Pedological diversity and the geoecological systems of Sierra de Guadalupe, central México

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ABSTRACT

The Sierra de Guadalupe, located north of Mexico City, is an important geoecological system of the dry Mexican basin. Its topographical features, lithological materials and soil characteristics influence its biodiversity and ecosystem processes; conversely, patterns of biodiversity affect the soil properties at different scales. Unfortunately, although widespread land disturbance, severe soil degradation, and slopes severely affected by slumps and landslides are present in this region, soil and landscape preservation strategies have received surprisingly little attention. This paper attempts to examine and define the pedodiversity context that characterizes the geoecological system of the Sierra de Guadalupe. We consider that characterizing this system provides a unique and indispensable tool for evaluating the environmental risks of the geoecosystem as well as the interactions and interrelations in the environment. The goals of this paper center on the rationale to identify soil units, determine their spatial distribution, define their variation in soil morphology and properties, and to classify them appropriately.

Our results revealed that the studied soils are derived from volcanogenic materials that are too young to be strongly weathered. Uncultivated and incipiently developed soils, polycyclic soils and buried soils were detected in the study area. Their soil characteristics and properties are ascribed mainly to successive processes of mass movement, erosion and redeposition (K cycles) as well as to their spatial arrangement on the slope profile. Laboratory analyses showed that these soils are slightly acid and rich in organic matter. In addition, they have high cation exchange capacity saturated by Ca^{2+} *and* Mg^{2+}*. The clay fraction is composed of halloysite > kaolinite > smectite. The soils exhibit large quantities of* SiO_2*, besides total oxides abundances in the order* SiO_2>Al_2O_3>Fe_2O_3*, which indicates their incipient degree of weathering. We conclude that the characteristics of the Sierra de Guadalupe soils can be explained within the context of a slope model, with an erosional and depositional toposequence pattern, common in the dry lands of the Mexican basin.*

Key words: soil genesis, volcanic soils, weathering, Sierra de Guadalupe, Mexico.

RESUMEN

La Sierra de Guadalupe, localizada al norte de la Ciudad de México, representa un sistema geoecológico importante de la cuenca seca de México. Sus rasgos topográficos, materiales litológicos y características del suelo influencian su biodiversidad y procesos del ecosistema; a la inversa, los patrones

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de biodiversidad afectan las propiedades del suelo a diferentes escalas. En esta región están presentes el disturbio diseminado de la tierra, degradación severa del suelo y pendientes severamente afectadas por hundimientos y derrumbes, no obstante, las estrategias para la preservación del paisaje y del suelo han recibido, sorprendentemente, poca atención. Este trabajo es un intento para examinar y definir el contexto de pedodiversidad que caracteriza el sistema geoecológico de la Sierra de Guadalupe. Se considera que su caracterización provee una herramienta única e indispensable para evaluar los riesgos ambientales del geoecosistema y las interacciones e interrelaciones en el medio ambiente. Las metas de esta investigación se centran en identificar las unidades de suelos, determinar su distribución espacial, definir su variación en morfología y propiedades del suelo y hacer una clasificación apropiada de ellos.

Los resultados revelaron que los suelos estudiados derivaron de materiales volcanogénicos que son demasiado jóvenes para estar intemperizados fuertemente. Con base en suelos con desarrollo incipiente, en el área de estudio fueron detectados suelos policíclicos y suelos sepultados. Las características y propiedades del suelo son atribuidas principalmente a procesos sucesivos de movimiento de masa, erosión y redepositación (ciclos K), así como a su arreglo espacial sobre la pendiente del perfil. Los análisis de laboratorio mostraron que estos suelos son ligeramente ácidos y ricos en materia orgánica. Además, tienen alta capacidad de intercambio catiónico saturada con Ca^{2+} y Mg^{2+}. La fracción de arcilla está compuesta de haloisita>caolinita>esmectita. De la misma manera, los suelos exhiben grandes cantidades de SiO_2 y la secuencia de abundancia de óxidos totales es SiO_2>Al_2O_3>Fe_2O_3, resultado de su grado incipiente de intemperismo. Se concluye que las características de los suelos de Sierra de Guadalupe se pueden explicar en el contexto de un modelo de pendiente, el cual acentúa un patrón de toposecuencia de erosión y depósito, común en las tierras secas de la cuenca de México.

Palabras clave: génesis de suelos, suelos volcánicos, intemperismo, Sierra de Guadalupe, México.

INTRODUCTION

Sierra de Guadalupe (SDG) is an important geoecological reserve of the dry Mexico Basin (Lugo-Hubp and Salinas-Montes, 1996). Furthermore, it is a natural barrier against contamination and anthropic environmental degradation, because it constitutes a natural boundary between urban and industrial areas (Figure 1).

Today, however, the management and the conservation of the SDG are only based on results of qualitative studies regarding plant and animal communities (Reyes-Castillo and Halffter, 1976; Rzedowski and Rzedowski, 1979; Méndez-de la Cruz *et al*., 1992), geographic and geomorphologic characteristics (Lugo-Hubp and Salinas-Montes, 1996), and geologic studies (Ordóñez, 1895; Lozano-Barraza, 1968; Mooser, 1977; Fraustro-Martínez, 1999; García-Palomo *et al*., 2006). In these studies, the soils and the landscape have received surprisingly little attention despite the fact that their characterization and systematic monitoring provide a unique and indispensable tool to evaluate the quality, health, and risks of the ecosystem (Bridges and Van Baren, 1997; Etchevers-Barra, 1999; Guo and Amundson, 2003; Bockeim *et al*., 2005).

