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GENESIS OF WHITE FRAGIPANS OF VOLCANIC ORIGIN

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ABSTRACT

The objectives of this study are: (1) to determine the main physical, chemical, petrographic and mineralogical properties of the soils and the indurated layers of the study area; (2) to establish the horizon and profile development; and (3) to state hypotheses about the genesis of both.

The main results are: (a) the three studied profiles show poor evolution, because of climate unencouraging to soil formation and felsic nature of the parent material; (b) the roundness and sphericity of the mineral particles are due to their aerial deposition; (c) the resistance to simple compression demonstrates that the studied indurated layers present specific diagnostic characteristics, that do not correspond to reports of other authors; (d) in profile 2, the total oxides losses and gains are consistent with the climate conditions on the zone; (e) petrographic study shows that indurated layers are tuffs moderately consolidated, with secondary pedogenetic processes.

The most important conclusions are: (a) the field morphologic classification indicates a limited evolution of the soils; (b) the white fragipans resistance to simple compression presents low values in two cases and intermediate in the third one; (c) the total oxides analysis, in such layers, identifies them as pyroclastic materials of felsic nature that present a low weathering grade; (d) the microanalysis of cement shows that this material is made up of silica gel that cementing clays.

Key words: White fragipans, genesis, soils of volcanic origin.

RESUMEN

Los objetivos de este trabajo son: (1) determinar las principales propiedades físicas, químicas, petrogáficas y mineralógicas de los suelos y las capas endurecidas del área de estudio; (2) establecer el desarrollo evolutivo de los suelos; y (3) plantear hipótesis sobre la génesis de ambos.

Los principales resultados son: (a) los tres perfiles estudiados manifiestan un desarrollo evolutivo pobre, debido a la baja agresividad climática y a la naturaleza félsica del material parental; (b) la redondez y esfericidad de los granos minerales se debe a su depósito aéreo; (c)la resistencia a compresión simple demuestra que las capas endurecidas estudiadas presentan características de diagnóstico específico, que no corresponden a lo reportado por otros autores; (d) en el perfil 2, las pérdidas o ganancias de óxidos totales son congruentes con las condiciones ambientales que prevalecen en la zona; (e) el estudio petrográfico manifiesta que las capas endurecidas son tobas moderadamente consolidadas, con procesos pedogenéticos secundarios.

Las principales conclusiones son: (a) la clasificación morfológica de campo indica un escaso desarrollo evolutivo de los suelos; (b) la resistencia a compresión simple de los fragipanes blancos presenta valores bajos en dos casos e intermedio en otro; (c) el análisis de los óxidos totales en tales capas, las identifica como materiales piroclásticos de naturaleza félsica que presentan un grado bajo de intemperismo; (d) el microanálisis del cementante muestra que se trata de geles de sílice, que unidos con las arcillas, promueven la cementación.

Palabras clave: Fragipanes blancos, génesis, suelos de origen volcánico.

INTRODUCTION

In Mexico, soils with indurated layers cover an area of about 660,000 km^2 (Flores-Román et al., 1991), which are total or partialy cemented by different agents like silica, calcium carbonate or sulphate, aluminum or iron oxides, and clays. According to these cementing agents, soils have different names.

In the Transmexican Volcanic Belt the cemented layers origin has been discussed by several researchers (Zebrowski, 1992; Quantin et al., 1993; Flores-Román et al., 1996). They offer hypotheses such as pyroclastic material hardening when volcanic deposition, or pedological cementation. This favours subsuperficial cementation and hardness or the combination of both processes.

Research on white cemented layers of volcanic origin is very limited in Mexico. Therefore, their physical, chemical, morphological, mineralogical and also their diagenetic and pedogenetic processes are unknown.

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Soil Survey Staff (1994) states that duripan is a subsurface horizon cemented by silica. Fragipan is a near to surface horizon, loamy texture, high bulk density, seems to be cemented when dry, fragile if wet, a dry piece fractures or collapses when placed in water. Both materials of volcanic origin are known in Mexico as tepetates.

The objectives of this study are: (1) to determine the main physical, chemical, petrographic and mineralogical properties of white tepetates and their soils; (2) to establish horizon and profile development; and (3) to consider hypothesis about soil origin and indurated layers.

CHARACTERISTICS OF THE STUDY AREA

The study area is located between the 19° 33' - 19° 45' N y 99° 10' - 99° 23' W, with an altitude from 2,350 to 2,420 m a.s.l. (Figure 1). Three representative profiles were selected, showing a white - light grey color and subsuperficial indurated layer.

The area belongs to Transmexican Volcanic Belt Physiographic Province and is included whitin the Tarango Formation, made up by volcanic ashes, pumice, lavas and tuffs of dacitic nature from mid Terciary (Mooser, 1967). The climate, according to Köppen, modified by García (1988), is Cb(wo)(w)(i'), which is temperate, the dryest of the subhumid climates, with summer rain regime, little thermal oscillation, total annual rain of 620.6 mm and average annual temperature of 15.7° C.

The area shows many hills with convex slopes, between 6 and 20%, where human influence upon the soil resource has been very strong. Its present use is depauperated induced grassland.

