SOILS DEVELOPED ON DIFFERENT PARENT MATERIALS
Suelos Desarrollados de Diferentes Materiales Parentales

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SUMMARY

Three soils were studied at a coffee growing farm El Nueve, Sierra Madre del Sur, Oaxaca, Mexico: Skeletic Phaeozem, Ferralic Umbrisol, and Epileptic Calcaric Phaeozem. The formation of these soils was regulated by the origin of parent material (Epileptic Calcaric Phaeozem formed on limestone), and by the age of the exposed surface (Skeletic Phaeozem was formed on the slope of a recently formed V-shaped valley, and Ferralic Umbrisol – on an ancient weathering crust, derived from the same gneiss). The three soils differed in their acidity, organic matter composition, clay mineralogical composition, and exchangeable complex characteristics. Ferralic Umbrisol differed from the two other soils by its lower cation exchange capacity and base saturation, mainly kaolinitic clay mineralogical composition, heavier texture, and higher acidity. Skeletic Phaeozem had coarser texture, higher rock fragments content, and high percentage of light organic matter. Epileptic Calcaric Phaeozem had the highest base saturation, a combination of clayey texture with abundant rock fragments, and humic acids as the main component of soil humic substances. The diversity of soils of tropical mountainous areas is high due to the diversity of parent materials and the age of exposed surfaces.

***Index words**: soil diversity, tropical soils, weathering, erosion.*

RESUMEN

Se investigaron tres suelos en la finca cafetalera El Nueve, Sierra Madre del Sur de Oaxaca, México: Phaeozem esquelético, Umbrisol ferrálico y Phaeozem calcárico epiléptico. La formación de estos suelos está relacionada con el origen del material parental (el Phaeozem calcárico epiléptico se formó sobre calizas), y por la edad de exposición de la superficie (el Phaeozem esquelético se formó sobre la pendiente de un valle en forma de V de formación reciente, y el Cambisol úmbrico ferrálico sobre una corteza de intemperismo antigua, derivados ambos del mismo gneiss). Los tres suelos difieren en acidez, composición de la materia orgánica, composición de la mineralogía de las arcillas y bases intercambiables. El Umbrisol ferrálico presenta menor capacidad de intercambio catiónico y de saturación de bases, composición caolinítica dominantemente, textura más pesada, y mayor acidez. El Phaeozem esquelético tiene textura más gruesa, pedregosidad abundante y presenta el mayor porcentaje de materia orgánica ligera. En el Phaeozem epiléptico calcárico ocurre la mayor saturación de bases, textura pesada con pedregosidad abundante, y los ácidos húmicos son los principales componentes de las sustancias húmicas. La diversidad de los suelos de áreas montañosas es alta, debido a la diversidad de sus materiales parentales y a la edad de exposición de sus superficies.

***Palabras clave**: edafodiversidad, suelos tropicales, intemperismo, erosión.*

INTRODUCTION

During the last decade, the concept of soil diversity was one of the most promising advances in soil geography. The concept was introduced by Ibañez *et al.* (1990), and later McBratney (1992) proposed the term *pedodiversity* to emphasize the significance of variation of soil properties for agriculture. Since that time, both theoretical basis and methods of soil diversity studies have been significantly developed (Ibañez *et al.*, 1995; Amundson *et al.*, 2003; Krasilnikov and Fuentes Romero, 2003). The concept was developed mainly in temperate areas, and was not applied for tropical regions. Actual concept of tropical soil formation is much far from the initial idea of uniformity of soils (Van Wambeke, 1991). Still, there is a general opinion that the diversity of soil

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properties is much lower in tropical areas than in temperate regions. It was shown that deeply weathered tropical soils formed on various parent materials (andesite, limestone, and conglomerate) have no significant difference in the properties of surface horizons (Yavitt, 2000). At plains, such as Central Africa and Amazon basin, in a stable environment the soils are deeply weathered and relatively uniform. The situation in mountainous areas is different from the plains; for instance, in uplands deeply weathered profiles and shallow sandy soils occur side by side (Schaefer *et al.*, 2002), in the steeplands mass movement along the slopes is widespread, and the parent material is periodically refreshed (Birkeland, 1999); although, well-developed deep soils are also widespread (Drees *et al*., 2003). When derived from the same parent rock, mountain soils formed on surfaces of different ages are characterized by contrasting chemical properties and mineralogical composition (Nieuwenhuyse *et al.*, 2000). Thus, in tropical mountains, soil diversity should be expected to be higher than in plain tropical areas.

We studied three representative soil profiles, two of them formed on gneiss-derived material, but differing in extent of weathering (one on sandy saprolite, and the other on clayey deeply weathered material), and the third on limestone. The objective of the study was to find out the difference in morphology, chemical and mineralogical characteristics of the profiles and give their genetic interpretation.