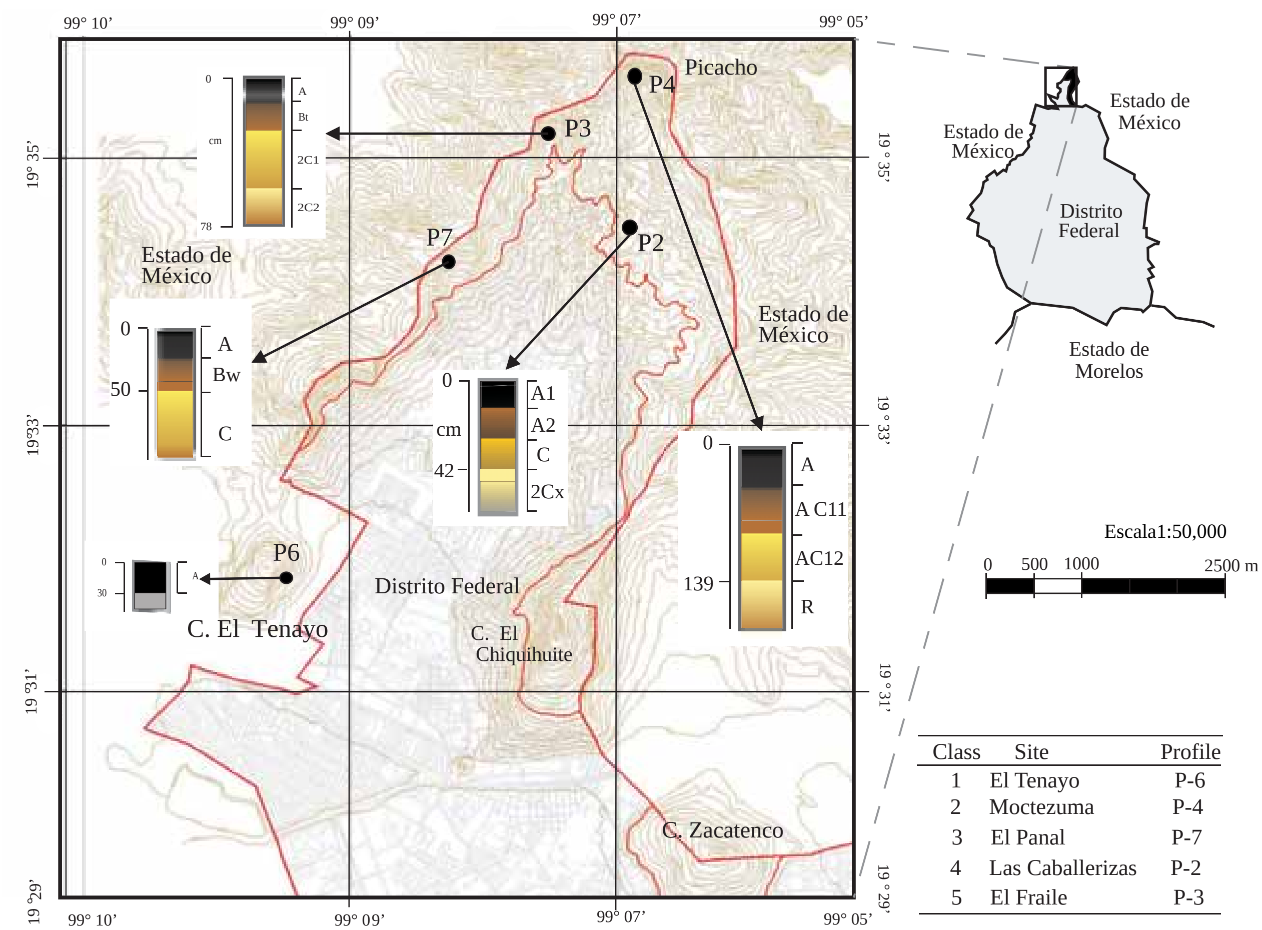
Based on the research by McBratney and Minasny (2007), we assume that the knowledge on the intrinsic variability of the soil within homogeneous landscape units could help to design better land use and conservation strategies and decisions. In agreement with this assumption, the goals of the present study were: (i) to examine the major environmental processes that determined the genesis of the SDG soils; (ii) to identify soil units and determine their spatial distribution; (iii) to define their variation in soil morphology and their properties; and (iv) to classify the soils appropriately.

A detailed field survey of soils was conducted over a four month period. Position-slope-geology computer displays were used for sampling and determining the distribution of soils. During the survey, 24 soil profiles were described from the soil surface to the upper boundary of a specified horizon or root-limiting layer. These profiles were sampled in the field and analyzed in the laboratory. Based on field investigations and laboratory data, we selected five typical pedons representative of such soils for analysis and soil classification. The five pedons are named after localities in the study area as follows: P2 Las Caballerizas, P3 El Fraile, P4 Moctezuma, P6 El Tenayo, and P7 El Panal.

CHARACTERISTICS OF THE STUDY ZONE

Sierra de Guadalupe lies to the north of Mexico City, 19º29’to 19º37’N and 99º02’ to 99º12’W (INEGI, 1984). The study area covered a surface of 1,021.08 ha of the southern part of the Sierra (Figure 1).

The Sierra is a volcanic formation whose main hills are compound, formed by Strombolian eruptions that culminated with pyroclastic activity. Outstanding among these are the Zacatenco, Panal and Moctezuma hills. Short-lived volcanic activity formed almost exclusively other lower cones, such as the Cerro Gordo, Chiquihuite, Tenayo and



Class	Site	Profile
1	El Tenayo	P-6
2	Moctezuma	P-4
3	El Panal	P-7
4	Las Caballerizas	P-2
5	El Fraile	P-3

Figure 1. Location of the study area, classes and morphology of the selected soil profiles.

Tepeyac domes, located on the periphery of the Sierra (Mooser, 1977; García-Palomo *et al.,* 2006).

Radiometric studies have estimated that the Barrientos area originated during the Cenozoic and, in particular, the eastern zone did so during the Pliocene (Mooser, 1990). The rocks that form the Sierra are andesites and dacites; the predominant material are lavas exposed by denudating processes that have removed less resistant material, such as ash, volcanic sand and pumice (Campa-Uranga, 1965; Lozano-Barraza 1968). Lugo-Hubp and Salinas-Montes (1996) report that the central part of the Sierra exhibits fractures and advanced weathering with evidence of hydrothermal alteration. Owing to slopes from 15 to 40% inclination in the area, velocity of erosion at present is from low to moderate; the estimated average soil loss due to erosion is 43.15 Mg/hectare/year (Pimentel *et al*., 2000).

According to the Köppen classification, modified by García (1988), the climate is C(wo)(w) temperate subhumid with scant precipitation in summer; annual temperature is 16ºC and total annual precipitation is 548.7 mm. Vegetation is characterized by an arboreous community based on *Eucalyptus* spp., *Casuarina equisetifolia* and *Cupressus lindleyi*, as well as by several species of pine, among which *Pinus cembroides*, *P. montezumae* and *P. radiata* are outstanding. In the highest, least accessible parts, are found *Quercus rugosa* and *Q. deserticola, Mammilaria rhodantha*, *Opuntia* sp. and *Yucca filifera*, among others (Rzedowski and Rzedowski, 1979) (Table 1).

MATERIALS AND METHODS

Field work and laboratory analysis

Available documents were analyzed, as well as cartographic material at 1:20,000, 1:50,000-scale thematic maps (INEGI, 1984) and aerial panchromatic black and white photographs at a scale of 1:37,000. A 1:20,000 topographic base chart was constructed, and the soil sampling sites were located using photointerpretation, trying to select sites that represent areas with shared characteristics as supported by field observation. Five soil profiles were selected: P2 Las Caballerizas, P3 El Fraile, P4 Moctezuma, P6 El Tenayo and P7 El Panal (Figure 1). The designation of horizons, description of profiles and soil sampling were conducted following Schoeneberger *et al*. (2002).

Soil samples were analyzed in the laboratory with the following methods: color was assessed with the Munsell Color (1954) charts, bulk density (Bd) and particle density (Pd) based on Soil Survey Staff (1984); and texture with the pipette method proposed by Day (1965). To explain mode and means of particle transport, we studied particle sphericity and roundness considering the scale proposed by Powers (1953).