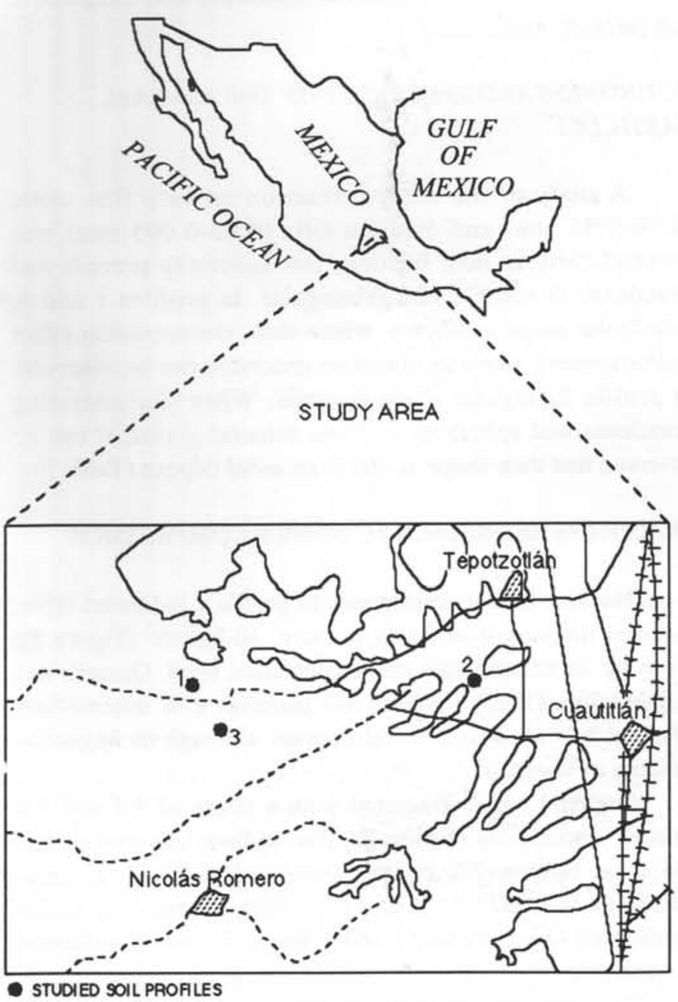

Figure 1. Location of the study area.

METHODOLOGY

Representative profiles selection was accomplished starting with a photointerpretation based on Van Zuidam (1979), where black and white panchromatic aerial photographs on a scale 1: 75,000 were studied. Cartographic suppport material was collected and a reconnaissance of the land was undertaken.

Profile morphological characterization was done according to Soil Survey Staff (1984). By means of the field morphological rating system (Birkeland *et al.*, 1990), horizon relative development (HRD) was determined by the comparison of two adjacent horizons and profile development index (PDI) by comparing each horizon with the cemented layer. The climatic aggression index for the zone, was accomplished by using Fournier paper, modified by FAO - PNUMA (1980).

Physical and chemical analysis of soil samples and indurated layers were done in the soil fertility laboratory of the Instituto de Geología of the Universidad Nacional Autónoma de México.

Dried and sieved samples were ready for the following tests: color, by comparing with the Munsell Color Chart (Munsell 1954); particle size distribution (pipette method) was accomplished by following the method of Day (1965); particle roundness and sphericity were studied according to Powers scale (1953) in an observation microscope; before this test, the adding effect among particles was eliminated (Day, *op. cit.*). Bulk and particle densities, total porous space percentage, exchangeable cations, organic matter, pH, cationic exchange capacity, organic carbon, total nitrogen and available phosphorous were determined as decribed by Soil Survey Staff (1984).

Resistance to single compression was determined in a carved nucleus, subject to increasing force, in an unconfined compression apparatus. Weathering of the soils with indurated layers was studied by means of the total oxides test (Verbeek *et al.*, 1982), determinated by atomic absorption in a Perkin Elmer spectrophotometer, model 3110. To establish total oxides losses or gains between the parent rock and the weathered horizons, the Al_2O_3 constant was applied (Krauskopf, 1979). The test of free oxides SiO_2, Al_2O_3 and Fe_2O_3 was undertaken according to Mehra and Jackson (1960). For the cement agent microanalysis 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. Sample preparation consisted of making thin, polished sections, covered previously with an ionized gold coat. Petrographic study was carried out on thin sections, examined under the petrographic microscope with magnifications up to 125x, by following Bullok and collaborators description (1985). For mineralogical analysis, an X-ray diffraction, a Philips PW 1130/96 generator, with filtered copper Koc radiation, graphite monochromator, and excitation conditions of 30kV-20 mA, were used. The procedures of clay mineral identification were based in Mineral Powder Diffraction File, Search Manual and Data Book (JCPDS, 1986a, b). Likewise, at samples, pretreatments with K-saturation and heating at 350° and 550° C were applied; later, confirmation evidence was realized.

RESULTS AND DISCUSSION

FIELD MORPHOLOGICAL RATING

Tables 1, 2 and 4 show the studied profiles morphological properties used to estimate the horizons relative development (HRD) and the profile development index (PDI). Table 3 displays the HRD and PDI values.

The HRD values resulting for the three profiles indicate slight horizon development, due to scarce effect of the prevailing weathering factors, except the indurated layers of profiles 2 and 3, that show values lower than 0.20 (Table 3). This explains the low degree of alteration by pedological processes.

The above facts are confirmed by PDI; values show that the three studied profiles indicate poor development. Probably, this is due to lithological discontinuity, climatic conditions that do not promote weathering on the study zone, and to parent material felsic nature. The obtained climatic aggression index was 93.07, which is considered low (FAO-PNUMA, 1980).

BULK DENSITY, PARTICLE DENSITY AND TOTAL POROSITY

Table 1 data indicate that of bulk density horizons and indurated layers on the studied profiles range from 0.99 to 1.91 g/cm^3. Profiles 1 and 2 show bulk density values larger than 1.3 g/cm^3 on top horizons, except profile 2 horizon A_{11}, 1.14 g/cm^3, that suggest a significant compression level (Primavesi, 1980), given by simple pressure or material consolidation due to water movement (Assally et al., 1998).

Profiles 1 and 3 indurated layers show bulk density of 1.27 g/cm^3 or lower, which is refered to the amount of vesicular pumice found in abundance and distributed through the tuff. Profile 2, at more than 43 cm depth, has bulk densities greater than 1.58 g/cm^3, indicating high consolidation and or compression, favoured in long part by organic matter absence and its own mass structure, that at the same time limited the permeability.

