit, to certain eolic transport, alluvial or colluvial, and to alteration processes.

Pore space characterization. In all the horizons above the duripan of the three profiles, the porous space showed: many pores (more than 200 per dm^2); a very small diameter (0.075–1 mm); *inner ped* distribution; interstitial morphology continuous and open. In the duripans, few pores (1–50 per dm^2), a micropore diameter less than 0.075 mm (discontinuous and partially closed) were observed. Such conditions are due to the degree of cementation presented, which impedes root penetration.

Bulk density, particle density and total porosity. Because of the cementation effect, the apparent density increased with

Table 4. Total oxides, free oxides and molar relations [%].

Profiles	II-1				II-2					II-3							
Horizons	A	B	B3	Cqm	A	B21t	B22t	B3	Cqm	A11	A12	E	B21t	B22t	B31	B32	Cqm
Depth [cm]	0–36	36–48	48–53	>53	0–14	14-42	42-70	70-110	>110	0–16	16–29	29–50	50–87	87–114	114–150	150–180	>180
SiO_2	53.48	53.81	54.08	54.90	52.65	40.07	40.25	44.59	53.31	46.94	47.36	47.33	46.96	59.03	55.57	47.61	57.37
TiO_2	1.25	1.37	1.17	2.10	0.82	1.91	1.91	1.62	0.81	0.89	0.81	0.94	1.47	1.47	1.85	1.68	1.60
Al_2O_3	21.04	20.05	22.95	20.40	23.32	25.12	21.93	23.51	19.14	18.86	19.33	20.80	22.28	16.15	17.24	21.34	19.18
Fe_2O_3	4.18	4.39	4.35	4.80	2.90	10.61	14.67	10.56	6.10	6.30	6.70	6.16	8.90	6.86	8.27	8.63	6.00
FeO	1.22	1.38	1.04	0.62	2.93	1.05	0.58	0.33	0.58	2.45	2.45	1.88	0.86	0.86	1.03	0.96	0.90
MnO	0.12	0.14	0.12	0.90	0.12	0.37	0.53	0.35	0.17	0.34	0.31	0.26	0.23	0.33	0.38	0.23	0.12
MgO	2.42	3.00	2.16	1.40	1.90	0.25	0.43	0.50	0.65	1.47	2.17	1.45	0.75	0.71	2.18	1.28	1.76
CaO	2.36	2.38	2.48	2.23	2.24	0.64	0.64	1.07	2.89	2.15	2.25	1.93	1.39	1.75	1.40	1.48	1.94
Na_2O	1.30	1.55	1.55	1.37	1.10	0.35	0.32	1.45	1.40	1.20	1.90	0.93	0.85	1.20	1.20	1.25	1.90
K_2O	0.25	0.30	0.25	0.25	0.40	0.24	0.32	0.36	0.48	0.59	0.64	0.56	0.44	0.62	1.15	1.20	1.50
P_2O_5	0.15	0.15	0.13	0.13	0.17	0.03	0.04	0.03	0.04	0.32	0.20	0.28	0.24	0.21	0.16	0.16	0.16
SO_3																	
H_2O^+	3.85	4.00	3.49	4.45	3.01	3.33	2.99	3.59	3.15	3.41	2.16	3.48	3.49	1.87	6.74	8.86	5.70
H_2O^-	8.52	7.49	6.34	6.60	8.50	15.23	14.68	12.05	10.68	14.38	12.98	13.22	11.56	8.61	2.98	5.14	2.01
Total	100.14	100.01	100.11	100.15	100.06	99.20	99.29	99.01	99.40	99.30	99.26	99.22	94.42	99.67	100.15	99.82	100.14
SiO_2 Free	9.5	10.0	11.0	7.5	10.0	9.5	10.5	7.5	6.0	5.0	6.0	8.0	7.0	8.0	6.0	6.5	5.5
Al_2O_3 Free	5.0	5.5	8.0	5.0	6.0	4.0	1.0	1.0	0.5	4.0	2.5	3.0	3.0	3.5	1.0	1.0	0.5
Fe_2O_3 Free	1.7	3.5	4.3	2.5	5.2	5.6	5.6	5.2	3.5	1.7	3.5	2.5	3.8	1.7	1.7	2.5	1.5
Molar ratios																	
s/a	4.45	4.68	4.09	4.55	3.95	2.75	3.19	3.21	4.88	4.33	4.33	3.90	3.71	6.53	5.75	3.95	5.27
s/f	34.23	32.96	33.33	30.33	48.33	10.00	7.36	11.21	23.15	20.00	10.02	20.52	14.18	23.33	18.03	14.90	25.67
s/R_2O_3	3.69	3.80	3.44	3.55	3.50	2.20	2.06	2.34	2.76	3.39	3.37	3.13	2.75	4.66	3.93	2.88	4.00
b/a	0.60	0.73	0.55	0.49	0.47	0.10	0.13	0.17	0.50	0.53	0.68	0.44	0.27	0.46	0.65	0.43	0.65