MATERIALS AND METHODS

The research was conducted at the coffee-growing farm El Nueve, situated in the Santa Maria Huatulco, Oaxaca state, Mexico (Figure 1). The study area is located at 15° 55’ 52" N and 96° 17’ 04" W. This region represents a typical landscape of the south-western slope of Sierra Madre del Sur mountains, the system formed by a tectonic uplift in Miocene (Morán *et al.*, 1996); minor uplifts also occurred in Pliocene and even Quaternary. The rocks are mainly gneiss and amphibolites formed during the Paleozoic epoch, and Cenozoic granites (Hernández *et al*., 1996). Limestone is present as small inclusions. The farm El Nueve is situated at 950 to 1420 m above sea level (masl). The mountain slopes are steep to very steep, with inclination ranging about 40°, and aspect varying from north-eastern to northern (Figure 1).

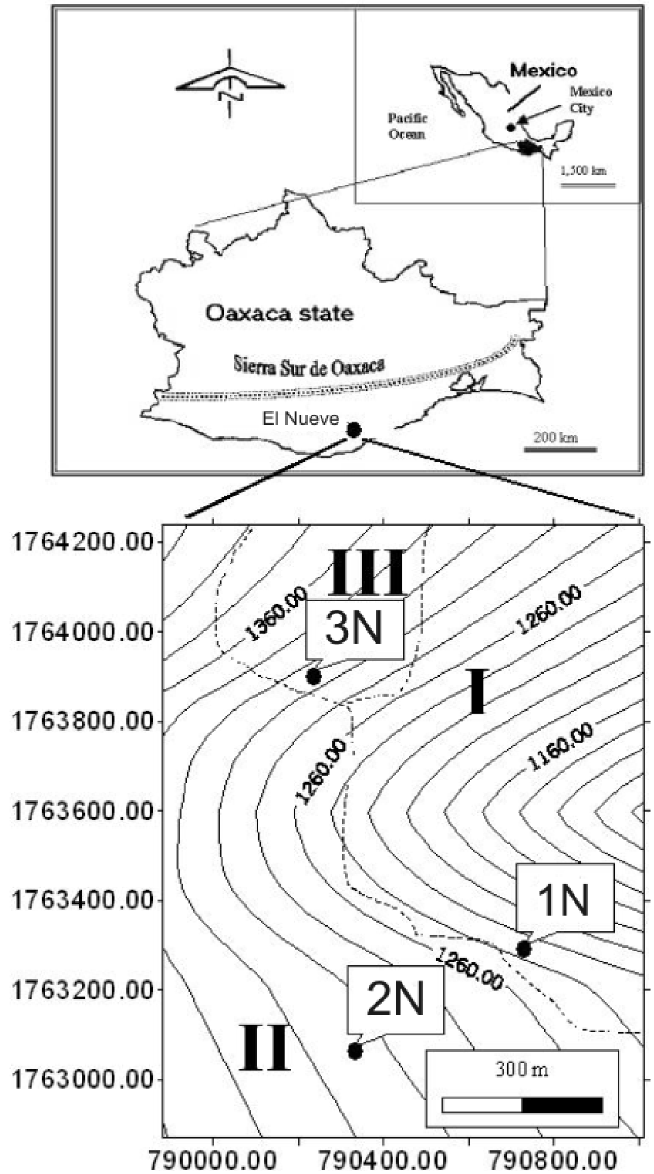

Figure 1. Schematic topographic map of the study area (coffee-growing farm El Nueve).

Climate is warm humid isothermal with annual precipitation of 1800 to 2000 mm and mean annual temperature of 21 to 21.9 ºC (García, 1973). The region has two main seasons: dry from December through May and wet from June through November. Vegetation in the area consists of coffee plantations (*Coffea arabica* var. typica L.) under the canopy of residual natural vegetation and tropical semideciduous forest (Rzedowsky, 1978). A soil study of the zone was published recently (García *et al.*, 2000); according to the data presented, the soils are mainly Acrisols [A/(E)/

Bt/C], Luvisols [A/(E)/Bt/C], and Cambisols (A/Bw/C) (FAO-ISRIC-ISSS, 1998). However, later studies showed a complex character of soils in Sierra Madre del Sur, most of the soils are affected by slope processes, such as erosion, landslides, and other types of mass movement (Fuentes *et al*., 2002; Krasilnikov *et al*., 2005; García *et al*., 2006). The territory of the coffee-growing farm El Nueve was selected because most soils seem to be less disturbed by recent mass movement, than other study areas. The sediments of major part of the territory of the farm are the products of gneiss weathering, varying from sandy saprolite to deeply weathered red clays. Minor area is occupied by limestone. Three profiles were selected for a detailed study: the first one on a steep slope, where the sediments are sandy and rich in rock fragments and outcrops, the second one (in a relatively gentle upland area) where red clayey sediments dominate, and the third one in the area of limestone outcrops (Figure 1).