Particle density of all profiles is consistent with parent material nature and may show, by its values (Table 1), a dominance of light minerals and lack of iron-magnesium.

Bulk and particle densities values from indurated layers of studied profiles, do not coincide with other author reports (Nimlos, 1989; Quantin et al., 1993; Flores-Román et al., 1992, 1996).

On profile 3, total porosity of indurated layers is high, decreases in profile 1, and is very low in profile 2.

PARTICLE SIZE DISTRIBUTION

Table 4 shows particle size distribution of the three profiles, which are dominated by medium sand (0.5-0.25 mm), fine sand (0.25-0.10 mm), and very fine sand (0.10-0.05 mm). These percentages, according to depth, decrease in profile 1, increase in profile 3 and they have stability in profile 2.

In the same table, total silt increases in profile 1 and decreases in profiles 2 and 3. Clay contents, in general, are high in profile 1, but increases with depth; in profiles 2 and 3 such contents diminish drasticly in C-horizon.

This particle size distribution, mainly in profiles 1 and 3, probably, is due to lithological discontinuity and unagressive soil forming conditions.

ROUNDNESS AND SPHERICITY OF THE MINERAL PARTICLES

A study of the mineral fraction on very fine sands (0.10-0.05 mm) and medium silts (0.02-0.005 mm) was accomplished. In both fractions low sphericity prevails and roundness is angular and subangular. In profiles 1 and 3, subangular shape dominates, where some transportation effect and/or primary minerals alteration processes can be observed. In profile 2, angular shape prevails. When characterizing roundness and sphericity of these mineral grains, it can be observed that their shape is due to an aerial deposit (Table 5).

FRAGIPANS RESISTANCE TO SIMPLE COMPRESSION

Nucleus 2, that corresponds to profile 2 indurated layer, required the largest stress to fracture, 30 kg/cm^2 (Figure 2), given by its compression and cementation level. Quantin and collaborators (1993) consider this material with intermediate behavior between fragipan and duripan, although its fragments collapse in water.

Nuclei 1 and 3 fractured with a stress of 9.3 and 5.8 kg/cm^2, respectively (Figure 2). Due to their behavior in this test, these indurated layers are considered fragipans (Flores-Román et al., 1992; Quantin et al., 1993). Resembling profile 2 indurated layer, profiles 1 and 3 layers fragments collapsed in water too.

This test proves that indurated layers of the studied profiles, show specific diagnosis characteristic that do not

Table 1. Color, density and total porosity of the studied profiles.

Profile	Horizon	Depth cm	COLOR Dry	Moist	DENSITY (g/cm^3) Bulk	Particle	Total porosity (%)
1	A_{11}	0-20	10YR 6/2 Ligth brownish gray	10YR 3/1 Very dark gray	1.91	2.35	18.72
	A_{12}	20-32	2.5Y 7/0	2.5Y 5/2	1.65	2.18	24.31
	AC	32-50	2.5Y 8/0 White	2.5Y 6/2 Light brownish gray	1.25	1.75	28.57
	2Cx1	50-80	2.5Y 8/0 White	2.5Y 7/2 Light gray	1.17	1.87	37.43
	2Cx2	80-110	2.5Y 8/0 White	2.5Y 7/2 Light gray	1.17	1.91	38.74
	2Cx3	110-140	2.5Y 8/0 White	2.5Y 7/2 Light gray	1.27	1.82	30.22
2	A_{11}	0-17	7.5YR 5/2 Brown	7.5YR 3/2 Dark brown	1.14	2.25	49.33
	A_{12}	17-31	7.5YR 4/2 Dark brown	7.5YR 2/0 Black	1.66	2.13	22.06
	AC	31-48	7.5YR 7/2 Pinkish gray	7.5YR 5/2 Brown	1.83	1.90	3.68
	Cx1	48-78	7.5YR 8/2 Pinkish wuite	7.5YR 6/2 Pinkish gray	1.59	2.00	20.50
	Cx2	78-108	7.5YR 7/2 Pinkish gray	7.5YR 6/2 Pinkish gray	1.58	2.11	25.11
	Cx3	108-133	7.5YR 7/2 Pinkish gray	7.5YR 6/2 Pinkish gray	2.05	2.03	0.00
3	A_{11}	0-80	10YR 6/3 Pale brown	10YR 3/3 Dark brown	1.03	2.06	50.00
	A_{12}	8-19	10YR 7/3 Very pale brown	7.5YR 5/4 Brown	1.07	2.20	51.36
	AC	19-40	10YR 8/4 Very pale brown	10YR 4/4 Dark yellowish brown	1.21	2.19	44.74
	2Cx1	40-70	2.5 8/2 White	2.5Y 5/4 Light olive brown	1.06	2.25	52.88
	2Cx2	70-100	2.5Y 7/2 Light gray	2.5Y 5/2 Grayish brown	0.99	2.23	55.60
	2Cx3	100-130	2.5Y 7/2 Light gray	2.5Y 6/4 Dark yellowish brown	1.01	2.32	56.46

correspond to other papers regarding indurated soils of volcanic origin. According to the above statement, these poorly compacted tuffs are classified as analogous to fragipans with medium cementation degree.

MAIN CHEMICAL PROPERTIES

Regarding chemical properties (Table 6), organic matter content, nitrogen, phosphorus and C/N ratio fluctuate from medium poor to poor on soil and indurated layers (Vázquez and Bautista, 1993). The pH ranges from alkaline to strongly alkaline, condition that increases at greater depth; this rise is due to pyroclastic secondary additions and to the parental material, where sodic and calcic feldespar predominate.

Interchangeable bases, Ca^{++} and Mg^{++}, show high to medium values, while K+ content ranges from low to very low, except on profile 2, high to medium values (Vázquez y Bautista, op. cit.). Generally, base saturation percentage is

Table 2. Morphological properties of the studied profiles.