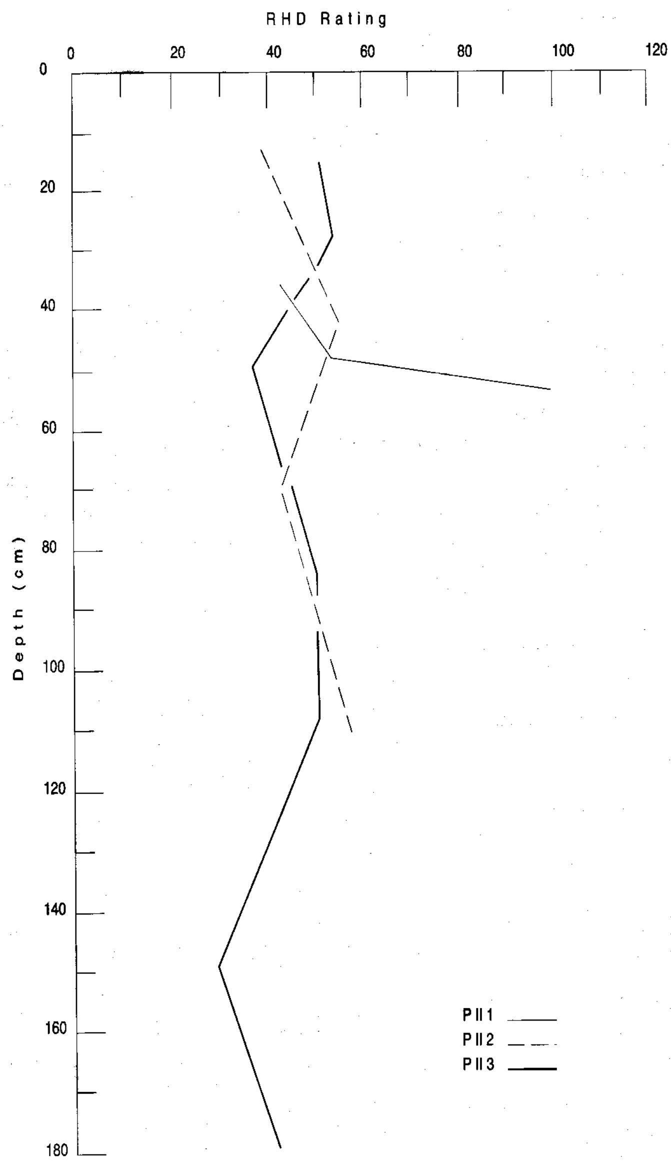

Figure 2. Relative horizon development (RHD) rating.

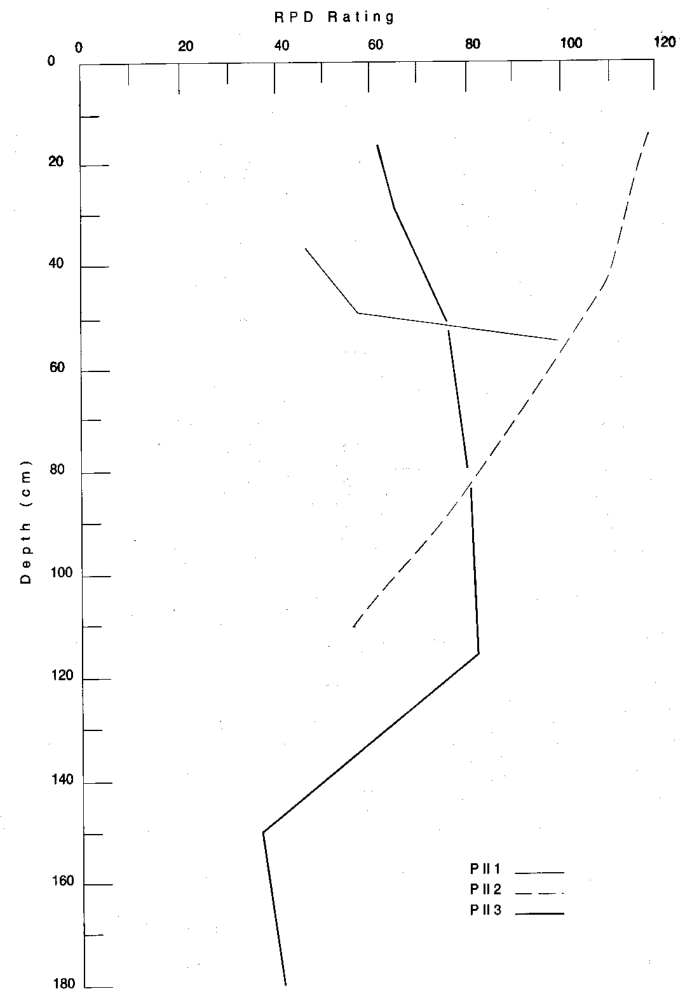

Figure 3. Relative profile development (RPD) rating.

depth in the three profiles. In the upper horizons, there was a variation from 1.28 to 1.36 g/cm^3, and in the duripans, from 1.80 to 1.92 g/cm^3. The particle density showed no defined tendency: in the horizons above the duripan, there was a fluctuation between 2.13 and 2.47 g/cm^3, and in the duripans, between 2.20 and 2.47 g/cm^3 (Table 5). Consequently, the total porosity decreased with depth, from 40–43% in the upper horizons, to 19–24% in the duripans. The values of bulk density are within the interval reported by Nimlos (1989) for some Mexican duripans.

Resistance of duripans to single compression. As can be observed in Figure 4, the duripan of profile II-1, owing to its cementation grade, required a greater force for compressional fracturing. The duripans of profiles II-2 and II-3 had a very similar behavior in their resistance to fracturing. The content of humidity at the moment of the test was higher in these profiles. Considering such an ample resistance to compression of some duripans in Mexico (Nimlos, 1989; Nimlos and Hillery, 1990), the determined values on this work were considered low.

Infiltration. The test of infiltration was made on the soil surface and directly over the duripan. On Figures 5, 6 and 7, the information on the speed of infiltration in cm/h and accumulated infiltration in cm of the profiles II-1, II-2 and II-3 was exposed, respectively. It can be observed in the three profiles that the values detected by the movement of water on the soil, in relation to the duripan are very different. Therefore, the consumptions of profile II-1 are greater than those of the other profiles.

The greatest infiltration of the *solum* of profile II-1 was probably due to the loam texture and clay loam that favored the displacement of water, and furthermore, the duripan was found at a depth of 53 cm, which causes the movement of water by lateral drainage. The infiltration in the *solum* of profiles II-2 and II-3 registered a lesser consumption, as they are deep soils with well-structured horizons of accumulation.

The infiltration of the three profiles in the duripan was slow and limited, due to the reduction of the porous space and the cementation that was present.

Table 5. Main physical properties.