Morphological description was done according to Schoeneberger *et al*. (2002); colour was identified using Munsell Soil Color Charts (2000); field observations were supported by mesomorphological studies using a stereoscopic microscope. Undisturbed samples were taken from selected soil horizons for micromorphological studies. Thin sections were prepared and described according to Bullock *et al*. (1985). Soils were classified according to the World Reference Base (FAO, 2006). Samples were collected from soil horizons, and analysed according to the routine methods of soil chemical and physical analysis (Van Reeuwijk, 2002). Bulk chemical composition was determined using standard chemical methods, as described in Page *et al*. (1982). The light organic matter (LOM) fraction was separated following Monnier *et al*. (1962) and Dabin (1971). The extractable humic substances were then isolated from the dried residue by repeated treatments with 0.1M $Na_4P_2O_7$ and 0.1M NaOH. The humic acid (HA) fraction was separated from the acid-soluble fulvic acid (FA) after precipitation with 6M HCl at pH 1.5. The residual heavy fraction of soil (contain the residual C fraction insoluble in alkaline reagents humin) was rinsed five times with deionized water, dried, grounded gently and weighed. The quantitative proportion (in C) of the above fractions was determined by Walkley and Black method. Clay fraction was separated and pre-treated using Dixon and White method (1999). X-ray diffractograms were obtained on a diffractometer DRON-3 (SIE "Burevestnik", St. Petersburg, Russia, 1987), Cu-Kα radiation with graphite monochromer, 2θ 2-45°, U = 40 kV, I = 25 mA.

RESULTS AND DISCUSSION

Profile 1N

The first soil profile (1N) is situated on a steep slope (50-60%), on plagioclase-amphibole gneiss debris. Vegetation consists of coffee plants under residual forest natural vegetation. The soil is sandy loam, with weak structure, and contains numerous angular rock fragments (Table 1). Soil material is colored with organic matter down to 60 cm depth; the roots and soil fauna were also evident down to the same depth. The pH values are in the range of slightly acid – close to neutral reaction throughout the soil profile (Table 2). The distribution of clay is relatively uniform. Exchangeable bases content and base saturation are the highest in the A horizon, with Ca as the main cation. The highest organic C content corresponds to the surface A horizon and gradually decreases with depth. Fe_d content is not very high and its distribution in the soil profile is irregular; Fe_o constituted 22 to 69% of Fe_d contents. Bulk chemical composition shows only insignificant variation in Si and Al contents (Table 3). The only elements, which show a notable redistribution in the profile, are: Fe (accumulated in the surface horizons, with a maximum in the A2 horizon), and K (with slightly higher contents in the AB and Bw horizons, than in the A horizons). Light organic matter dominates in the composition of humus in the surface horizons of the soil (Table 4). The main part of the extractable humic substances consists of fulvic acids, with a HA/FA ratio of 0.27 and 0.55 in the A1 and A2 horizons, respectively. Soil humin fraction content is lower at 0-25 cm and its content increases from 25-45 cm. X-ray diffraction data show the dominance of 1.4 nm minerals in all the horizons (Figure 2). After heating to 550 ºC, a part of these minerals contracts to 1.04 nm, and the other part to 1.16–1.21 nm, indicating the presence of both vermiculite and mixed-layered chlorite-vermiculites. The ratio of chlorite-vermiculite to vermiculite increases with depth. Also, there is a weak signal at 1.4 nm in the Bw horizon, indicating the presence of chlorite. The data were interpreted as an evidence of gradual transformation of chlorites in soil to mixed-layered chlorite-vermiculites and vermiculites.

This soil profile is classified as Skeletic Phaeozem. It was formed on recent regolith of fragmented gneiss. The exposure of this material resulted from the erosion,

Table 1. Morphological description of soil profiles of the El Nueve farm, Oaxaca state, Mexico.

Horizon depth	Colour (moist)	Field texture[†]	Structure[‡]	Rock fragments, volume	Skeletans	Coats[§] Silt coats	Shiny surfaces	Roots[¶]	Soil fauna	Pores[¶]	Border[¶¶]
cm				%							
Profile 1N. Skeletic Phaeozem											
A1 0-25	10YR 2/2 very dark brown	LS	GR	40	VF			3vf,f,m	worms and *Diplopoda*	2m	W
A2 25-45	10YR 3/3 dark brown	LS	GR	40	VF			2f,m	worms	2m	W
AB 45-60	10YR 3/4 dark yellowish brown	LS	GR, SAB	50	F			2f,m	worms	1f,m	W
Bw 60-100	10YR 4/6 dark yellowish brown	LS	SAB	60	C			1f		1f,m	I
Cr 100+	10YR 4/6 dark yellowish brown	LS		<90							
Profile 2N. Ferralic Umbrisol											
A 0-55	5YR 3/3 dark reddish brown	CL	GR	<10	F	VF		3vf,f,m	worms	2m,co	I
Bw1 55-100	2.5YR 4/6 red	CL	SAB	<10		C		2f,m,co		3f,m	S
Bw2 100-155	2.5YR 5/6 red	C	ABK	<10			M	2f,m		1vf	S
BC 155-185	2.5YR 5/6-4/6 red	CL	SAB	20			F	1m		1vf,f	S
C 185-200	2.5YR 3/6 dark red	SCL	SAB	40							
Profile 3N. Epileptic Calcaric Phaeozem											
A 0-25	5YR 3/3 dark reddish brown	SCL	GR	40	VF			3vf,f,m,co	worms, lichens	2m,co	I
Bw 25-50	5YR 4/4-3/4 reddish brown to dark reddish brown	CL	GR, SAB	60	F			2vf,f,m	worms	1f,m	I
Cr 50-100	5YR 4/6 reddish yellow	SL	SAB, GR	>90				1f,m			

[†] LS = loamy sand, SL = sandy loam, SCL = sandy clay loam, CL = clay loam, C = clay; [‡] GR = granular, SAB = subangular blocky, ABK = angular blocky; PR = prismatic; [§] VF = very few coats, F = few, C = common, M = many; [¶] 0 = no roots or pores, 1= few, 2 = common, 3 = many; vf = very fine, f = fine, m = medium, co = coarse; [¶¶] S = smooth, W = wavy, I = irregular.

having formed a V-shaped valley (Birkeland, 1999). The soil was developed in leaching environments. However, it is saturated in bases; it can be ascribed to intensive release of bases from relatively fresh parent material, rich in weatherable minerals.