The pH ratio 1:2.5 in H_2O was determined by means of a Corning 220 pHmeter with a glass electrode. Organic matter was quantified using the wet combustion method of Walkley and Black (1947). Cation exchange capacity (CEC) was measured by saturation with ammonium acetate and tested with EDTA, following Jackson (1976). Exchangeable Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} cations were determined following Soil Survey Staff (1984). Free oxides and total oxides were determined as described by Merha and Jackson (1960) and Verbeek *et al*. (1982), respectively. Total oxide losses and gains between parent material and soil horizons were estimated assuming that Al_2O_3 is most stable and can be used as "witness" as proposed by Krauskopf (1979). In the soils with hard layers, the bonding agent was identified by immersing fragments in 30 % KOH, in accordance with the method described by Soil Survey Staff (1999), the chemical analysis was performed with a X-ray energy dispersive spectrometer (Tracor), attached to a scanning electron microscope. The mineralogical data were obtained by means of a Phillips PW 1130/96 X-ray diffractometer with copper K_α radiation, graphite monochromator and vanadium filter, and under excitation conditions of 30 kV and 20 mA; pretreatment of samples consisted of potassium saturation and heating at 350 ºC and 550 ºC.

RESULTS AND DISCUSION

Our results revealed that the studied soils have morphological, physical, chemical and mineralogical properties which can be attributed to the influence of a combination of factors involved in their development: (i) nature of parent material; (ii) relative position on a slope (*i.e.*, from the toe to the summit); (iii) a series of stepped pedogenic episodes; and (iv) seasonal moisture conditions.

Field work concerned soil-forming processes, soil profile features, the environment in which they form, and resulting spatial distribution of soils. Based on the results of this work, we propose to group these soils in five provisional classes.

Class 1. Shallow soils with little or no developmental evidence of pedogenetic horizons, except a light colored horizon A. Profile P6 represents the class.

Class 2. Polycyclic soils derived from the re-deposited debris and earth flows. Profile P4 represents the class.

Class 3. Soils that have some subsoil pedogenic development but lack diagnostic features common in mature soil units. Profile P7 represents the class.

Class 4. Soils that have a dark colored surface horizon and are base rich. Profile P2 represents the class.

Class 5. Soils with dark top soil and buried soil. Profile P3 represents the class.

Morphological, physical and chemical characterization of the studied soils

Class 1. Profile P6 El Tenayo

Based on USDA (2006) outlines, we estimate that this soil is an intergradation between the soil genetic units and non-soils. Morphological observations show that the profile development is limited to formation of a low coherence, light colored surface horizon (Ochric horizon) over unaltered parent material (Figure 1). We consider that the paucity of pedogenetic transformation products explains the low coherence of the matrix material and determines soil colors by the composition of the mineral soil fraction.

Generally, there are very unstable areas either because of high erosion rates, impenetrable areas for roots which therefore prevent plant growth, or areas characterized by steep slopes (≥ 25 percent) where soil formation is inhibited. Table 1 summarizes some of the main factors that characterize their environmental context.

These soils are also associated with geomorphic processes such as rockfalls, deep faults in slopes and the sliding of earth materials under the influence of gravity (García-Palomo *et al*., 2006). Erosion and mass movement remove material from such areas faster than most pedogenic horizons form. In addition, anthropogenic activity may affect the formation of these soils, *i.e.*, deforestation, changes of original slope, heavy traffic transit and mining.

Morphologically, the top horizon has a weakly developed prismatic sub-angular structure, marked transition between horizons, and fine roots; furthermore, it is not stony (Table 2). Such characteristics denote the physiographic factors cited before.

In the representative profile, horizon A bulk density is 0.95 Mg/m^3 due to the organic matter present, reflected in porosity over 50%. Particle size fractions are found in similar proportions, and thus the texture is dominated by clay loam, fine sand and coarse silt; the clay fraction (≤0.002 mm) is 32.6% (Table 3), suggesting incipient clay formation from the alteration of recently deposited pyroclastic materials (Rodríguez-Tapia *et al*., 1999). El Tenayo is a volcanic dome with slopes of more than 20%. Its piedmont is completely urbanized (García-Palomo *et al.*, 2006). These soils were formed from volcanic ash and by materials carried and deposited by wind, rain and gravity. The forms that dominate in the mineral fraction are angular and very angular with low sphericity (Table 4), and so are considered colluvial.

Table 1. Physiographic aspects of the studied soil profiles in the Sierra de Guadalupe.

Location	Altitude m a.s.l.	Slope (%) Exposition	Slope profile position	Lithology	Vegetation
Class 1. P6 El Tenayo					
19º33'25" N 99º09'36" W	2,400	25 250°00'	Medium slope	Andesites with rocky outcropping	*Schinus molle*, *Opuntia* sp., *Cynodon dactylon*, *Bouteloua filiformis*, *Setaria geniculata*
Class 2. P4 Moctezuma					
19º35'17" N 99º07'16" W	2,980	40 15°00'	High slope	Andesites tuffs	*Pinus radiata*, *P. hallepensis, Quercus robusta, Agave* sp., *Q. microfila, Opuntia* sp.
Class 3. P7 El panal					
19°34'10''N 99°08'37''W	2,500	25 270°00'	High slope	Altered Andesites tuffs	*Cupress lindleyi*, *Eucalyptus* spp., *Schinus mollle, Quercus microphylla,* *Prosopis juliflora, Cynodon spp.*
Class 4. P2 Las Caballerizas					
19°34'15''N 99°07'25''W	2,620	10 20°00'	Lower Slope	Altered Andesites tuffs	*Cupressus lindleyi, Eucalyptus globulus,* *Schinus molle*
Class 5. P3 El Fraile					
19º34'50" N 99º07'57" W	2,475	12 320°00'	Slope base	Andesites tuffs	*Pinus radiata*, *Cupressus* sp., *Cuasuarina equisetifolia, Eucalyptus* sp.

Table 2. Morphological properties of the soils studied in the Sierra de Guadalupe.

Class / Profile depth (cm)	Hz	Structure (type, grade)	Consistency (dry, moist)	Transition	Roots	Stony (quantity, size, class)
Class 1. P6 El Tenayo						
0–28	A	Ps, Wd	W, fr	m, h	c, f	-----
Class 2. P4 Moctezuma.						
0–40	A	Pa, Md	W, vf	t, h	a, f, t	s, m, A
40–63	AC11	Pa, Wd	W, f	t, u	c, t	s, m, A
63–90	AC12	Ps, Wd	Lw, f	t, h	c, f, t	s, m, A
90–139	C	Ps, Md	Lw, f	m, h	s, t	ls, m, A
Class 3. P7 El Panal						
0–18	A	Ps, Md	W, f	m, h	a, f	ls, sm, A
18–50	Bw	Pa, Md	W, f	m, h	a, f	ls, sm, A
>50	C	Ps, Md	W, f	m, h	s, f	ls, sm, A
Class 4. P2 Las Caballerizas						
0–14	A1	Ps, Wd	W, f	t, h	c, f	-----
14–28	A2	Ps, Wd	W, f	t, h	c, t	-----
24–42	C	Ps, Wd	W, vf	m i	a, f	-----
>42	2Cx	m, Ws	Lw, vf	-----	s, f	-----
Class 5. P3 El Fraile						
0–7	A	Ps, Wd	Lw, f	t, h	a, f	-----
7–39	Bt	Pa, Md	Lw, f	t, h	L, f	-----
39–56	2C1	-----	W, f	t, h	c, t	vs
56–78	2C2	-----	W, f	-----	vs, m	-----