			Particle-size distribution [mm]										Roundness and sphericity in silt and very fine sand						Densities and total porosity		
			Sand						Silt			Clay									
P	H	Depth [cm]	2-1	1–0.5	0.5–0.25	0.25–0.1	0.1–0.05	Total	0.05–0.02	0.02–0.002	Total	0.002	A HS	A LS	SA HS	SA LS	SR HS	SR LS	[g/cm³] BD	PD	% TP
			Percentage of less than 2-mm particles																		
II-1	A	0–36	7	7	9	18	8	49	10	27	37	14	23	68	9				1.30	2.15	40
	B	36–48	0	2	8	20	8	38	14	32	46	16			23	57	15	5	1.62	2.18	26
	B3	48–53	0	2	7	18	8	35	13	32	45	20			18	53	22	7	1.71	2.22	23
	Cqm	>53	0	1	2	3	3	9	19	46	65	26			5	6	40	49	1.80	2.20	19
II-2	A	0–14	1	3	10	20	11	45	10	25	35	20		15	40	45			1.28	2.20	42
	B21t	14–42	0	2	3	6	3	14	5	11	16	70			15	22	37	26	1.51	2.13	30
	B22t	42–70	0	3	6	8	4	21	6	13	19	60		20		15	40	25	1.69	2.35	29
	B3	70-110	0	1	3	12	9	25	10	25	35	40		25			33	42	1.70	2.42	30
	Cqm	>110	0	2	5	9	7	23	13	29	42	35				6	41	53	1.92	2.40	20
II-3	A11	0–16	0	1	5	11	27	44	10	26	36	20		35	10	30	10	15	1.36	2.38	43
	A12	16–29	0	2	9	19	12	42	11	27	38	20		25	20	15	24	16	1.38	2.25	39
	E	29–50	0	1	7	22	16	46	10	24	34	20	4	16	20	20	15	25	1.55	2.28	33
	B21t	50–87	0	3	10	24	8	45	5	10	15	40		15	17	44	6	18	1.69	2.40	30
	B22t	87–114	0	1	8	17	9	35	4	18	22	43			21	26	17	36	1.60	2.35	32
	B31	114–150	0	1	2	11	16	30	9	24	33	37			17	22	23	38	1.71	2.47	31
	B32	114–150	0	1	8	7	13	29	15	36	51	20			10	17	23	50	1.75	2.40	28
	Cqm	>180	0	1	7	9	5	22	15	45	60	18				8	46	46	1.90	2.47	24

The determination of the particle-size distribution was carried out after the treatments for eliminating aggregate compounds. A: angular, HS: high sphericity, LS: low sphericity, SA: subangular, SR: subrounded, BD: bulk density, PD: particle density, TP: total porosity.

CHEMICAL PROPERTIES

Alteration complex. The cationic exchangeable capacity (T) is medium in the three profiles (Table 6), which coincides with the types of clays that are present: kaolinite and metahalloysite. The base saturation percentage (base sum [s]/T) increases with depth on the profiles II-1 and II-2; and on the II-3 increases in an illuviation horizon, which indicates lixiviation. The pH follows the tendency of S/T at a reduced interval closer to

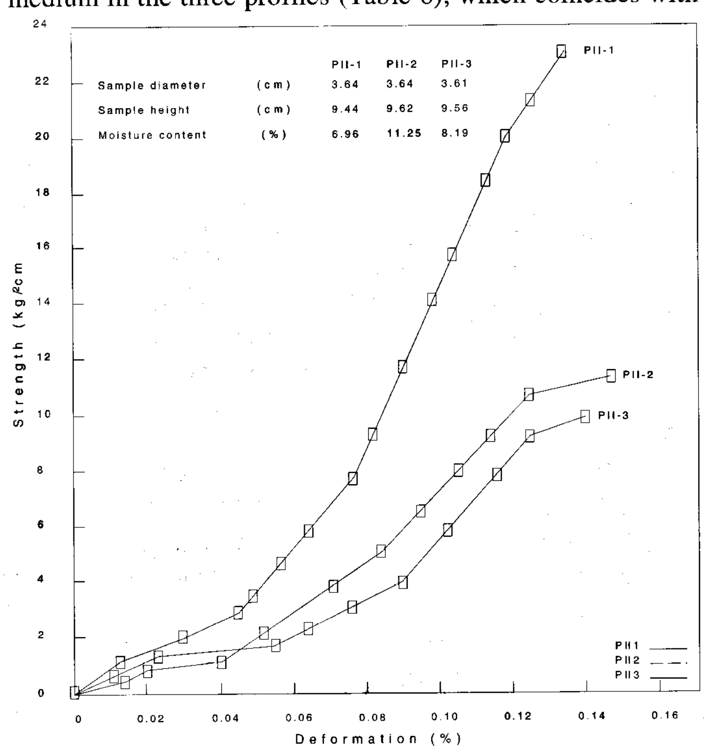

Figure 4. Resistance to unconfined compression in the duripans of the studied profiles.

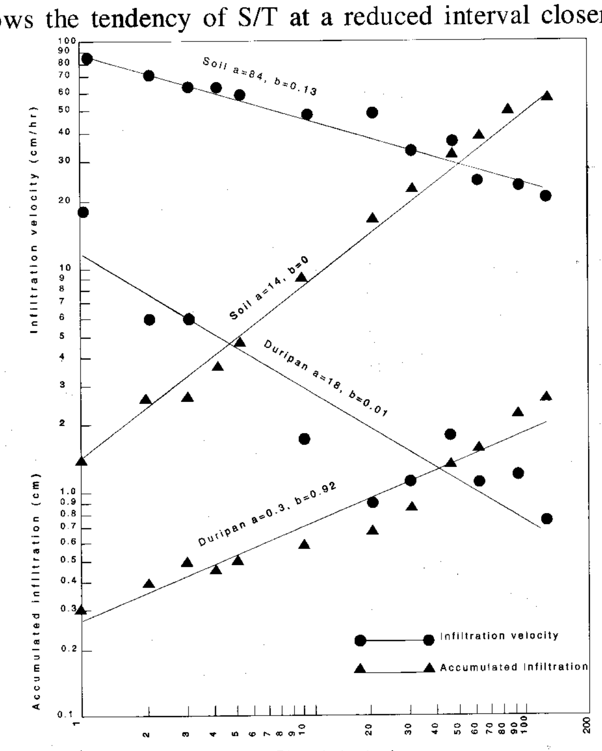

Figure 5. Components of infiltration on soil and duripan of profile II-1.