Profile	Horizon	Depth cm	Structure	Consistency dry	Consistency moist	Clay films	Lower boundaries
1	A_{11}	0-20	sab-f-mo	h	fm	a	gradual
	A_{12}	20-32	sab-me-mo	h	fm	a	clear
	AC	32-50	g-f-mo	so	fr	a	-
2	A_{11}	0-17	sab-f-mo	so	fr	a	gradual
	A_{12}	17-31	sab-th-mo	h	fr	a	gradual
	AC	31-43	sab-me-mo	lh	fr	a	gradual
	Cx	43-133	m	h	fm	a	-
3	A11	0-8	sab-f-mo	h	fr	a	gradual
	A12	8-19	sab-me-mo	lh	fr	a	gradual
	AC	19-40	sab-f-mo	h	fr	ds-ti-v	gradual
	2Cx	40-130	m	h	fm	a	-

a = not present; sab = subangular blocks; f = fine; mo = moderate; me = medium; g = granular; m = massive; th = thick; h = hard; so = soft; vh = very hard; lh = lightly hard; fm = firm; fr = friable; ds = discontinous; ti = thin; v = vertical.

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

Profile	Horizon	RHD	PDI	Profile	Horizon	RHD	PDI	Profile	Horizon	RHD	PDI
1	A_{11}-A_{12}	0.38	0.21	2	A_{11}-A_{12}	0.28	0.16	3	A_{11}-A_{12}	0.19	0.18
	A_{12}-AC	0.36			A_{12}-AC	0.29			A_{12}-AC	0.24	
	AC-2Cx1	0.30			AC-Cx1	0.29			AC-Cx1	0.37	
	2Cx1-2Cx2	0.20			Cx1-Cx2	0.13			Cx1-Cx2	0.21	
	2Cx2-2Cx3	0.22			Cx2-Cx3	0.19			2Cx2-2Cx3	0.18	

0.0-0.20 Young soil 0.61-0.80 Developed
0.21-0.40 Lightly developed 0.81-1.00 Strongly developed
0.41-0.60 Moderately developed

RHD: Relative horizon development PDI: Profile development index

high; calcium and magnesium saturate the complex. This indicates cation lixiviation processes, from the surface to inside the profile. Profile indurated layer shows a lower bases saturation percentage, considering the other two profiles.

Cationic exchange capacity (CEC) ranges from medium to very high (Vázquez y Bautista, op. cit.) In this study such capacity coincides with the present minerals—halloysite and montmorillonite clays and also amorphous silica gel shaped or proto-opal (Parfit et al., 1980; Shoji et al., 1993).

FREE OXIDES

Steinhardt and collaborators (1982) mention that free oxides, SiO_2, Al_2O_3 and Fe_2O_3 are cemented agents joining mineral particles. Their percentages on studied profiles are considered scarce and decrease with depth. This condition is due to already quoted factors: zone environmental conditions, low aggression and felsic nature of geological material.

Cruz and collaborators (1990) found on the State of Mexico tepetates fluctuations on weight percentages of SiO_2 from 6.3 to 8.6, and Al_2O_3 from 0.19 to 0.83. Flores and collaborators (1992) obtained on fragipans from the State of Morelos, for SiO_2: 10.7-31.0, for Al_2O_3: 6-10, and for Fe_2O_3: 0.14-1.80. Also, Flores-Román and collaborators (1996), on duripans from the State of Morelos, mark contents of SiO_2: 5.5-7.5, Al_2O_3: 0.5-5.0, and Fe_2O_3: 1.5-3.5. For the present study the percentages are: SiO_2: 0.11-0.17, Al_2O_3: 0.01-0.05, and Fe_2O_3: 0.02-0.14; such values indicate the low grade of minerals alteration. At the same time, when co-relating free oxides percentages addition and clay content, weathering is manifested (Duchaufour, 1984), where clay percentages prevail in all horizons, in relation to free oxides.

On alteration indexes from the three profiles, SiO_2/Al_2O_3 ratio for the first 50 cm indicates volcanic glass alteration and desilicification fine processes, as a product of geochemical weathering that characterize temperate climate. SiO_2/Fe_2O_3 ratio shows that alteration appears only on superficial horizons, which means weakly developed soils. Free molar ratios SiO_2/Al_2O_3 (Table 7), vary on indurated layers as follows: profile 1: 14.4-23.7; profile 2: 2.6-4.6, and profile 3: 6.1-10.9; values that again show the weathering incipient degree of these

Table 4. Particle size distribution.