Hz: Horizon. *Structure type*. Pa: Prismatic angular; Ps: prismatic subangular; m: massive. *Structure grade.* Wd: weakly developed; Md: Moderately developed; Sd: strongly developed; Ws: without structure. *Consistency.* W: Weak; Lw: lightly weak; Eh: extremely hard; f: friable; vf: very friable; fr: firm. *Transition*. m: marked; t: tenuous; h: horizontal; u: undulated; i: irregular. *Roots*. vs: very scarse (<1/3 dm^2), s: scarse (3 to 5/3dm^2), l: little (5 to 10/3 dm^2), c: common (10 to 100/3 dm^2) a: abundant (100 to 500/3 dm^2); f: fine (< 1mm of diameter); t: thin (1 a 3 mm of diameter), m: medium (3 a 10 mm of diameter). Stony; *quantity.* ls: lightly stony (1 to 5 %); s: stony (5 to 20 %); vs: very stony (20 to 50 %); es: extremely stony (50 to 75 %). Stony; *size.* sm: small (1 to 5 cm of diameter); m: medium (5 to 10 cm of diameter); b: big (10 to 20 cm of diameter). Stony; *class:* A: Andesite.

Table 3. Density, porosity and soil particle-size distribution in soils from Sierra de Gualdalupe.

Class Profile / Hz	Depth	Bd	Pd	Porosity	Sand						Silt				Clay	Textural classification
					vc	c	m	f	vf	Total	c	m	f	Total		
	cm	Mg m^{-3}		%												
Class 1. P6 El Tenayo																
A	0-28	0.95	2.21	57.01	2.42	11.29	5.07	9.67	4.49	32.94	16.70	10.94	6.79	34.43	32.60	Cl
Class 2. P4 Moctezuma																
A	0-40	0.98	2.38	58.82	3.28	5.08	2.71	2.15	0.34	13.56	22.82	17.97	8.25	49.04	37.40	Scl
AC11	40-63	1.01	2.50	59.60	0.36	1.92	0.41	1.32	0.74	4.75	37.83	48.15	1.89	87.87	7.38	Sl
AC12	63-90	1.15	2.25	48.88	5.19	2.77	2.08	5.88	1.04	16.96	26.99	23.07	11.42	61.48	21.57	Sl
C	90-139	1.08	2.20	50.91	4.01	5.61	2.52	5.96	2.63	20.73	29.21	8.36	7.56	45.13	34.13	Cl
Class 3. P7 El Panal																
A	0-18	0.88	1.66	49.98	1.2	8.4	0.1	9.1	2.2	21.0	33.2	8.4	6.9	48.5	30.50	Cl
Bw	18-50	1.11	1.68	33.93	2.7	17.4	3.8	2.7	9.1	35.7	29.4	8.4	2.2	40.0	24.30	L
C	>50	1.15	1.68	31.54	1.6	15.0	3.0	2.2	6.5	28.3	24.3	7.0	0.6	31.9	39.80	Cl
Class 4. P2 Las Caballerizas																
A1	0-14	0.89	1.75	49.14	0.11	3.58	0.00	1.68	1.23	6.60	24.30	10.97	6.27	41.54	51.84	Sc
A2	14-28	0.99	1.64	36.63	0.21	3.40	0.00	6.48	3.29	13.38	26.67	11.69	4.25	42.61	43.99	Sc
C	28-42	1.01	1.69	40.24	0.08	3.22	3.54	10.38	9.41	26.63	42.63	8.77	2.90	54.30	19.07	Sl
2Cx	>42	1.02	1.71	40.35	0.22	8.41	0.78	9.98	8.41	27.80	35.54	7.62	1.79	44.95	27.24	L
Class 5. P3 El Fraile																
A	0-7	1.06	1.44	26.39	0.83	5.41	3.43	3.12	1.77	14.56	22.79	14.98	6.66	44.43	40.99	Sc
Bt	7-39	1.10	1.46	24.65	0.73	3.63	1.97	2.49	0.93	9.75	5.71	9.24	6.96	21.92	68.33	C
2C1	39-56	1.95	2.38	18.06	0.73	3.02	1.56	2.19	0.94	8.44	6.05	23.57	44.73	74.35	17.20	Sl
2C2	56-78	1.98	2.24	11.61	0.42	1.99	0.42	5.15	2.20	10.18	15.34	53.78	3.47	72.59	17.23	Sl

Hz: Horizon; Bd: Bulk density; Pd: Particle density. *Sand.* vc: very coarse (2 – 1 mm); c: coarse (1 – 0.5 mm); m: medium (0.5 – 0.25 mm); f: fine (0.25 – 0.10 mm); vf: very fine (0.10 – 0.05 mm). *Silt.* c: coarse (0.05 – 0.02 mm); m: medium (0.02 – 0.005 mm); f: fine (0.005 – 0.002 mm). *Clay.* <0.002 mm. *Textural classification.* Cl: Clay loam; Scl: silty clay loam; Sl: Silt loam; L: Loam; C: Clay; Sc: Silt clay.

In horizon A, pH is slightly acid, favored by the presence of organic materials, mainly derived from grasses (Table 5). This horizon has a thickness of 28 cm, but the process of mineralization is very slow, possibly because the mild climate in the Sierra favors a slow release of humus and organic acids, a situation that is reflected in a low CEC. As in the rest of the soils in the Sierra, the exchange complex is dominated by Ca^{2+} (Table 5).

Class 2. Profile P4 Moctezuma

In SDG, polycyclic soils are located in receptive areas and were developed in materials that possibly underwent previous pedogenesis. In all these soils, morphologic discontinuities were found in the form of stony deposits, stone or gravel lines and net limits. These discontinuities were confirmed by means of physicochemical analysis that indicated differences in texture, gravel or organic matter content between cycles. In general, mineralogical composition of fine earth fractions and clay hardly showed variations between cycles.

Although polycyclic soils are used for many purposes, some relevant to agricultural and forest sciences, these intensively managed and disturbed soils have not been extensively investigated yet. Because these soils, located in suburban and urban areas of SDG, are often developed on mixed colluvial-urbic materials, spatial heterogeneity is a typical feature. Their evolution is controlled almost exclusively by humans, who impose very rapid transformation cycles compared with those occurring in less disturbed areas. However, there is a continuum from the natural soils to the extensively disturbed soils, and their basic functions are essentially the same (De Kimpe and Morel, 2000).

In profile P4, which represents this class, the morphology manifested the presence of cycles. The differences lie between upper horizons and deep horizons, mainly in structure, consistency and roots (Table 2).

Bulk density in increases from 0.98 Mg/m^3 in horizon A to 1.35 Mg/m^3 in C where the materials are less weathered and more compact. Particle density was high in superficial horizons and slightly lower in deep horizons, which means a different mineralogical composition of soil particles. As to porosity, the values were high in superficial horizons and they decreased with depth where materials are more compact. Andesites form a rocky bed.