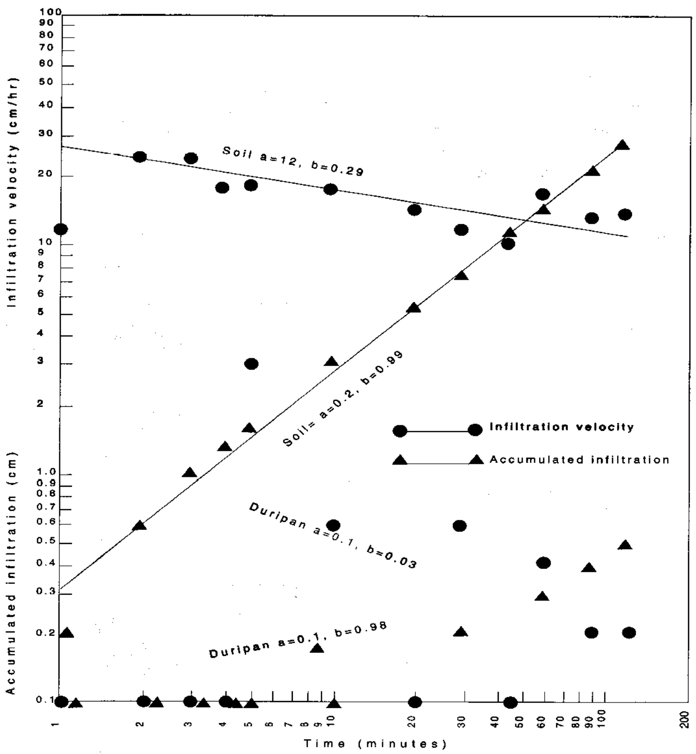

Figure 6. Components of infiltration on soil and duripan of profile II-2.

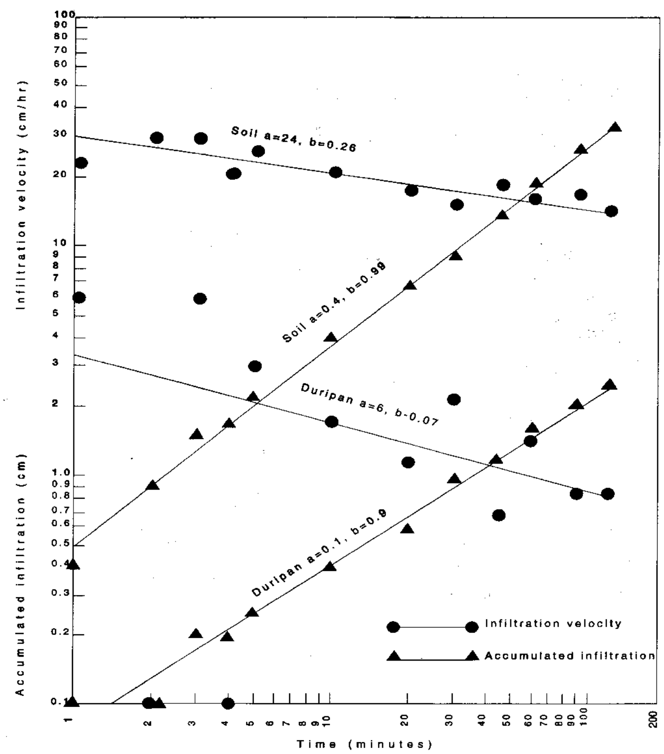

Figure 7. Components of infiltration on soil and duripan of profile II-3.

neutrality. The relation (Ca^{++} + Mg^{++})/K^+ shows a certain deficiency of Ca^{++} and Mg^{++} in the majority of the horizons of the three profiles and partially of K^+ on the II-1 and II-2 profiles, which is very probably due to processes of lixiviation. The interchangeable Al^{3+} is low and there is an increase in the accumulated horizons, which is congruent with the pH.

The content of organic matter in the upper horizons varies from medium to rich and decreases drastically with depth. The medium and low values of the C/N relation indicate stability and liberation of the mineral nitrogen, respectively.

Total oxides: losses and gains. In Table 4 the results of the total oxides of all the horizons of the studied profiles are presented. In Tables 7, 8 and 9 the losses and gains of the total oxides of the II-1, II-2 and II-3 profiles are shown.

After applying the aluminum constant and comparing the total oxides contained in the duripans with the accumulated

Table 6. Chemical analysis.