Profile 2N

The soil profile 2N is situated on a moderate to steep slope (20-30%), on a deeply weathered regolith of gneiss rocks, and, possibly, transported slope sediments, derived from the same regolith situated on the upper part of the slope. The vegetation is a recently abandoned coffee plantation under residual forest vegetation. The soil has mainly clay loamy texture and reddish colors (Table 1). The surface horizon is deep and has a well-developed granular structure. The Bw1 horizon is porous, with a weakly developed subangular blocky structure, and the Bw2 has hard angular aggregates with shiny surfaces. The Bw1 horizon has loose silt coatings on the peds surfaces (Figure 3a), and shows no soil matrix orientation (Figure 4a). The Bw2 horizon has compact silt clay coatings on the aggregate surfaces (Figure 3c) and shows slight orientation of soil particles in these coatings (Figures 4c and 4d). Sandy grains in all soil horizons are represented mainly by quartz and, in a lesser extent, by feldspars, amphiboles, and biotite. The latter group of minerals is represented by grains varying in extent of weathering from completely (Figure 3b) and highly

Table 2. Chemical and physical properties of soil profiles of the El Nueve farm, Oaxaca State, Mexico.

Horizon depth	pH H_2O	pH KCl	Clay	Silt	Sand	Ca^{2+}	Mg^{2+}	K^+	Na^+	EA†	CEC	CEC‡	BS	C	Fe_d	Fe_o	Fe_o/Fe_d
cm			- - - g kg^{-1} - - -			- - - - - - cmol$_c$ kg^{-1} - - - - - - -						cmol$_c$ kg	%	- - - - - g kg^{-1} - - - - -			
Profile 1N. Skeletic Phaeozem																	
A1 0-25	6.3	5.1	129.8	344.2	509	21.5	3.4	tr.	0.4	8.5	33.8		75	58.6	19.2	6.1	0.32
A2 25-45	6	5.4	163.8	236.9	530.3	23.6	3.5	0.1	0.3	9.6	37.1		74	33.8	10.9	7.5	0.69
AB 45-60	6.3	5	131.8	96.8	731.4	7.8	1.6	tr.	0.2	5	14.6		66	4.1	19.1	4.2	0.22
Bw 60-100	6.2	4.7	123.8	71.4	768.8	7.3	1.6	tr.	0.2	4.6	13.7		66	0.4	11.1	3.8	0.34
Profile 2N. Ferralic Umbrisol																	
A 0-55	4.3	4	351.8	188.3	412.9	2.2	0.3	0.1	0.2	15.6	18.4	52.6	18	55.6	65.4	4.5	0.07
Bw1 55-100	4.3	4	327.8	253	364.2	0.1	0.1	tr.	0.2	3.5	3.9	11.8	10	2.4	62.7	4.2	0.07
Bw2 100-155	4.3	4.1	299.8	383	280.2	0.1	0.1	tr.	0.2	7.6	8	26.7	5	0.4	66.7	1.2	0.02
BC 155-185	4.3	4.2	311.8	393	275.2	0.2	tr.	tr.	0.2	6	6.4	21.3	6	1.2	62.3	2.1	0.03
C 185-200	4.3	4.3	128	290.7	534.3	0.2	tr.	tr.	0.2	5.3	5.7	43.8	7	0.4	60.6	2	0.03
Profile 3N. Epileptic Calcaric Phaeozem																	
A 0-25	6.6	6.6	391.8	310	298.2	37.6	1	0.7	0.4	9.1	48.8	125.1	81	68.5	34.7	3.2	0.09
Bw 25-50	6.7	6.7	471.8	304.7	223.5	29.1	0.9	0.3	0.4	4.5	35.2	74.9	87	29.8	48.7	2.7	0.06
Cr 50-100	7.2	7.3	399.8	376.7	223.5	31	1	0.2	0.4	3.8	36.4	91	90	12.2	43.5	1.9	0.04

† Extractable acidity, $BaCl_2$-triethanolamine method (Van Reeuwijk, 2002); CEC = cation exchange capacity; BS = base saturation; Fe_d = iron extracted by dithionite-citrate solution; Fe_o = iron extracted by acid oxalate solution; tr = traces.
‡ The value is not calculated for light-textured horizons.

decomposed minerals (Figures 4e and 4f) to fresh unweathered grains (Figure 3d). The pH values are in the range of acid reaction (Table 2) with low ΔpH values (from 0.3 in the surface horizon to 0 in the parent material). The distribution of clay is almost uniform; at least, no distinct increase is detected in the B horizons. Exchangeable bases content is relatively high in the surface of the A horizon and low in the other horizons. The surface of the A horizon has a high exchangeable acidity, while the subsoil horizons show much lower

Table 3. Bulk elemental composition of the fine earth of soils of the El Nueve farm, Oaxaca State, Mexico.