Profile	Horizon	Depth cm	Very coarse sand 2-1	Coarse sand 1-0.5	Medium sand 0.5-0.25	Fine sand 0.25-0.10	Very fine sand 0.10-0.05	Total	Coarse silt 0.05-0.02	Medium silt 0.02-0.005	Fine silt 0.005-0.002	Total	Clay <0.002	*
1	A_{11}	0-20	3.03	11.38	8.63	17.76	12.44	53.24	10.69	7.42	0.00	18.11	28.63	1
	A_{12}	20-32	2.46	8.68	7.59	12.50	9.15	40.38	13.76	7.30	8.22	29.28	30.30	2
	AC	32-50	4.95	14.91	8.07	13.19	8.08	49.20	8.52	12.83	6.05	27.40	23.36	3
	2Cx1	50-80	1.56	8.14	5.76	9.37	5.36	30.19	13.25	16.69	9.46	39.40	30.37	4
	2Cx2	80-110	0.41	4.25	3.82	7.92	5.94	22.34	12.58	21.21	7.75	41.54	36.07	5
	2Cx3	110-140	1.12	7.22	5.69	7.84	5.03	26.90	10.29	21.78	8.75	40.82	32.23	6
2	A_{11}	0-17	2.54	9.48	7.22	12.69	8.65	40.58	14.20	6.61	4.26	25.07	34.30	7
	A_{12}	17-31	2.86	11.24	10.01	18.12	11.35	53.58	6.22	5.89	4.63	16.74	29.64	8
	AC	31-43	0.65	9.25	9.05	15.37	9.35	43.67	13.75	15.39	2.36	31.50	24.79	9
	Cx1	43-73	0.73	9.96	12.12	21.71	18.11	62.63	8.54	15.22	3.54	27.30	10.01	10
	Cx2	73-103	0.80	11.81	11.94	18.96	14.14	57.65	11.22	15.01	8.04	34.27	8.03	11
	Cx3	103-133	0.61	9.81	9.11	13.80	10.24	43.57	14.05	18.16	6.40	38.61	17.77	12
3	A_{11}	0-8	1.14	8.10	8.90	17.85	11.30	47.29	12.28	10.26	5.83	28.37	24.29	13
	A_{12}	8-19	0.54	4.83	8.73	17.69	10.69	42.28	13.99	12.80	1.83	28.62	28.87	14
	AC	19-40	1.40	9.93	12.44	19.97	10.44	54.18	13.53	13.49	3.15	30.17	15.60	15
	2Cx1	40-70	1.34	16.56	23.29	27.24	9.53	77.96	3.75	6.85	2.09	12.69	9.30	16
	2Cx2	70-100	1.93	21.07	25.78	25.24	6.11	80.13	1.89	5.94	1.36	9.19	10.64	17
	2Cx3	100-130	5.17	33.16	22.97	15.63	4.87	81.80	1.51	5.41	0.00	6.92	11.23	18

*Textural class:
1. Sandy clay loam; 2. Clay loam; 3. Sandy clay loam; 4. Clay loam; 5. Clay loam; 6. Clay loam; 7. Clay loam; 8. Sandy clay loam; 9. Loam; 10. Sandy loam; 11. Sandy loam; 12. Loam; 13. Sandy clay loam; 14. Sandy clay loam; 15. Sandy loam; 16. Sandy loam; 17. Sandy loam; 18. Sandy loam.

Table 5. Roundness and sphericity of the studied particles.

Profile	Horizon	Prof. cm	A %	B %	C %	D %	E %
1	A_{11}	0-20	3.84	26.92	34.61	30.76	3.84
	A_{12}	20-32	0.00	27.27	40.90	31.81	9.09
	AC	32-50	4.54	18.18	36.36	31.81	9.09
	2Cx1	50-80	0.00	11.76	11.76	70.58	5.88
	2Cx2	80-110	0.00	5.00	10.00	75.00	10.00
	2Cx3	110-140	12.5	4.16	20.83	41.66	20.83
2	A_{11}	0-17	7.57	46.96	25.75	18.18	4.54
	A_{12}	17-31	2.00	62.00	18.00	16.00	2.00
	AC	31-43	2.63	57.89	21.05	18.42	0.00
	Cx1	43-73	1.81	43.63	27.27	21.81	5.45
	Cx2	73-103	4.65	55.81	25.58	13.95	0.00
	Cx3	103-133	5.26	56.14	22.8	12.28	3.50
3	A_{11}	0-8	2.90	20.29	69.56	5.80	1.45
	A_{12}	8-19	2.63	10.53	78.95	7.89	0.00
	AC	19-40	4.08	12.24	77.55	6.12	0.00
	2Cx1	40-70	3.85	15.38	67.3	13.46	0.00
	2Cx2	70-100	1.79	21.43	75.00	1.79	0.00
	2Cx3	100-130	4.35	26.09	69.56	0.00	0.00

A. Very angular
B. Angular
C. Subangular
D. Subrounded
E. Rounded.

In all levels, low sphericity is dominant.

materials. Free oxides abundance order observed on indurated layers is: $SiO_2 > Al_2O_3 > Fe_2O_3$, indicating weathering first stage (Chesworth, 1977).

TOTAL OXIDES

As showing on Tables 8, 9 and 10, SiO_2 contents indicate that they are pyroclastic material of felsic nature.

Total oxides molar ratios in all profiles indicate reduced weathering; these are materials of low degree alteration. Si, Al and Na oxides prevail in the three profiles, mainly the last one. Similar results were obtained by Pacheco and Estrada (1987), Hidalgo and collaborators (1992), Quantin and collaborators, Flores-Román and collaborators (1996); these last ones say that the predominant mineral in Morelos and Mexico States are sodic feldespars.

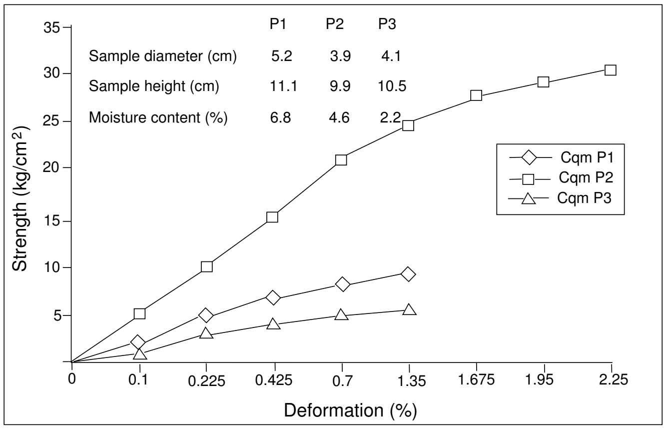

Figure 2. Resistance to unconfined compression in the fragipans of the studied profiles.

Silicon oxide high percentages on indurated layers indicate little alterated material; besides, feldespars and volcanic glass have been partialy weathered. This was confirmed by petrographic studies.

SiO_2 weight percentages on studied tuffs, range from 61.9-87.7. Flores-Román and collaborators (1992), obtained for fragipans in the State of Morelos intervals of 46.5-52.6. At the same time, Goudie (1973) shows that SiO_2 contents of 93.7 and 95.6 characterize respectively South African and Australian duripans. The indurated layers of the present study manifest intermediate contents.