P	H	Depth [cm]	Ca^{2+}	Mg^{2+}	Na^+	K^+	Bases sat. [%]	Al^{3+} inter. [meq/100 g]	Organic matter [%]	pH H_2O 1:2.5	C.E.C.[cmol(+) per kg soil]	C [%]	N [%]	C/N
II-1	A	0-36	8.6	7.3	1.8	0.5	62	0.3	1.81	5.6	29	1.15	0.17	7
	B	36-48	9.8	7.3	1.5	0.3	55	0.5	0.60	6.2	34			
	B3	48-53	16.3	9.4	2.1	0.5	85	0.3	0.60	6.2	33			
	Cqm	>53	17.2	12.7	2.6	1.2	87	0.3	0.06	6.4	39			
II-2	A	0-14	9.4	4.2	1.4	1.0	80	0.4	4.35	5.9	20	2.65	0.17	15
	B21t	14-42	11.6	4.3	1.5	0.3	45	0.6	0.48	5.9	39			
	B22t	42-70	9.4	6.1	1.6	0.4	50	1.3	0.41	6.0	35			
	B3	70-110	8.6	7.7	1.0	0.3	75	1.3	0.22	6.0	23			
	Cqm	>110	8.6	7.7	2.3	0.6	87	0.6	0.06	6.2	22			
II-3	A11	0-16	12.4	5.5	0.9	1.3	80	0.6	4.00	5.8	25	2.38	0.21	11
	A12	16-29	8.6	4.3	1.7	0.8	59	0.8	3.50	5.8	26	1.98	0.15	13
	E	29-50	7.7	5.9	1.8	1.0	60	0.2	1.00	6.1	27	0.58	0.09	6
	B21t	50-87	9.0	7.2	2.8	1.5	73	0.6	0.47	6.1	28			
	B22t	87-114	6.4	5.1	2.0	1.5	51	1.1	0.46	6.0	29			
	B31	114-150	5.5	4.2	0.7	0.3	36	1.0	0.40	6.0	29			
	B32	114-150	9.4	4.7	0.9	0.7	56	0.3	0.33	5.8	28			
	Cqm	>180	5.1	2.1	0.7	0.2	26	0.3	0.02	5.6	31			

Table 7. Losses or gains of the weathered horizons in relation to the basal rock of profile II-1 [%].

Total Oxides	Horizons					Losses or gains			
	Cqm	B	A	B.K* Al_2O_3	A.K Al_2O_3	B	A	B	A
SiO_2	54.75	53.80	53.34	54.71	51.73	-0.04	-3.02	-0.07	-5.51
TiO_2	2.10	1.37	1.25	1.39	1.21	-0.71	-1.39	-34.00	-66.19
Al_2O_3	20.40	20.05	21.04	20.40	20.40	0	0	0	0
Fe_2O_3	4.80	4.39	4.18	4.46	4.05	-0.34	-0.75	-7.08	-15.62
FeO	0.62	1.38	1.22	1.40	1.18	+0.78	+0.56	+125.80	+90.32
MnO	0.90	0.14	0.12	0.14	0.12	-0.76	-0.78	-84.44	-86.67
MgO	1.40	3.00	2.42	3.05	2.34	+1.65	+0.94	+117.85	+67.14
CaO	2.23	2.38	2.36	2.42	2.28	+0.19	+0.05	+8.52	+2.24
Na_2O	1.37	1.55	1.30	1.57	1.26	+0.20	-0.11	+14.60	-8.03
K_2O	0.25	0.30	0.25	0.30	0.24	+0.05	-0.01	+20.00	-4.00
P_2O_5	0.13	0.15	0.15	0.15	0.14	+0.02	+0.01	+15.38	+7.69
SO_3									
H_2O^+	4.45	4.00	3.85						
H_2O^-	6.60	7.49	8.52	7.61	8.26	+1.01	+1.66	+15.30	+25.15
Total	100.00	100.00	100.00	97.60	93.21				

*The aluminum constant (K) is obtained dividing the aluminum percentage of the unaltered rock (Cqm) between the aluminum percentage of the altered rock (B or A). This constant is multiplied for each oxide of the altered horizons. The results are compared with the unaltered rock and by substraction the losses or gains are obtained (Krauskopf, 1979).

Table 8. Losses or gains of the weathered horizons in relation to the basal rock of profile II-2 [%].

Total Oxides	Horizons					Losses or gains			
	Cqm	B	A	B.K Al_2O_3	A.K Al_2O_3	B	A	B	A
SiO_2	53.91	40.96	52.59	35.74	43.17	-18.17	-10.74	-33.70	-19.92
TiO_2	0.81	1.91	0.82	1.66	0.67	+0.85	-15.00	+104.93	-18.52
Al_2O_3	19.14	21.93	23.32	19.14	19.14	0	0	0	00
Fe_2O_3	6.10	14.67	2.90	12.80	2.38	+6.70	-3.72	+109.83	-60.98
FeO	0.58	0.58	2.93	0.50	2.40	-0.08	+1.82	-13.79	+313.79
MnO	0.17	0.53	0.12	0.46	0.10	+0.29	-0.07	+170.58	-41.17
MgO	0.65	0.43	1.90	0.37	1.56	-0.28	+0.91	-43.07	+140.00
CaO	2.89	0.64	2.24	0.55	1.84	-2.34	-1.05	-80.96	-36.33
Na_2O	1.40	0.32	1.10	0.28	0.90	-1.12	-0.50	-80.00	-35.71
K_2O	0.48	0.32	0.40	0.28	0.33	-0.20	-0.15	-41.67	-31.25
P_2O_5	0.04	0.04	0.17	0.03	0.14	-0.01	+0.10	-25.00	+250.00
SO_3									
H_2O^+	3.15	2.99	3.01						
H_2O^-	10.68	14.68	8.50	12.81	6.98	+2.13	-3.70	+19.94	-34.64
Total	100.00	100.00	100.00	84.62	79.61				

horizons, the following results were obtained: profile II-1, gains of FeO, MgO, CaO, Na_2O, K_2O, P_2O_5 and H_2O; losses of SiO_2, TiO_2, Fe_2O_3 and MnO. Profile II-2, gains of TiO_2, Fe_2O_3, MnO and H_2O; losses of SiO_2, FeO, MgO, CaO, Na_2O, K_2O and P_2O_5. Profile II-3, gains of SiO_2, TiO_2, Fe_2O_3, FeO, MnO, CaO, P_2O_5 and H_2O; losses of MgO, Na_2O and K_2O.

On profile II-1, the gains of FeO and MgO are due to the alteration of iron magnesium pyroxene and also to the presence of hematite and magnetite, both detected in the petrographic analysis. The Ca, Na and K oxides originated from the weathering of the calciumsodic and potassium feldspars and the P_2O_5 from the apatite and the H_2O, from the presence of clays and the opaline silicate. The losses on this profile coincide with intense alteration conditions in these soils.