Horizon A has a silty clay loam texture; AC11 and AC12 are silty loam, and C is clay loam (Table 3). This soil is believed to have been formed from a layer of consolidated ash that is found on the rocky bed. The forms that dominate in the mineral fraction are very angular in horizon A with a low sphericity (Table 4). In horizons AC11 and AC12 roundness increases, although the particles continue to be somewhat sharp. This is attributed to particles be-

Table 4. Roundness, sphericity and color of the soil particles in the profiles studied in Sierra de Guadalupe.

Class Profile	Depth (cm)	Hz	Roundness (%)			Sphericity (%)		Color	
			VA	A	SA	high	low	dry	wet
Class 1. P6 El Tenayo									
	0–28	A	50	50		20	80	10YR4/2	10YR2/1
Class 2. P4 Moctezuma									
	0–40	A	90	10		15	85	10YR4/2	10YR2/!
	40–63	AC11	80	20		30	70	10YR4/2	10YR2/1
	63–90	AC12	65	35		25	75	10YR5/3	10YR3/3
	90–139	C	65	35		25	75	10YR4/2	10YR3/4
Class 3. P7 El Panal									
	0–18	A	90	10		10	90	2.5Y4/2	7.5YR3/2
	18–50	Bw	100			40	60	10YR5/4	10YR4/4
	>50	C	85	15	-----	30	70	10YR5/6	10YR4/3
Class 4, P2 Las Caballerizas									
	0–14	A1	80	20		25	75	2.5Y5/2	7.5YR3/2
	14–28	A2	85	15		40	60	2.5Y5/2	10YR3/4
	28–42	C		95	5	25	75	10YR5/6	10YR4/4
	>42	2Cx		100		15	85	10YR5/6	10YR4/4
Class 5. P3 El Fraile									
	0–7	A	90	10		15	85	10YR4/1	10YR3/1
	7–39	Bt	100			40	60	10YR5/1	10YR4/2
	39–56	2C1	85	15		30	70	10YR6/1	10YR5/2
	56–78	2C2	100			35	65	2.5Y6/2	10YR5/3

Hz: horizon, VA: very Angular; A: angular; SA: sub-angular.

ing dragged by gravity, wind and rain, thus giving rise to colluvial soil formation. The site is a small plain formed by accumulated sediments from the higher areas. Silt and clay dominate over sand in horizon A, while coarse and medium silt dominate deeper in horizons AC11 and AC12. This is related to the degree of alteration generally present in the upper horizons. Although horizon C has a clay loam texture, the predominant materials are clay, coarse silt, fine and very coarse sand.

As reported by Vazquez (1997), soils tend to be neutral, yet in horizons A and AC11 they are slightly acid because of the organic matter present (Table 5). The content of organic matter is poor in A and AC11 and very poor in AC12 and C, horizons where the biological activity is lower (Table 5). According to Cottenie (1980), the CEC is high in all of the horizons due as much to organic matter content as to the type and quantity of clay. Ca^{2+} and Mg^{2+} dominate among the exchangeable cations, condition related to pH and scant precipitation in the zone.

Class 3. Profile P7 El Panal

Soils in this class show soil formation by either of the following: color change compared to parent material, soil structure development, formation of silicate clays and sesqui(hydr)oxides as a result of the weathering of primary minerals, but lacking sufficient soil development to classify for another taxonomic unit.

These soils occur in areas of the SDG where water movement is fast and free, mainly in the upper and middle part of the slope. The dry season of the year shows water scarcity. The soils are formed from unconsolidated deposits with a silty and loamy texture; between them are alluvial and solifluction deposits. They can develop not only in intermediate materials, but also in basic and ultra basic materials. The high silt content is important. In some cases their occurrence is in the Holocene period, and their parent material could be weathered rock or old material formed in the Tertiary. Their natural fertility is high.

The morphology is very similar in all the horizons in the representative profile P7, where the dominant values are as follows: structure: prismatic sub-angular; consistency: weak and friable; transition: marked and horizontal; roots: abundant and fine; and stoniness: slight and medium (Table 2). This similarity shows the low level of evolution (McBratney and Minasny, 2007).

The color in horizon A is dark, clear in Bw and clearer in horizon C. This condition is due to the high organic matter content in superficial horizons and to the mineralogical nature of the subsurface horizons. Bulk density is less than 1 in horizon A and increases in deep horizons, also due to the high organic matter content and lixiviation-accumulation processes. Particle density presents similar low values in all horizons. As in the majority of studied profiles, porosity is 50% in surface soil and decreases with depth (Table 3).

Horizon A has a clay loam texture, Bw is loam and C is also clay loam. In the superficial horizons, silts dominate over clays; sands do so in the deepest clays. Coarse fractions prevail in the silts of all horizons. Fine fractions (0.25–0.10 mm) are dominant in the sands of horizon A, and coarse fractions predominate in deeper horizons. Such are the textural characteristics typical of these soils according to USDA (2006) (Table 3). The form of mineral particles in all profiles is very angular with low sphericity (Table 4). Such characteristics indicate that the particles were deposited by air, like pyroclasts, as a result of a volcanic eruption (Flores-Román *et al*., 1992).

The pH is slightly acid in horizon A and neutral in deep horizons; such acidity is a result of the higher abundance of organic matter in the superficial horizon. The organic matter content is high in horizon A and extremely low in Bw and C (Vázquez-Alarcón, 1997). CEC is high in superficial horizons and very high in deeper ones (Cottenie, 1980); in the first case, this occurs as result of the high organic matter content and in the second because of the clays present. Base saturation is high in horizon A and decreases with depth (Table 5), which indicates the high alteration of primary minerals on the surface (Fassbender and Bornemiza, 1987); furthermore, the dominant bases are Ca^{2+} and Mg^{2+}.

Class 4. Profile P2 Las Caballerizas

Soils in this class have thick dark topsoil and are rich in organic matter. In the first horizon, quick decomposition of organic matter occurs, which contributes to high base saturation. The color is grayish brown in superficial horizons and yellowish brown in deeper ones, basically because of the high content of organic matter.

In SDG these soils are developed in moderated slopes, from 10 to 15%, with sufficient hydric drainage and where the evaporation-transpiration is greater than precipitation. The soils have excellent hydro-physical characteristics, which allow the excess of water to infiltrate freely, while at the same time they retain a large quantity of the liquid in their pores (Fitzpatrick, 1993).

The natural fertility of these soils is very high, sufficient for obtaining good harvests. The danger in these soils is aeolian and hydric erosion; thus, control measures must always be applied.

The parent material consists of consolidated deposits accumulated in small plains which have received contributions from the higher areas. Rain and gravity have dragged the fine soil particles, depositing them in the A1 and A2 horizons. Likewise, we consider that the conditions of moderate drainage have favored the formation and deposit of clays in the deep horizons.

In its morphology, profile P2 exhibits homogenous properties in the three superficial horizons, but different with 2Cx discontinuity (Table 2).

Bulk density is 0.89 Mg/m^3 in horizon A1 and increases up to 1.02 Mg/m^3 in horizon 2Cx, where less weathered and more compact materials are found (Vela-Correa and Flores-Román, 2004a). According to Primavesi (1982), these soils are very hard when dry, but they become friable when they are wet; this can be explained by the high level of consolidation caused by simple pressure or by water

Table 5. Chemical properties of the Sierra de Guadalupe soils.