Horizon depth	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
cm	- - - - - - - - - - - - - g kg^{-1} - - - - - - - - - - - - -										
Profile 1N. Skeletic Phaeozem											
A1 0-25	514	18.4	213	98.2	38	2.3	15.2	62.3	31.6	15.4	21.6
A2 25-45	500.7	21.3	202.7	110.3	52.6	3	17.1	68	26.5	14.2	24.9
AB 45-60	512.7	14.5	217.7	84	33.3	1.8	13.8	66.1	36.1	16.2	19.9
Bw 60-100	497.2	16.3	218.1	76.8	38.4	1.8	14.6	77.8	34.5	16.5	23.4
Profile 2N. Ferralic Umbrisol											
A 0-55	576.1	15.1	276.6	128.2	14.9	0.6	6.1	4	0.6	15.9	2.4
Bw1 55-100	579.7	10.7	279.1	126.3	7.6	0.6	3.9	3.4	0.5	11.1	1.7
Bw2 100-155	564.8	11	296.5	126.5	4.6	0.5	6.4	1.9	0.5	11.9	1.5
BC 155-185	582.3	10.2	281.3	124	4.6	0.8	5.6	1.6	0.6	11.4	1.7
Profile 3N. Epileptic Calcaric Phaeozem											
A 0-25	727.6	6.2	166.2	70.1	7.6	1.6	30	20.9	1	21	3.2
Bw 25-50	718.1	5.6	169.5	77.1	1.6	1	28.2	13.6	0.7	19.5	2.1
Cr 50-100	660.8	5.2	175.4	72.7	1.6	0.9	33.9	59.4	0.6	22.1	2.4

Table 4. The composition of the organic matter in surface horizons of the profiles of the coffee-growing farm El Nueve, Oaxaca State, Mexico.

Horizon depth	Ct	LOM		FA (H_3PO_4)		FA		HA		HA/FA	Humins	
cm	g kg^{-1}	g kg^{-1}	% Ct	g kg^{-1}	% Ct	g kg^{-1}	% Ct	g kg^{-1}	% Ct		g kg^{-1}	% Ct
					Profile 1N. Skeletic Phaeozem							
A1 0-25	58.6	35	59.7	1.5	2.6	11.3	19.3	3.5	6	0.27	3.6	6.1
A2 25-45	33.8	12	35.5	1.9	5.6	8.2	24.3	5.6	16.6	0.55	5.4	16
					Profile 2N. Ferralic Umbrisol							
A 0-55	55.6	1.5	2.7	3.9	7	18.4	33.1	6.2	11.2	0.28	25.1	45.1
					Profile 3N. Epileptic Calcaric Phaeozem							
A 0-25	68.5	8.2	12	4.8	7	6.8	9.9	12.3	18	1.06	36.7	53.6
Bw 25-50	29.8	1.1	3.7	2	6.7	3.1	10.4	6.7	22.5	1.31	16	53.7

Ct = total organic carbon; LOM = light organic matter; FA = fulvic acids; HA = humic acids.

values. The cation exchangeable capacity (CEC) is also high in the surface horizon and low in the subsoil; its lowest value after recalculating to clay content is detected in the Bw1 horizon. Organic C content is high in the A horizon and decreases drastically with depth. Fe_d contents are high and uniform throughout the profile,