On profile II-2, the gains of TiO_2 are due mainly to the weathering of the amphiboles, and the pyroxenes. The presence of MnO is a consequence of its liberation under seasonal hydric conditions, from different igneous materials (Stumm, 1986). The gains of Fe_2O_3 and H_2O are explained in a similar way as on profile II-1. In the same way, the losses are due to weathering.

Profile II-3 behaves in a similar way as the previous ones. Only the SiO_2 is different and this is due to the alteration of volcanic glass.

When the total oxides contained in the duripans were compared with those of horizons A, the following results were obtained: for profiles II-1 and II-3, the behavior of the oxides from horizon A is very similar to the one from horizon B, only two oxides from each profile showed losses. On profile II-2, there are losses and gains, but there are more losses. Such losses are related to the eluviation processes.

Molar ratios. As can be observed on Table 4, the silica/alumina relation (s/a) shows low values, although greater than two, which represents a level of high weathering. The silica/iron relation (s/f) shows proportions greater than that of s/a, due to a greater abundance of aluminum over iron, which confirms the aforementioned level of weathering. The silica/sesquiox-

Table 9 . Losses or gains of the weathered horizons in relation to the basal rock of profile II-3 [%].

Total Oxides	Horizons					Losses or gains			
	Cqm	B	A	B.K Al_2O_3	A.K Al_2O_3	B	A	B	A
SiO_2	57.23	59.36	47.64	70.49	48.44	+13.26	-8.79	+23.16	-15.35
TiO_2	1.60	1.47	0.89	1.74	0.90	+0.14	-0.70	+8.75	-43.75
Al_2O_3	19.18	16.15	18.86	19.18	19.18	0	0	0	0
Fe_2O_3	6.00	6.86	6.30	8.14	6.40	+2.14	+0.40	-35.67	+6.67
FeO	0.90	0.86	2.45	1.02	2.49	+0.12	+1.59	+13.34	+176.67
MnO	0.12	0.33	0.34	0.39	0.34	+0.27	+0.22	+225.00	+183.34
MgO	1.76	0.71	1.47	0.84	1.49	-0.92	-0.27	-52.27	-15.34
CaO	1.94	1.75	2.15	2.07	2.18	+0.13	+0.24	+6.70	+12.37
Na_2O	1.90	1.20	1.20	1.42	1.22	-0.48	-0.68	-25.26	-35.78
K_2O	1.50	0.62	0.59	0.73	0.60	-0.77	-0.90	-51.34	-60.00
P_2O_5	0.16	0.21	0.32	0.24	0.32	+0.08	+0.16	+50.00	+100.00
SO_3									
H_2O^+	5.70	1.87	3.41						
H_2O^-	2.01	8.61	14.38	10.22	14.62	+8.21	+12.61	+408.45	+627.36
Total	100.00	100.00	100.00	116.48					

ides (s/R_2O_3) and base/aluminum (b/a) ratios, also with low values, support what was mentioned before.

Free oxides. Steinhardt and coworkers (1982) pointed out that the contents of free oxides are directly proportional to the contents of clay; nevertheless, in this research, the clay shows very high percentages in relation to the free oxides, which, in part, is explained by the great clay formation that has occurred in these soils (Tables 5 and 1).

On the other hand, the sum of the free oxide percentages and the clay contents, reflects a high grade of alteration in these soils.

On profile II-1, only in horizons A and B3 does the sum of the free oxides passes the contents of clay. In the rest of the profiles, the clay is clearly greater than the free oxides, principally on the B21t and B22t horizons (argiles). Likewise, the highest contents of the mentioned oxides were present in horizon B and the lowest values in the duripans.

Microanalysis of the cement of the duripans. It was detected, by means of microanalysis, for profiles II-1, II-2 and II-3, the percentages of SiO_2 were 60.80, 61.36 and 57.50, respectively. The Al_2O_3 was 28.65, 22.02 and 31.46% in the same order.

The FeO was 9.02, 17.05 and 9.29% in the same sequence. The rest of the oxides showed very low percentages. The SiO_2/Al_2O_3 relations were of 2.12, 2.78 and 1.32, respectively. On Figures 8, 9 and 10, photomicrography of the duripans, where the cement matrix can be observed, is shown.

The high percentage of Al_2O_3, in this siliceous or protoopal material, is very notorious, and it is considered due to the presence of clays and amorphous compounds. This can be confirmed with the cationic exchange capacity in the duripans. Although the clay contents in the latter were from medium to low, such capacity of interchange was highest in the duripans of profiles II-1 and II-3.

Petrographic analysis of the duripans. The study was done principally in the fractions of silt and sand. The three duripans presented the following characteristics:
Fabric: glass with abundant fragments and microlite of crystals.
Mineralogy: plagioclase (andesine), pyroxene, apatite, magnetite and quartz in fragments or small microlites.
Interpretation: the degree of alteration of the sample is medium; it conserves the original structure of a pyroclastic deposit. It initiates the formation of some clayish minerals, such as kaolinites and metahalloysites and also of the PII-1, montmorillonite. Furthermore, incipient chalcedony forms were detected.

These duripans are classified as pyroclasts of an intermediate composition and are similar in their nature and composition to an andesitic tuff. Its deposit probably originated as an ash flow or as an ash cloud.

Mineralogic analysis. In Table 10, the result of the mineralogic analysis by X-ray diffraction, in the clay fraction of all the horizons of the studied profiles, is presented. It can be seen that the kaolinite dominates in general, with metahalloysite following in importance, in relatively low percentages, in two horizons of profile II-1.