Class Profile Hz	Depth (cm)	pH 1:2.5	OM (%)	C (%)	CEC cmol kg^{-1}	Extractable bases (cmol kg^{-1})				BS %
						Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	
Class 1. P6 El Tenayo										
A	0–28	6.7	3.35	1.94	11.76	30.8	0.7	2.1	0.7	100.0
Class 2. P4 Moctezuma										
A	0–40	6.7	2.68	1.55	27.86	28.0	9.1	2.2	1.0	100.0
AC11	40–63	6.7	1.40	0.81	23.06	15.4	9.1	0.5	0.4	100.0
AC12	63–90	7.0	0.43	0.25	21.00	9.1	14.7	0.7	0.3	100.0
C	90–139	7.0	0.40	0.23	20.66	15.4	10.5	0.7	0.4	100.0
Class 3. P7 El Panal										
A	0–18	6.5	4.14	2.30	30.06	5.0	17.0	0.86	0.61	78.07
Bw	18–50	7.2	0.56	0.32	47.17	5.0	22.0	0.69	0.35	59.44
C	>50	7.4	0.25	0.14	48.05	8.0	15.0	0.65	0.33	49.90
Class 4. P2 Las Caballerizas										
A1	0–14	6.8	3.66	2.12	48.05	13.0	27.0	0.8	2.4	90.00
A2	14–28	7.4	1.90	1.12	42.76	8.0	24.0	0.9	1.5	80.45
C	28–42	7.3	1.09	0.63	37.95	6.0	25.0	1.2	0.6	86.42
2Cx	>42	6.7	0.45	0.23	42.76	9.0	21.0	1.7	0.3	74.83
Class 5. P3 El Fraile										
A	0–7	6.2	4.52	2.62	44.69	32.9	4.2	0.8	2.8	91.0
Bt	7–39	6.8	2.21	1.28	34.60	28.0	12.6	1.7	3.2	100.0
2C1	39–56	8.1	0.73	0.42	36.52	23.8	19.2	1.5	3.4	100.0
2C2	56–78	8.2	0.26	0.15	31.71	37.1	17.5	2.6	2.7	100.0

Hz: Horizon, pH in water, OM: organic matter; C: organic carbon, CEC: cation exchange capacity, BS: base saturation.

flow. The variation in particle density is minimal; in horizon A1 was 1.75 Mg/m^3 and decreased slightly in horizon A2 and layer C reaching 1.71 Mg/m^3 in 2Cx. Porosity was 49.14% in the superficial soil and it decreased with depth up to 35.08% in horizon 2Cx; this is considered a common value in compacted materials as has been reported by other authors (Flores-Román *et al*., 1992 and Acevedo-Sandoval and Flores-Román, 2000).

Horizons A1 and A2 have a silty clay texture; as of 28 cm deep, the texture is clay loam in horizon C and loam in horizon 2Cx. The clays are believed to originate from the weathering of horizon C, which has fragipan-type characteristics attributed to the presence of compacted clays (Table 3). In horizons A1 and A2, sand, coarse and medium silt, and clays are present in similar quantities, so that the texture of these horizons is silty clay. This is related to the degree of alteration of the upper horizons, which in turn makes them more susceptible to erosion because of low particle cohesion and high separability (Lozano-P. *et al*., 2002). Horizon C has a larger quantity of fine and very fine sands, as well as a high proportion of coarse silts that make up a clay loam texture. Although horizon 2Cx has a loam texture, the predominant materials are clay, coarse silt, fine and very fine sands.

The forms that dominate the mineral fraction are very angular in horizons A1 and A2, with low sphericity (Table 4); therefore, this material is considered to have deposited *in situ*, although a certain amount of aeolian, alluvial or colluvial transport and moderate processes of alteration are not ruled out (Acevedo-Sandoval *et al*., 2003). In Horizons C and 2Cx, the particles are subangular with low sphericity due to weathering and scant transport of mineral particles; consequently, we believe that there could have been processes of formation *in situ*, although very incipient. The particles of the upper horizons, however, exhibited greater sphericity; thus, they are thought to have been affected by water and gravity transport. This site is found on an alluvial plain that has received contributions of material from higher parts during different phases, in which rain and gravity deposited fine soil particles, mostly on horizons A1 and A2 (Table 4).

Horizons A1and 2Cx are slightly acid, while horizons A2 and C are neutral because of the contribution of bases from the upper horizons (Table 5). The content of organic matter is medium in A1, low in A2 and C, and very low in 2Cx. The last of these is in an area of little vegetation where most of the trees are found at the edge of the roads. Organic carbon content is poor in the entire profile. However, CEC is high in all of the horizons, due more to the higher clay content than to organic matter. The high saturation of bases, in which Ca^{2+} and Mg^{2+} predominate, indicates accumulation, despite low precipitation in the Sierra (Duncan and Franzmeier, 1999).

Class 5. Profile P3 El Fraile

Buried soils are those that have been covered by ash or other depositions. In this case, profile P3 soils in SDG show a textural discontinuity between Bt and 2C1 horizons. They are covered with a surface mantle of new soil material that is 30 to 50 cm thick and has a thickness that equals at least half the total thickness of the named diagnostic horizons, which are preserved in the buried soil (Soil Survey Staff, 1999). In profile P3, the morphological properties typical of this class are very similar in the horizons that constitute the mantle, but very different from those of the buried soil (Table 2).

Bulk density oscillates between 1.06 and 1.1 Mg/m^3 in horizons A and Bt, but increases notably in 2C1 and 2C2 where the least weathered and most compact materials are found (Table 3). Particle density has a behavior similar to bulk density: the values 1.44 and 1.46 Mg/m^3 corresponding to horizons A and Bt almost double in layers 2C1 and 2C2. Porosity is a little more than 25% in horizon A, decreasing drastically with depth to values of 18 and 11% for 2C1 and 2C2, respectively, where materials are consolidated and less exposed to the action of weathering factors.

In horizon A, the dominant material is coarse and medium silt. The Bt horizon presents the highest clay content of this soil. Layers 2C1 and 2C2 exhibit a predominance of silt, fine in 2C1 and medium in 2C2. We consider this high clay content to have originated from neo-formation processes through hydrolysis of volcanic glass and calcic plagioclases (Flores-Román *et al*., 1992).

The forms of mineral fraction were dominantly very angular in all horizons and sphericity was low (Table 4). The form of mineral particles is considered to be a result of pyroclastic deposits.

Horizon A is slightly acid, but pH increases with depth and becomes alkaline. 2C1 and 2C2 are the most alkaline due to the contribution of bases resulting from the alteration of materials in the upper horizons, and to illuviation, which has enriched these horizons, particularly with Ca^{2+} and Mg^{2+} ions. These ions can not be leached out from the soil completely because of the scant precipitation and their tendency to form white crusts, which are precipitations of calcium carbonate (Table 5). Organic matter content is medium in horizon A, while it is poor in Bt and very poor in 2C1 and 2C2. The content of organic carbon is also poor to very poor throughout the profile, decreasing with depth on account of reduced biologic activity. According to the intervals proposed by Cottenie (1980), cationic exchange capacity is high in all of the horizons, including 2C1 and 2C2, where organic matter is practically absent. This capacity, then, is attributed to the presence of clays and amorphous materials (Hidalgo *et al.,* 1997). The base saturation is very high, dominated by Ca^{2+} and Mg^{2+} (Table 5).