TOTAL OXIDES LOSSES AND GAINS

As given in Tables 8, 9 and 10, total oxides losses and gains can be observed. Profiles 1 and 3, mainly 1, manifest the lithological discontinuity mentioned before. Thus, it is not possible to compare the upper horizons with C-horizon. For instance, A_{11}-horizon of profile 1, shows a loss of Si up to -63.58; it indicates very advanced weathering. However this condition does not exist.

Furthermore, high quantities of Na and Ca can not be explained by weathering. More adequate explanation is that this horizon contains higher values of unweathered Na and Ca rich feldespars than C-horizon, due to lithologic discontinuity.

Profile 2 shows a low losses of Si, Al, Ca, Mg, Na and K (Table 9), and it has gains of Fe, Ti and Mn, that are not significant.

Environmental conditions prevailing in the area, limit free cations and oxides liberation. Molar ratios are high, as it happens with low altered materials.

MICROANALYSIS OF THE CEMENT OF THE FRAGIPANS

Table 11 shows this microanalysis. In the profiles 1 and 2 high percentages of SiO_2 are observed. This compound, joininig with clays, produces cementation layers. Other oxides have very low percentages. Molar ratio SiO_2/Al_2O_3 have high values. Profile 3 indurated layer shows that the SiO_2 and Al_2O_3 abundance, and the molar ratio, are high.

The high content of Al_2O_3 in the cement is due to the clays (Flores-Román et al., 1992). Figures 3 and 4 show the photomicrographies obtained in the scanning electronic microscope in the indurated layers of the profiles 1 and 3, respectively. Cement covers and form bridges on the mineral particles.

PETROGRAPHIC ANALYSIS

The petrographic study revealed a closed porphyric distribution; dominates the massive microstructure, formed mainly by phenocrystals, chamber type pores and fissures. Such pores are coated by illuvial, clay which characterizes pore and straited grain birefringence fabric. Clay deposit

Table 6. Chemical analysis of the samples.

Profile	Horizon	Depth cm	pH 1:2.5	Org. mat. %	C %	N %	C/N	C.E.C. cmol⁺kg⁻	Extractable bases Na	K	Ca	cmol⁺kg⁻ Mg	Base sat. %	P. avail. ppm
1	A_{11}	0-20	7.40	1.66	0.96	0.13	7.38	17.30	9.00	0.14	9.00	9.00	100.00	0.10
	A_{12}	20-32	7.50	0.49	0.28	0.10	2.80	21.80	11.50	0.15	7.00	11.50	100.00	0.05
	AC	32-50	8.30	0.28	0.16	0.03	5.33	28.90	19.50	0.24	19.50	19.50	100.00	0.05
	2Cx1	50-80	9.00	0.14	0.08	0.03		61.90	20.50	0.19	4.50	20.50	73.81	0.05
	2Cx2	80-110	9.10	0.35	0.20	0.03		50.50	8.00	0.12	8.00	8.00	47.76	0.05
	2Cx3	110-140	8.60	0.00	0.00	0.01		29.50	1.50	0.22	14.00	1.50	58.37	0.05
2	A_{11}	0-17	7.40	3.19	1.85	0.25	7.40	30.80	0.20	1.28	27.50	2.00	100.00	0.05
	A_{12}	17-31	8.20	2.77	1.61	0.21	7.67	22.90	0.20	0.07	36.00	1.00	100.00	0.05
	AC	31-48	8.20	1.94	1.12	0.08	14.00	29.80	0.22	0.44	32.50	2.00	100.00	0.05
	Cx1	48-78	8.20	0.28	0.16	0.04		36.00	0.22	0.92	19.50	6.00	74.00	0.05
	Cx2	78-108	8.10	0.14	0.08	0.02		22.10	0.35	0.96	21.00	9.50	100.00	0.05
	Cx3	108-133	8.50	0.49	0.28	0.01		34.60	0.39	0.54	9.50	10.50	60.49	0.05
3	A_{11}	0-8	7.40	2.85	1.65	0.15	11.00	19.50	0.24	0.32	12.50	5.50	95.18	0.10
	A_{12}	8-19	7.80	1.94	1.12	0.08	14.00	21.90	0.26	0.24	14.50	5.00	91.32	0.05
	AC	19-40	8.00	0.00	0.00	0.04	0.00	25.10	0.74	0.19	9.50	7.50	71.43	0.05
	2Cx1	40-70	8.30	0.21	0.12	0.02		11.90	0.54	0.14	6.50	3.50	89.75	0.05
	2Cx2	70-100	8.10	0.28	0.16	0.02		7.70	0.91	0.15	7.50	1.50	100.00	0.05
	2Cx3	100-180	8.30	0.00	0.00	0.01		7.60	0.42	0.12	4.50	2.50	99.21	0.05

Table 7. Molar ratio of free oxides.

Profile	Horizon	Depth cm	SiO_2/Al_2O_3	SiO_2/Fe_2O_3
1	A_{11}	0-20	2.90	1.65
	A_{12}	20-32	2.82	1.88
	AC	32-50	9.05	6.99
	2Cx1	50-80	14.42	11.16
	2Cx2	80-110	23.75	7.35
	2Cx3	110-140	18.66	14.48
2	A_{11}	0-17	1.19	0.73
	A_{12}	17-31	1.00	0.87
	AC	31-43	2.13	2.03
	Cx1	43-73	2.61	3.06
	Cx2	73-103	4.02	2.85
	Cx3	103-133	4.69	6.22
3	A_{11}	0-8	1.68	0.54
	A_{12}	8-19	1.93	0.49
	AC	19-40	2.28	0.52
	2Cx1	40-70	10.92	3.39
	2Cx2	70-100	10.05	4.47
	2Cx3	100-130	6.16	2.06

shows microsections shape of oriented clays, halloysite or montmorillonite, and minerals with significant amounts of silica like proto-opal and quartz. In addition, silica gels are present, which favor cementation and reduce porosity. Also, iron-magnesium nodules were observed, that indicate oxide-reduction processes.