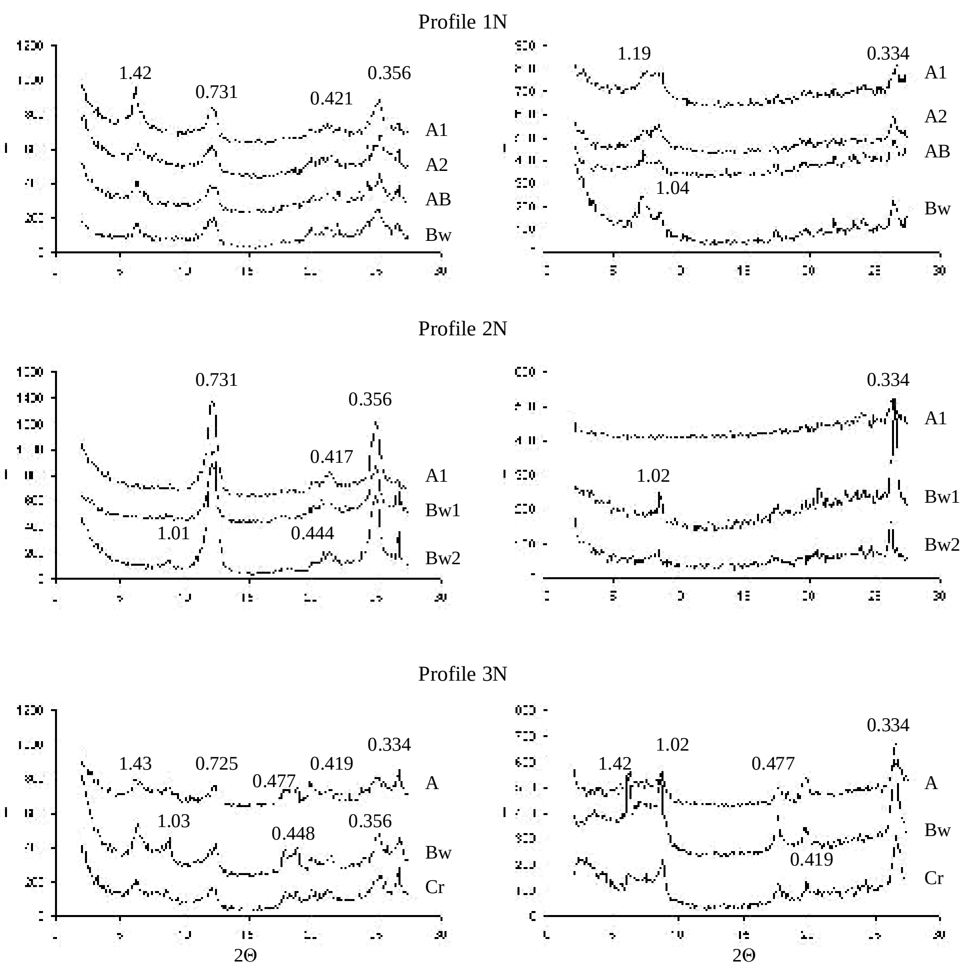

Figure 2. X-ray difractograms of oriented clay fractions of the horizons of the profiles 1N (Skeletic Phaeozem), 2N (Ferralic Umbrisol), and 3N (Epileptic Calcaric Phaeozem); left column are air dried, Mg-saturated samples, right column are the same after heating to 550 °C.

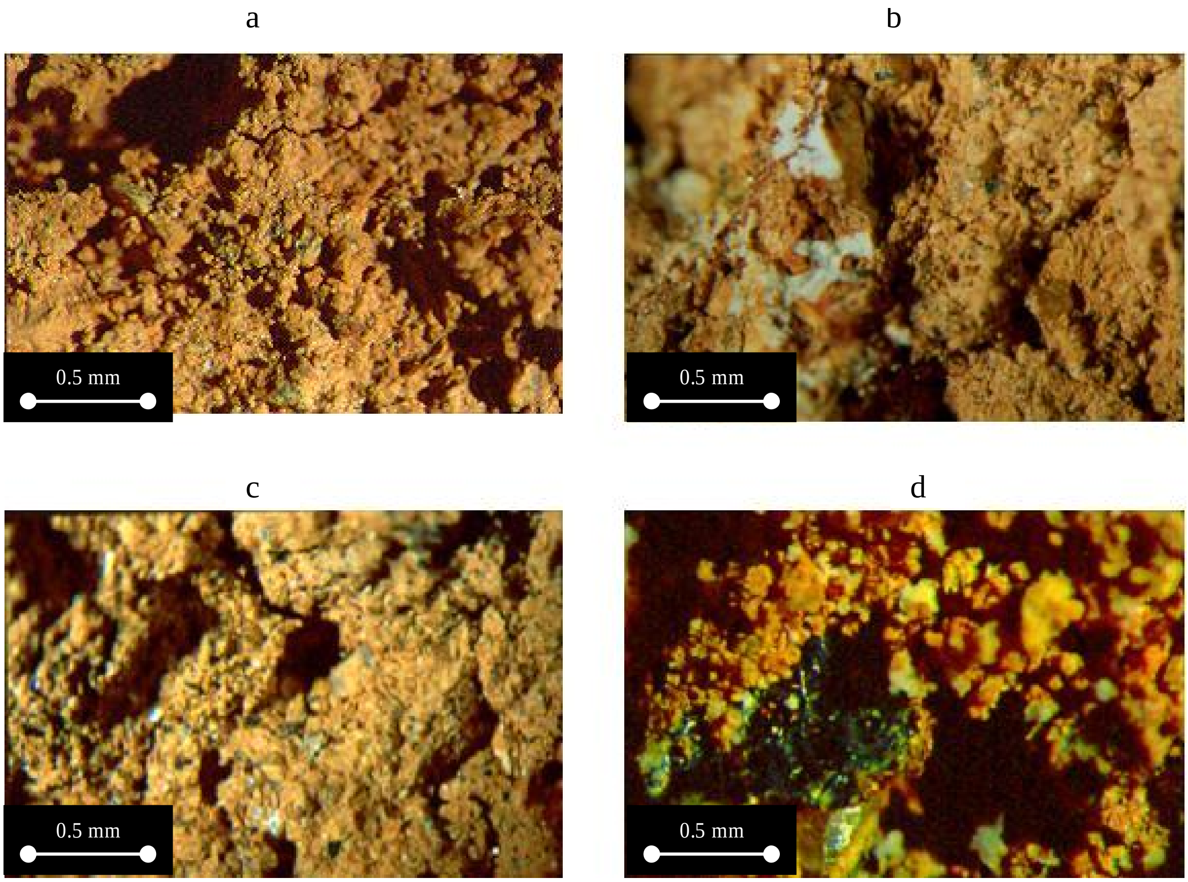

Figure 3. Soil mesomorphology of the profile 2N (Ferralic Umbrisol): a) loose silt coating in the horizon Bw1; b) kaolinite substituting a feldspar in Bw1 horizon; c) compact silt-clay coating on an aggregate from Bw2 horizon; d) fresh biotite grain from BC horizon.