Analysis of hardened horizons

Most of the soils in the central part of the Sierra de Guadalupe have hardened horizons, as is the case of P2 Las

Caballerizas, which had a hardened layer 2Cx as of 42 cm deep. This layer was identified by immersing fragments of the material in water; these disintegrated rapidly, which is characteristic of a fragipan, as reported by Flores-Román *et al*. (1992) and Acevedo-Sandoval and Flores-Román (2000).

A test of resistance to non-confined compression was conducted specifically for this material. We prepared a hand-worked nucleus 4 cm in diameter and 10 cm long, which had 7.2% moisture. Maximum resistance was determined to be 26.31 kg cm^{-2} for this material that had a closed matrix formed by high compaction of clays, but no cementation. The chemical analysis produced: SiO_2, 45.93%; Al_2O_3, 18.41%; and Fe_2O_3, 7.01%. The Fe_2O_3 content supports the hypothesis that the 2Cx horizon has been moderately altered by weathering; it is composed basically of highly compacted clays leached from surface horizons. Dry and wet alternating periods have conferred the material fragic qualities (Duncan and Franzmeier, 1999).

Weathering of the soils

In general, the losses and gains between horizons are insignificant because the materials were deposited during different periods. They have been considered, in some cases, lithological discontinuities, particularly profiles P2 and P6 (Vela-Correa and Flores-Román, 2004a). In order of abundance, total oxides were SiO_2>Al_2O_3>Fe_2O_3 (Table 6) attributable to the fact that in most of the SDG soils the impact of weathering is not big, Given that the values of SiO_2 vary between 56 and 60%, the rocks are considered intermediate to acid, whereas the values of K_2O are considered characteristic of acid andesites, exhibiting a proportional increment in sodium and potassium (Aragón *et al*., 2004). The least weathered materials were found at a greater depth, with slight increase in iron oxidation due to the alteration of ferromagnesians. Also, CaO was gained in horizons A2 and C, particularly in P2. This compound originates from the degradation of calcic feldspars and it accumulates drawn by scarce lixiviation. For the Sierra, the climatic aggressiveness index is 88.7, according to Fournier (1960), with a low index of erosion by rain in the soils, so that this type of materials is not displaced from the soil profile (Pascual-Aguilar *et al.,* 2001; Acevedo-Sandoval *et al.,* 2003).

Soil genesis and evolution

The soils of Sierra de Guadalupe were formed from volcanic materials under seasonal climate conditions. They are shallow to moderately deep since they are found on slopes with gradients above 15%. In the flatter areas, soils are more stable and deeper. The younger soil has greater influence of the parent material and has the closest relationship with it (Buol *et al.,* 1981). Particularly for the Sierra, development of the soils is considered to be due to the parent material, relief and climate. This idea is reinforced by evidence that the Sierra was formed during several geological periods in which diverse structures with basic lavas were formed. Later, acid lavas flowed, and these were covered by ash, sands and gravel, as well as by pyroclastic materials which formed tuffs that were consolidated as reported by Campa-Uranga (1965) and Acevedo-Sandoval and Flores-Román (2000).

Evolutionary phases are four: 1) A/2R, 2) A or Ap/AC/R, 3) A or Ap/Bt/C or Cx/2Cqm and 4) A or Ap/2Cqm (Figure 1). The formation phase A/2R is common in volcanic domes where pyroclastic materials are intermixed with andesites and basalts, such as the Tenayo and Chiquihuite domes; however, where pyroclasts and tuffs are intermixed, the development phase can be an A or Ap horizon if agriculture is practiced over a layer of Cqm or Cx.

The central part of the Sierra is the most complex because of the diversity of materials that can form soil, the relief in the form of slopes, and the small flat areas. In some cases, the soils are more developed, with Bt horizons rich in montmorillonitic-type smectite clay where the slopes are less than 5%. An example of this is found in P2 Las Caballerizas and P3 El Fraile. An important fact is that site P4 comprises main areas of reforestation with *Pinus radiata*, *P. montezumae* and *Cupresus lindleyi*; however, the areas reforested with *Eucalyptus* sp., *Casuarina equisetifolia* and *Acacia farnesiana* are found in soils where the development phase is A/R. This last phase occurred in P6 El Tenayo, but in this site grasses predominate over tree species.

In general, the soils have a development scheme of horizons A/R and A/C, although Bt horizons can be found in some sites. They are shallow to moderately deep, with fine texture, slightly alkaline to neutral, depending on the organic matter content. Cationic exchange capacity can be medium to high depending on this content as well as on the quantity and type of clay present. These soils are rocky and most are found on hillsides with remains of original rock, mainly iron- and magnesium-rich andesites containing abundant calcium and sodium feldspars that weather rapidly, thereby producing a large quantity of clay and conserving a high content of bases.

Rocky outcrops are frequent, and rockiness is the result of disintegration by natural physical agents. The rocks are broken into more or less large blocks, later into fragments and finally into particles formed by one or several crystals. The fragments constitute the surface rockiness, with respect to the relative proportion of stones more than 25 cm in diameter on the soil surface. Rockiness, depth (<40 cm), slope (15 to 45 %), relief (from slightly hilly to steeply sloped), and erosion forming in many cases colluvium, all suggest that these soils, in spite of an incipient process of formation *in situ*, are basically of colluvial origin.

The mineralogical analysis performed on a fraction less than 0.002 mm in diameter showed that the most common mineral is halloysite. This was found present in all of

Table 6. Total oxides and losses or gains by weathering in soils of the Sierra de Guadalupe.