Primary minerals observed were: plagioclases, volcanic glass, biotite and pyroxenes. These minerals are included in a mosepic plasmic fabric.

Indurated layers are moderately consolidated tuffs, in which secondary pedogenetic processes are present. These layers were classified as pyroclast material of rhyolitic (profile 1), and dacitic (profiles 2 and 3) nature.

MINERALOGIC ANALYSIS

This analysis showed that the ratio 1:1 for clays are abundant and 2:1, secondary, furthermore cristobalite.

Halloysite clay is present due to silica concentration in the soil solution, which, when crystallizing in dry season, favors its formation (Kittrick, 1969; Thiry, 1992).

The origin of montmorillonite could be the mica clays, that evolve under well drainage conditions, in wet season, by mineral layers opening to vermiculite and finally to degradation montmorillonite (Duchaufour, 1984; Flores-Román et al., 1992).

SOIL CLASSIFICATION

According to FAO-UNESCO (1990), the soils of profile 1 and 3 are classified as Eutric Regosols; according to the Soil Survey Staff (1994), Order Entisols, Suborder Orthents, Great Group Udorthents, subgroup Vitrandic.

The soil of the profile 2 is classified as Umbric Regosol (FAO-UNESCO, 1990) and belongs to Order Entisol, Suborder Orthents, Great Group Ustorthens, subgroup Lithic (Soil Survey Staff, 1994).

Table 8. Losses or gains of the weathered horizons in relation to the basal rock of profile 1.

Total Oxides	Horizons Depth (cm) 2Cx1	AC	A_{12}	A_{11}	AC.K*	A12.K	A11.K	Losses or gains		
	50-80	32-50	20-32	0-20	Al_2O_3	Al_2O_3	Al_2O_3	AC	A_{12}	A_{11}
SiO_2	80.91	75.56	65.97	67.99	39.20	21.61	17.33	-41.71	-59.30	-63.58
Fe_2O_3	1.15	2.2	2.78	2.29	0.56	0.63	0.73	-0.59	-0.52	-0.42
Al_2O_3	3.89	8.03	13.6	14.81	1.88	2.30	3.57	-2.01	-1.59	-0.32
TiO_2	0.5	1.33	2.25	2.1	0.24	0.38	0.59	-0.26	-0.12	-0.09
MnO	0.21	0.17	0.52	0.52	0.10	0.05	0.14	-0.11	-0.16	-0.07
CaO	1.72	1.33	1.66	2.21	0.83	0.39	0.43	-0.89	-1.33	-1.29
MgO	1.38	2.09	2.17	2.12	0.66	0.61	0.56	-0.72	-0.77	-0.82
Na_2O	3.35	5.092	7.504	10.98	1.61	0.77	0.75	-1.25	-1.64	-1.66
K_2O	2.41	2.65	2.89	2.89	1.16	0.77	0.75	-1.25	-1.64	-1.66
P_2O_5	0.11	0.25	0.11	0.11	0.05	0.07	0.03	-0.06	-0.04	-0.08
H_2O^+	4.95	5.56	2.12	1.46						
H_2O^-	6.52	6.01	4.92	5.18	3.13	1.74	1.28	-3.39	-4.78	-5.24
Total	107.1	110.3	106.5	112.7						

	2Cx1	AC	A_{12}	A_{11}
SiO_2/Al_2O_3	35.29	15.97	8.23	7.79
$SiO2/Fe_2O_3$	186.99	91.28	63.07	78.91
$SiO_2/Al_2O_3+Fe_2O_3$	29.69	13.59	7.28	7.09

*The aluminum constant (K) is obtained dividing the aluminum percentage of the unaltered rock (Cqm) between the aluminum percentage of the altered rock (AC, A_{12} or A_{11}). 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 9. Losses or gains of the weathered horizons in relation to the basal rock of profile 2.

Total Oxides	Horizons Cx1	Depth (cm) AC	A_{12}	A_{11}	AC.K*	A12.K	A11.K	Losses or gains		
	50-80	32-50	20-32	0-20	Al_2O_3	Al_2O_3	Al_2O_3	AC	A12	A11
SiO_2	63.41	55.28	59.09	61.74	67.82	53.42	56.72	4.41	-9.99	-6.69
Fe_2O_3	1.76	1.71	2.42	2.37	1.88	1.65	2.32	0.12	-0.11	0.56
Al_2O_3	14.62	13.67	15.13	15.23	15.64	13.21	14.52	1.02	-1.41	-0.10
TiO_2	1.23	1.83	2.1	1.91	1.32	1.77	2.02	0.09	0.54	0.79
MnO	0.52	0.72	0.61	0.62	0.56	0.70	0.59	0.04	0.18	0.07
CaO	2.46	4.31	2.85	1.96	2.63	1.25	0.74	0.17	-1.21	-1.72
MgO	1.81	1.77	2.2	1.92	0.87	0.51	0.57	-0.94	-1.30	-1.24
Na_2O	8.04	6.96	9.11	8.57	3.86	2.02	2.37	-4.18	-6.02	-5.67
K_2O	2.89	2.89	3.13	3.13	1.39	0.84	0.81	-1.50	-2.05	-2.08
P_2O_5	0.32	0.23	0.55	0.41	0.15	0.07	0.14	-0.17	-0.25	-0.18
H_2O^+	3.85	3.66	2.35	2.48						
H_2O^-	7.65	12.05	16.5	8.97	3.67	3.49	2.44	-3.98	-4.16	-5.21
Total	108.56	105.08	105.08	109.31						

	2Cx1	AC	A_{12}	A_{11}
SiO_2/Al_2O_3	7.36	6.86	6.63	6.68
$SiO2/Fe_2O_3$	55.75	85.92	64.89	69.23
$SiO_2/Al_2O_3+Fe_2O_3$	6.83	6.35	6.01	6.26

ORIGIN OF SOILS AND INDURATED LAYERS

Profile 1 soil formation has been, mainly, by colluvial geomorphological processes. In the superficial 30 cm of soil, rounded stones are observed. The soils of the profiles 2 and 3 have a *in situ* formation, it means that their origin is the vitric tuff alteration.