Fe_o contents are higher in the A and Bw2 horizons; the Fe_o/Fe_d ratios are found to be exceptionally low. Bulk elemental composition shows almost no variation with depth (Table 3). The content of silica is slightly lower in the surface horizon than in the subsoil and the content of Ca, K, P, and Fe (II) is slightly higher. Light organic matter percentage in the composition of the surface horizon is low (Table 4). Humins constitute almost a half of SOM. Fulvic acids represent the majority of extractable humic substances and the HA/FA ratio is 0.28.

X-ray data show the dominance of kaolin minerals (mainly kaolinite *sensu stricto*) in all the soil horizons. Only minor contents of 1.0 nm minerals (illites) are detected in the Bw1 and Bw2 horizons.

The classification of the second profile is more difficult than of the first one, due to the fact that the CEC of clay fraction is low enough to qualify as a ferralic horizon. However, the sand fraction of the horizon has about 20-30% of weatherable minerals (semiquantitative evaluation in thin section) instead of < 10% required by WRB (FAO, 2006) criteria. Thus, the criteria were insufficient for ferralic horizon but sufficient for ferralic properties, and the final classification is Ferralic Umbrisol. This soil was derived from the same parent rock as Skeletic Phaeozem, described above. The difference between these soils was in the extent of parent material weathering. Ferralic Umbrisol formed on much more weathered parent material. Still the profile is not very deep in comparison with deep weathered tropical soils of plain areas. We consider that in the past the soil could undergo some erosional processes, which reduced the depth of the profile. Unlike in Skeletic Phaeozem, in Ferralic Umbrisol, where the majority of weatherable minerals are destroyed, or covered by iron oxides coatings, the bases are almost completely leached. Though the properties of Ferralic Umbrisol generally corresponded to actual bioclimatic environments, it should be considered that its properties are strongly affected by deeply weathered parent material. Both Ferralic Umbrisol and Skeletic Phaeozem are considered to be productive for coffee. However, they are not