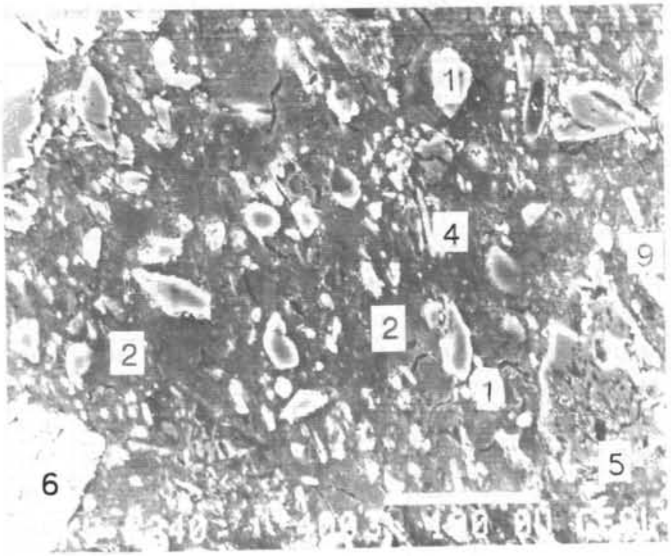

Figure 8. Photomicrograph of the duripan of profile II-1. From the right side, a sort of orientation of the minerals can be seen. Its deposit was probably formed from mass flow. Explanation for figures 8, 9 and 10: 1, Volcanic glass, zones of glass alteration. 2, Matrix of glassy cement. 3, Apatite. 4, Phytolith. 5, Quartz in advanced alteration state. 6, Pyroxene, chloritized augite. 7, Pyrite and volcanic glass. 8, Pyrite. 9, Plagioclase. 10, Apatite crystal.

SOIL CLASSIFICATION

According to FAO-UNESCO (1990), the soils of profiles II-1 and II-2 are classified as Chromic Luvisols; and according to the Soil Survey Staff (1990), as Udic Haplustalfs.

Likewise, the soils represented by profile II-3 corresponded, at the beginning, with units of Ortic Acrisols or Tipic

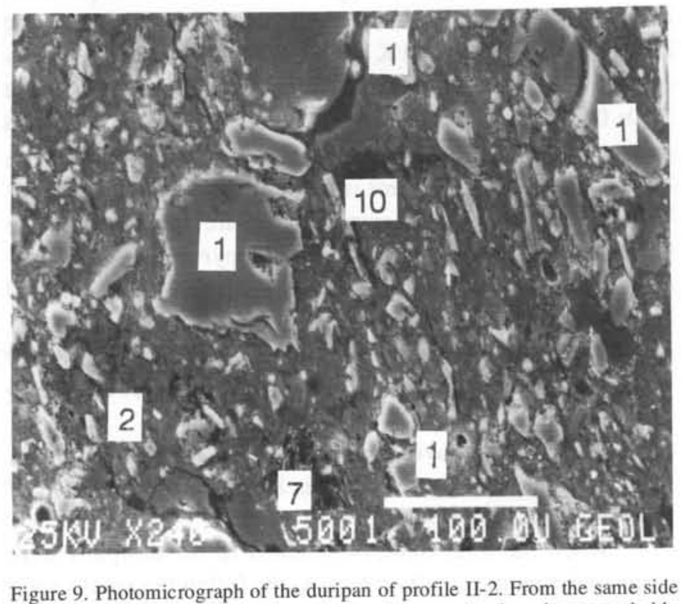

Figure 9. Photomicrograph of the duripan of profile II-2. From the same side as on Figure 8, the mineral orientation can be seen. Its deposit was probably formed in the same way as on profile II-1. Explanation in Figure 8.

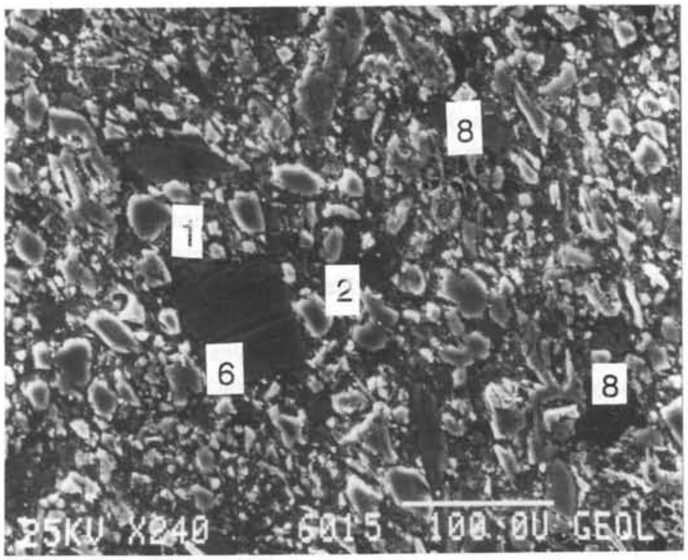

Figure 10. Photomicrograph of the duripan of profile II-3. It can be seen that the minerals show no orientation. Its deposit was probably in the form of an ash cloud. Explanation in Figure 8.

Hapludults, respectively. Nevertheless, the rejuvenation that they have suffered places them in the Alfisol order.

ORIGIN OF SOILS AND DURIPANS

The formation of the soils began with andesitic tuffs in the Pleistocene epoch (Fries, 1965) process that was interrupted by the successive appearance of acidic pyroclasts (Figure 11). Nevertheless, a very intense weathering took place, producing a strong lixiviation, the formation of illuviation horizons with high clay contents, iron oxides, concretions of manganese oxides, oxidation-reduction and decreasing of porosity with depth.

This condition is considered to be due to the presence of a catastrophic event such as glaciation (Flores-Román *et al.*, 1992), which produced a weight and lixiviation effect. With the current climate, the formation of these soils would probably not have been possible. For this reason, paleosoils are considered to be the result of a paleobioclimatic event (Solleiro *et al.*, in press). It is also very probable that holartic vegetation, which could have withstood the imperant weather conditions and contributed to the formation of the soils, could have existed. Later, with the appearance of more pyroclastics and the current climate, these soils would have rejuvenated their upper horizons, giving them brown lixivial soil characteristics (Duchaufour, 1984).