Indurated layers were formed by pyroclastic deposits, they have their components soldered by burning; by this reason are named tuffs (Blyth and de Freitas, 1995). These materials are of felsic nature, its origin is due to geological processes, with pedogenetic secondary ones, that increase the induration. Subsequently, cement agent, the silica, that originates from plagioclases and volcanic glass alteration, produce a close packing and a good matrix for the grains skeleton, which is joined by clay bridges (Figure 4).

CONCLUSIONS

According to the results, the following can be concluded:

•Morphological field classification of these soils showed a weak development.

Table 10. Losses or gains of the weathered horizons in relation to the basal rock of profile 3.

Total Oxides	Horizons 2Cx1	Depth (cm) AC	A_{12}	A_{11}	AC.K*	A12.K	A11.K	Losses or gains		
	50-80	32-50	20-32	0-20	Al_2O_3	Al_2O_3	Al_2O_3	AC	A12	A11
SiO_2	61.91	64.78	62.55	62.3	59.00	60.83	60.46	-2.91	-1.08	-1.45
Fe_2O_3	2.96	2.59	3.16	3.14	2.82	2.43	3.05	-0.14	-0.53	0.09
Al_2O_3	14.78	15.51	15.74	15.29	14.08	14.56	15.21	-0.70	-0.22	0.43
TiO_2	2.58	2.43	3.25	2.75	2.46	2.28	3.14	-0.12	-0.30	0.56
MnO	0.72	0.55	0.73	0.73	0.69	0.52	0.71	-0.03	-0.20	-0.01
CaO	2.6	1.99	2.11	2.15	2.48	0.58	0.55	-0.12	-2.02	-2.05
MgO	3.7	2.25	2.39	2.52	1.78	0.65	0.62	-1.92	-3.05	-3.08
Na_2O	8.04	8.04	8.04	7.5	3.86	2.33	2.09	-4.18	-5.71	-5.95
K_2O	2.89	2.89	2.65	2.89	1.39	0.84	0.69	-1.50	-2.05	-2.20
P_2O_5	0.37	0.21	0.14	0.09	0.18	0.06	0.04	-0.19	-0.31	-0.33
H_2O^+	1.68	2.29	2.15	2						
H_2O^-	3.42	5.04	6.7	7.21	1.64	1.46	1.74	-1.78	-1.96	-1.68
Total	105.65	108.57	109.61	108.57						

	2Cx1	AC	A_{12}	A_{11}
SiO_2/Al_2O_3	7.11	7.09	6.74	6.91
$SiO2/Fe_2O_3$	55.59	66.47	52.61	52.73
$SiO_2/Al_2O_3+Fe_2O_3$	6.30	6.40	5.98	6.11

Table 11. Microanalysis of the cement of the fragipans.

Profile	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	SiO_2/Al_2O_3
1	97.66	0	0.61	0.29	0	0.11	0.39	0.15	0.02	268.21
2	99.27	0.04	0.16	0.08	0.13	0.11	0	0.32	0	139.43
3	75.28	0.17	15.64	1.31	0	0.6	2.36	2.07	2.58	8.06

•Medium sand, fine sands and very fine sands fractions were dominant. The medium silts dominate in the indurated layers. The clays content disminish in function of depth in the profiles 2 and 3.
•The resistance to simple compression of the white fragipans has low values in two cases and intermediate in another.
•The total oxides contents of the white tepetates classified them as pyroclastic materials of felsic nature, with a low grade of weathering.
•The mineralogy of the clay fraction is constituted by halloysite (7Å), montmorillonite, silica minerals and non crystalline materials.
•The white indurated layers are of igneous origin, formed by rhyolitic and dacitic tuffs, with moderate cementation.
•The principal cement agent is silica, which is adsorbed by clays.
•The free oxides content is considered scarce, due to low grade climatic aggressiveness and to material of felsic nature, where the alteration processes are limited.
•The cement microanalysis showed that this is a silica gel that joined with clays promote cementation.
•In the petrographic study, the main distribution was close porphyric pattern, B-fabric of striated pore and grain, with abundant pores-like chamber and fissure. The primary minerals are in an argilic matrix.

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Figure 3. Photomicrograph in scanning electronic microscope (SEM) of the fragipans of the profile 1. The mineral particles covered by silica are observed.

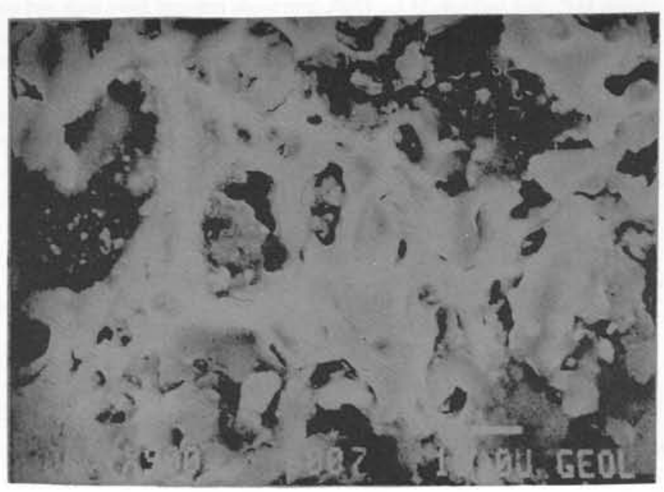

Figure 4. Photomicrograph in the same microscope in the fragipan of the profile 3. It is possible to see bridges of amorphous silica.

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