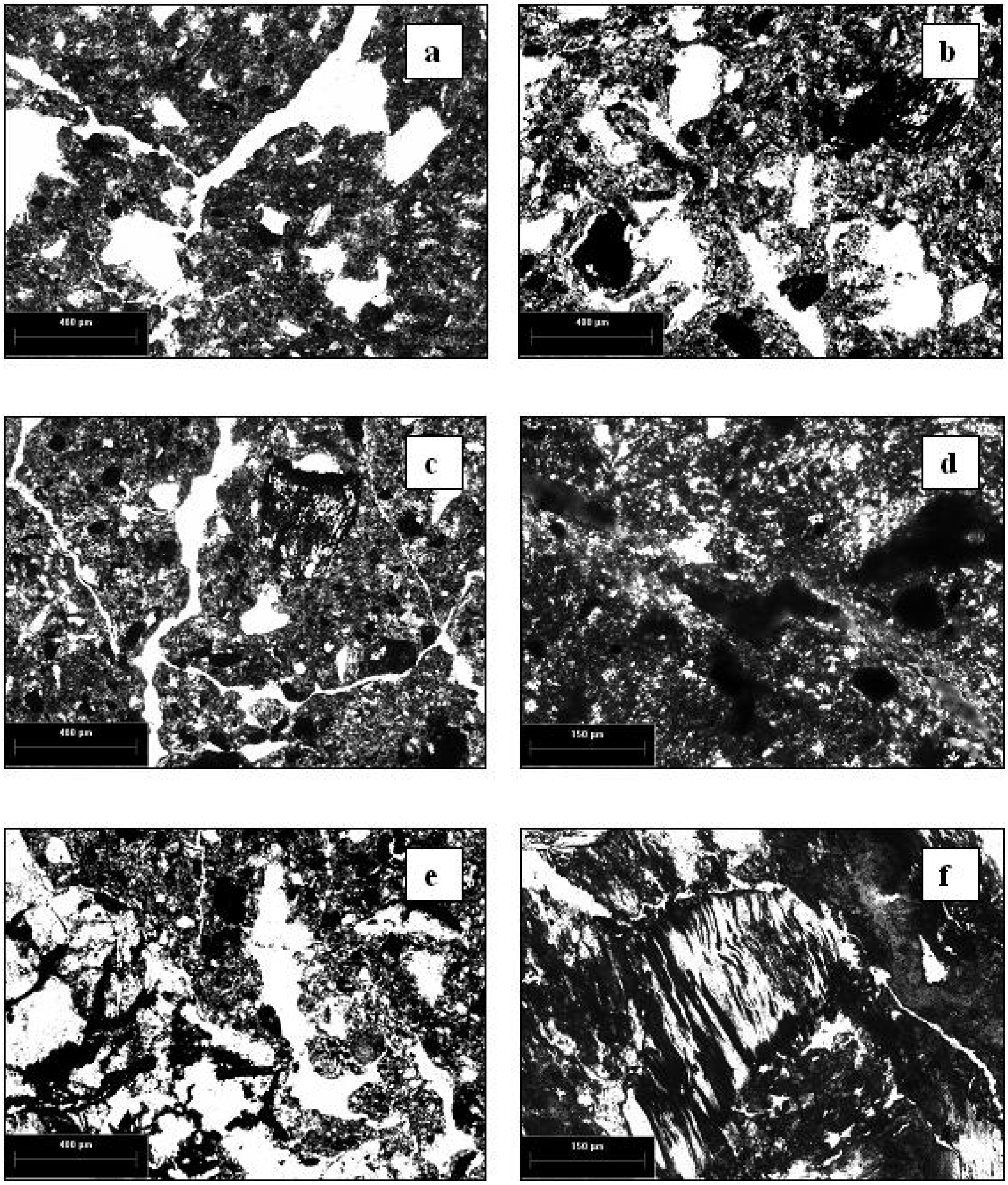

Figure 4. Soil micromorphology of the profile N2 (Ferralic Umbrisol): a) silt coatings in the horizon Bw1; b) iron oxide coatings on weatherable minerals in the horizon Bw1; c) the structure of Bw2 horizon; d) partial orientation of clay in coatings in Bw2 horizon (crossed nicols); e) complete amphibole destruction in Bw2 horizon; f) biotite weathering in BC horizon.

equally good: local people consider red clayey soils to be the best ones for coffee because of their greater water-holding capacity (*tierra colorada húmeda*).

Profile 3N

The soil profile 3N is situated on a steep slope (30-40%) on a shallow regolith of limestone. The vegetation is a secondary forest. There are frequent limestone outcrops in the area. The soil is clayey, well aggregated, and has brownish red color (Table 1). The content of rock fragments increases with depth and at 50 cm it is a consolidated rock with fine earth in cracks. The pH values are in the neutral range (Table 2), with a zero or negative ΔpH values. Clay content is the highest in the Bw horizon, though no morphological evidences of clay illuviation are detected. Base content is high, with Ca as a dominant cation, and base saturation increases from 80 to 90% with depth. Organic C content is high in the surface horizon and decreases with depth, but even in the Cr horizon it is still higher than 1%. The highest Fe_d content is detected in the Bw horizon, while Fe_o content decreases with depth; the Fe_o/Fe_d ratio is low throughout the profile, decreasing with depth. In bulk elemental composition, there is a decrease with depth in Si and Fe (II) contents, and an increase in Al content (Table 3). The other elements have a minimum in the Bw horizon. The distribution was most evident for Ca, which shows high concentration in the Cr horizon and elevated concentration in the A horizon (most probably, due to biological accumulation). Light organic matter is a minor component in SOM (Table 4); its content is higher in the A horizon than in the Bw horizon. In both horizons, humins constitute more than a half of organic matter. The content of humic acids is higher than the FA content.

X-ray analysis shows the presence of 1.4, 1.0, and 0.7 nm clay minerals. After heating, the peak 1.4 nm decreases,and the peak 1.0 nm increases their intensities; it is interpreted as the presence of chlorite, mica, and vermiculite minerals. The peak 7.0 nm completely disappears after heating; thus, it should be attributed to kaolin minerals and not to a basal signal of chlorites. Almost no variation in clay minerals composition is detected between the horizons.

This profile, formed on limestone, is classified as Epileptic Calcaric Phaeozem. There are two main scenarios in the carbonates-derived soils in humid (sub)tropical environments: the formation of a thick residual red-colored soil and total dissolution of limestone, when residual products are removed by erosion and karst. In the case of the studied soil, mainly the latter scenario takes place. Though residual red-colored weathered material formed in the course of pedogenesis, most of this material was removed by erosion due to steep sloping of the site. We did not find deep profiles formed on limestone in the study area, though they have been detected in the region.

Epileptic Calcaric Phaeozem has the highest base saturation, a combination of clayey texture with rock fragments, and HA as the main component of soil humic substances. It could be related to the influence of active calcium and also to the calcaric attributes of this soil that enhances the stabilization mechanisms of organic matter, corresponding with the results obtained by Shang and Tiessen (2003) in the calcareous soils of Yucatan, Mexico. Epileptic Calcaric Phaeozem is a soil unsuitable for coffee growing (Moguel and Toledo, 1996), and it is left under forest vegetation.

CONCLUSIONS

- Three soils were investigated at a coffee growing farm El Nueve, sierra Madre del Sur, Oaxaca, Mexico: Skeletic Phaeozem, Ferralic Umbrisol, and Epileptic Calcaric Phaeozem.
- The formation of these soils was regulated by the origin of parent material (Epileptic Calcaric Phaeozem formed on limestones) and by the age of the exposed surface (Skeletic Phaeozem was formed on the slope of a V-shaped valley, and Ferralic Umbrisol on a deeply weathered regolith, derived from the same gneiss).
- The three soils differed in their acidity, organic matter composition, clay mineralogical composition, and exchangeable complex characteristics. The diversity of soil properties resulted in the diversity of soil use and soil ecological functions.
- The diversity of soils of tropical mountainous areas is regulated by the high variety of parent materials and the age of exposed surfaces.

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