Class/Profile/ Hz	**Total oxides (%)**								
	SiO_2	**FeO**	**Fe_2O_3**	**Al_2O_3**	**TiO_2**	**CaO**	**MgO**	**Na_2O**	**K_2O**
Class 2. P4 Moctezuma									
A (0-40)	56.25	3.76	2.06	18.36	0.06	0.42	0.27	3.37	0.65
AC11 (40-63)	56.16	4.31	2.36	19.05	0.06	0.32	0.43	3.03	0.65
AC12 (63-90)	58.03	4.24	2.34	20.43	0.00	0.33	0.16	4.41	0.82
C (90-139)	58.26	4.07	2.23	20.50	0.00	0.30	0.16	3.08	0.82
A(K)Al_2O_3	62.81	4.20	2.30	20.50	0.07	0.47	0.30	3.76	0.73
AC_{11}(K)Al_2O_3	63.63	4.64	2.54	20.50	0.06	0.34	0.46	3.26	0.70
AC_{12}(K)Al_2O_3	58.23	4.25	2.35	20.50	0.01	0.33	0.16	4.42	0.82
Losses or gains									
A	4.55	0.13	0.07	0.00	0.06	0.17	0.14	0.68	-0.09
AC_{11}	5.37	0.57	0.31	0.00	0.05	0.04	0.30	0.18	-0.12
AC_{12}	-0.03	0.18	0.12	0.00	0.00	0.03	0.00	1.34	0.00
Class 3. P7 El Panal									
A (0-18)	59.13	3.56	1.96	19.91	0.12	0.35	0.00	3.15	0.78
Bw (18-50)	56.15	3.56	1.96	19.02	0.14	0.36	0.02	3.37	0.78
C (>50)	56.21	3.82	2.10	19.19	0.13	0.45	0.10	4.77	0.84
A.(K Al_2O_3)	56.99	3.43	1.89	19.19	0.12	0.34	0.00	3.04	0.75
Bw.(K Al_2O_3)	56.65	3.59	1.98	19.19	0.14	0.36	0.00	3.40	0.79
Losses or gains									
A	0.78	-0.39	0.21	0.00	0.01	-0.11	-0.10	-1.73	-0.09
Bw	0.44	-0.29	-0.12	0.00	0.01	-0.09	-0.08	-1.37	-0.05
Class 4. P2 Las Caballerizas									
A1 (0-14)	55.72	3.82	2.10	13.40	0.10	2.12	0.33	2.27	1.05
A2 (14-28)	56.48	4.32	3.39	14.75	0.09	2.07	0.11	2.91	1.21
C (28-42)	54.54	4.19	2.30	17.84	0.10	2.37	0.31	3.27	1.68
2Cx (>42)	53.79	4.92	2.70	19.89	0.16	0.27	0.50	2.41	1.74
A1.(K Al_2O_3)*	82.47	5.65	3.11	19.83	0.15	3.14	0.49	3.36	1.55
A2.(K Al_2O_3)	76.25	5.83	4.58	19.91	0.12	2.79	0.15	3.93	1.63
C.(K Al_2O_3)	59.99	4.61	2.53	19.62	0.11	2.61	0.34	3.60	1.85
Losses or gains									
A1	28.68	0.73	0.41	0.00	-0.01	2.87	-0.01	0.95	-0.19
A2	22.46	0.91	1.88	0.00	-0.04	2.52	-0.04	1.52	-0.11
C	6.20	- 0.31	-0.17	0.00	-0.05	2.34	-0.02	1.19	0.11
Class 5. P3 El Fraile									
A (0-7)	48.56	2.12	2.53	13.87	0.07	0.18	0.03	0.68	0.19
Bt (7-39)	53.96	3.72	2.04	19.30	0.10	0.11	0.01	0.35	0.19
2C1 (39-56)	54.49	3.81	2.09	21.62	0.10	0.23	0.06	0.27	0.23
2C2 (56-78)	56.12	4.08	2.25	20.38	0.04	0.27	0.07	2.37	0.35
A.(K Al_2O_3)	71.35	3.11	3.72	20.38	0.10	0.26	0.04	1.00	0.28
Bt.(K Al_2O_3)	56.98	3.93	2.15	20.38	0.11	0.12	0.01	0.37	0.20
2C1.(K Al_2O_3)	51.36	3.59	1.97	20.38	0.09	0.22	0.06	0.06	0.25
Losses or gains									
A	15.23	-0.97	1.47	0.00	0.06	-0.01	-0.03	-1.37	-0.07
Bt	0.86	-0.15	-0.10	0.00	0.07	-0.15	-0.06	-2.00	-0.15
2C1	-4.76	-0.49	-0.28	0.00	0.05	-0.05	-0.01	-2.31	-0.16

* The aluminum constant (K) is obtained by dividing the aluminum percentage of the unaltered rock (C or R) between the aluminum percentage of the altered rock (A, AC, AC11 or AC12). 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).

the soils studied, especially in the upper horizons. It is considered a product of hydrolysis suffered by volcanic glass found in these soils (Quantin, 1992). In P2, clay contained montmorillonitic-type smectites, whose formation from halloysite is attributed to moderate drainage conditions of sites where the slope is less than 5%. The soil profile is also characterized by vertical cracks, giving it certain vertic properties derived from the 2:1 presence of clay.

A mineral found especially in P4 is kaolinite, which could have originated from the weathering of halloysite, passing through an amorphous phase, with partial loss of silica favored by past hydrothermal activity in the Sierra (Vela-Correa and Flores-Román, 2006). The alteration of volcanic glass generated major quantities of amorphous compounds, mainly in the upper horizons of P3 El Fraile. Chlorite, an accessory mineral, are reported in this same site; these are the product of the alteration of ferromagnesians that are found in igneous rock (Lozano-Santa Cruz and Bernal, 2005).

Soil units in the Sierra de Guadalupe

From the point of view of soil classification, Class 1 and Class 2 meet many of the taxonomic requirements for Ustorthents (USDA, 2006) and could be correlated with the Leptosol and Regosol soil Units proposed by FAO (2006). Class 3 and Class 4, respectively, satisfy the diagnostic characteristics for Haplustepts and Haplustolls (USDA 2006) and could be correlated with the Cambisols and Phaeozems proposed by FAO (2006). Class 5, superficial horizons correspond to Haplustolls (USDA 2006)-Phaeozems (FAO 2006) and buried soils.

CONCLUSIONS

The analysis of thematic maps of SDG, combined with field transect information and through photo interpretation, provided the necessary geospatial data to propose an environmental-pedogenic model for the study area. This model presents a topo-system in which the soils have an integral significance toward understanding and unraveling landscape evolution.

The soils are found mostly on hillsides with slopes greater than 15%; they are shallow and rocky, slightly acid, rich in organic matter, with a high CEC value and a high percentage of base saturation. Some have hardened layers formed from pyroclastic materials that consolidated on deposition, generating andesitic dacitic tuffs. Besides, the incipient process of leaching, seasonality and scant precipitation cause saturation to occur mainly by Ca^{2+} and Mg^{2+}.

The soils with AC horizons are of recent formation. They are affected by parent material, relief and climate, which propitiate formation by colluvial processes on the hillsides. Soils with an ABC horizon sequence originated from the alteration of andesitic dacitic tuffs, favoring the *in situ* processes of formation and enrichment by clays in the Bt accumulative horizons in parts where the slope is less than 5%.

The hardened material of P2 is considered to be of fragipan type since, in spite of its hardness, it collapsed on contact with water thus confirming that the materials were strongly compacted by clays rather than cemented. The principal minerals found in the fraction less than 0.002 mm in diameter were halloysite, kaolinite and smectite; halloysite is found in all of the soils and is produced by alteration of feldspar and volcanic ash.

Most of the soils of the Sierra were formed by materials transported from the higher parts and deposited in the middle and lower parts of the hillsides. This is reflected in an A/R horizon sequence since there is no indication of a horizon of accumulated materials. We classified the soils as Ustorthents, Haplustepts and Haplustolls, USDA (2006) and were able to correlate them with the Leptosols, Regosols, Cambisols and Phaeozems (FAO, 2006).

The context of the Sierra de Guadalupe soils constitutes a slope model that emphasizes an erosional and depositional toposequence pattern, common in the dry lands of the Mexico basin. The soils are propitious for forestry land use, whereas agricultural land use is not convenient because of physical limitations such as soil thickness, slope, stoniness, mass movement and erosion.

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