Concerning the duripans, these consist of the preceding andesitic tuffs. The subsequent appearance of acidic pyroclastics enriched them in silicate cement material, derived from volcanic glass and amorphous material (Flach *et al.*, 1969). In soil leaching, this silicate material is transferred from the top to the bottom of the profile, during the rainy period. In the same manner, very fine clays follow the same way, carrying a negative charge, as does the soil matrix, and tend to disperse unless something is present to keep them flocculated. Sodium ions, between critical limits of concentration, increase the dispersion of clay (Soil Survey Staff, 1990). When the rainy period finishes and the profile moisture has gone, the silica precipitates like cement and joins the mineral particles. This phenomenon occurs in the boundary between the soil and the tuffy material, which gradually is cemented. Later, after the soils form, the appearance of silicate material in the duripans decreases (Table 4), but the new formation and illuviation clay has increased (Benayas *et al.*, 1991). This was proved with the C.E.C. values observed in these materials (Table 5). It is considered that these duripans are of igneous origin with secondary pedologic appearances.

Table 10. Mineralogic analysis.

Profile	Horizon	Depth [cm]	Mineralogic analysis by X-ray diffraction in the clay fraction [%]						
II-1	A	0-36	KK48	MH25	GE10	QC8	FD6	MT2	
	B	36-48	KK50	MH25	QC10	FD10	GE5		
	B3	48-53	KK41	FD27	MH23	QC6	MT2		
	Cqm	>53	KK49	MH18	FD17	QC10	GE6		
II-2	A	0-14	KK53	MH28	GE8	QC6	Qz2	MI1	FD1
	B21t	14-42	KK60	QC18	MH10	GE8	Qz2	FD1	
	B22t	42-70	KK50	MH28	QC15	AM3	Qz2	MI1	
	B3	70-110	KK50	MH40	QC6	FD3			
	Cqm	>110	MH38	KK25	FD13	QC11	GE8	Qz4	
II-3	A11	0-16	KK58	MH21	FD12	QC8			
	A12	16-29	KK68	FD13	MH9	QC9			
	E	29-50	KK45	QC23	MH21	FD10			
	B21t	50-87	KK60	MH19	QC13	FD6	MI1		
	B22t	87-114	KK45	MH30	FD13	QC10	MI1		
	B31	114-150	KK70	QC12	FD10	MH6	MI1		
	B32	114-150	KK42	MH40	FD9	QC7	MI1		
	Cqm	>180	KK47	MH16	QC14	Qz12	FD10		

KK: Kaolinite. MH: Metahalloysite. QC: Cristobalite. GE: Goethite. FD: Feldspars. MT: Montmorillonite. Qz: Quartz. MI: Mica. AM: Amphiboles.

CONCLUSIONS

According to the results, the following can be concluded:

- The morphological field classification of these soils showed a high development.
- The percentage of clay varied by the clay formation and contribution with depth, reaching its greatest concentration in the illuviation horizons. The greatest percentages of total silt were present in the duripans and most of it corresponded to medium and fine silt. The highest proportions of total sand were detected in the upper horizons, where fine and very fine sand dominated.
- The particles of subangular roundness and low sphericity were more abundant in silt and very fine sand.

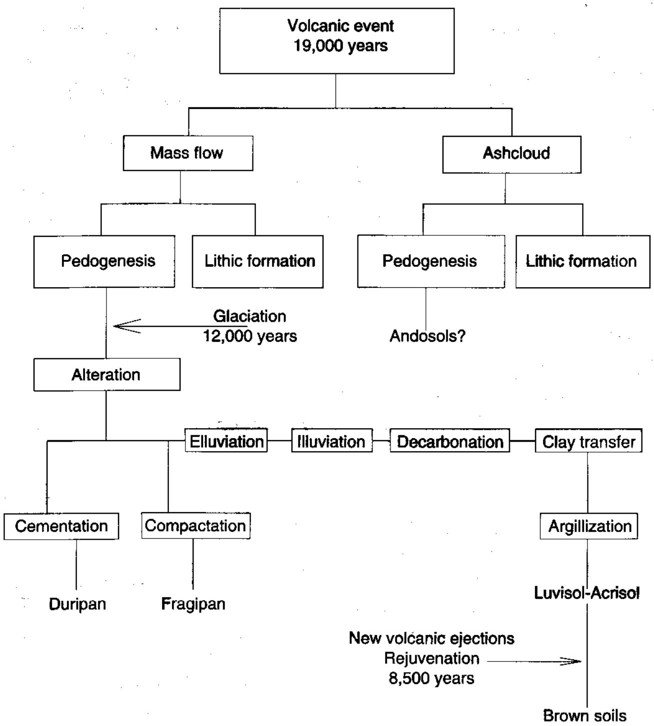

Figure 11. Possible sequence of the soil and duripan genesis.

- The duripans, in relation to the upper horizons, presented a lower number of discontinuous and partially closed pores of lesser diameter.
- The resistance to simple compression of the duripans presented low values.
- The duripans showed very low infiltration levels in relation to the superior horizons.
- The levels of cationic exchange capacity, pH, interchangeable Al^{3+}, saturation of bases, Ca^{2+}, Mg^{2+}, K^{+}, organic matter and C/N relation that were detected, were congruent with the development degree of the soils studied here.
- The losses and gains of total oxides showed the high weathering to which these soils were subject and the rejuvenation that they now present, especially in the Acrisols case.
- The high contents of Al_2O_3 in the cement of the duripan indicated the presence of clays, of neoformation, as well as illuviation which stayed within the proto-opaline matrix.
- The petrographic study of the duripans permitted their classification as intermediate composition pyroclastics, similar to an andesitic tuff.
- The mineralogy of the clay fraction was mostly made up of kaolinite and metahalloysite.
- The soils were considered paleosols, resulting from a paleobioclimatic event which occurred during the Pleistocene epoch.
- The duripans were of igneous origin with secondary pedogenetic appearances.
- The methodologic design employed was satisfactory.

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