Revista Mexicana de Ciencias Geológicas, v. 21, núm. 1, 2004, p. 18-29

Micromorphology of paleosols at the continental border of the Buenos Aires province, Argentina

Andrea Cumba* **and Perla Imbellone**

Instituto de Geomorfología y Suelos, Universidad Nacional de La Plata,
Calle 3 No. 584, 1900 La Plata, Argentina.
** andrea_c@netverk.com.ar*

ABSTRACT

*The sediments with loessial characteristics of the Pampean plain are called "*loess y limos pampeanos*" (Pampean loess and silts), to distinguish those of purely eolian origin (loess) from those reworked by water (silts). In the continental border of La Plata River, mainly loess-like sediments of the late and middle Pleistocene outcrop, approximately at 20 km from the shoreline. Between that border and the shoreline they underlie at 2–5 m depth the Holocene sediments deposited by the regressive events in a successive lowering of sea level during the late 6,000 years.*

The objectives of this work are: a) to integrate previous and new information on several sedimentary successions, b) to study the micromorphological features of the paleosols and c) to carry out a regional correlation of paleosols between the localities of San Pedro and La Plata based on field and micromorphological features.

The profiles are between 18.5 and 12.5 m a.s.l. with macroscopic pedological features which show partially continuous development. The buried paleosols are superposed and welded, with different degrees of pedogenesis indicated by macro- and micromorphological features of illuviation and hydromorphism. In some cases, these features would have formed simultaneously with the deposition of the eolian dust trapped by grass. The degree of pedogenesis would depend on the ratio between the intensity of the accretion and reworking processes, and pedogenesis. The sedimentary units were affected partially or totally by pedogenesis.

Two zones rich in volcanic glass were detected at San Pedro profile; new information reveals the same situation near La Plata city. The uppermost zone, with 20–30% volcanic glass, constitutes in some cases the parent material of the present soil; the deeper zone, contains 50–70% volcanic glass. Micromorphological observations confirm the presence of scarce to abundant clasts of old illuvial horizons and loess embedded in the matrix of most of the paleosols.

Pedological processes are most evident in the deeper part of the profiles, indicated by a strong grade of structure and abundant laminated and juxtaposed textural and amorphous features. The lower paleosols can be considered pedostratigraphic units useful for correlation in the continental border in northeastern Buenos Aires Province, Argentina.

Key words: buried soils, micromorphology, reworked loess, Argentina.

RESUMEN

*Los sedimentos con características loéssicas de la llanura pampeana se denominan "*loess y limos pampeanos*", para distinguir los de origen puramente eólico (loess) de aquellos retrabajados por el agua (limos). En el margen continental del río de la Plata, afloran sedimentos principalmente loessoides del Pleistoceno medio y tardío, aproximadamente a 20 km de la línea de costa. Entre el margen y la línea de* *costa suprayacen a 2–5 m de profundidad los sedimentos del Holoceno depositados por eventos regresivos, en un descenso sucesivo del nivel del mar durante los últimos 6,000 años.*

Los objetivos de este trabajo son: a) integrar información antecedente y nueva de varias sucesiones sedimentarias, b) estudiar los rasgos micromorfológicos de los paleosuelos y sedimentos, c) llevar a cabo una correlación regional de paleosuelos entre las localidades de San Pedro y La Plata basada en observaciones de campo y rasgos micromorfológicos.

Los perfiles están localizados entre los 12.5 y 18.5 m s.n.m. con rasgos pedológicos macroscópicos que muestran un desarrollo parcialmente continuo. Los paleosuelos están superpuestos y soldados, con diferentes grados de pedogénesis indicados por rasgos macro y micromorfológicos de iluviación e hidromorfismo. En algunos casos, estos rasgos se habrían formado simultáneamente con la deposición del polvo eólico atrapado por la vegetación de gramíneas. El grado de pedogénesis dependería de la relación entre la intensidad de los procesos de sedimentación y erosión y la pedogénesis. Las unidades sedimentarias están afectadas parcial o totalmente por la pedogénesis.

Dos zonas ricas en vidrio volcánico se observan en los perfiles de San Pedro; la nueva información revela la misma situación cerca de la ciudad de La Plata. La zona superior, con 20 a 30% de vidrio volcánico, constituye en algunos casos el material parental del suelo actual; la zona profunda contiene entre 50 y 70% de vidrio volcánico. Observaciones micromorfológicas confirman la presencia de escasos hasta abundantes clastos de horizontes iluviales y loess inmerso en la matriz de la mayoría de los paleosuelos.

Los procesos pedológicos son más evidentes en la zona profunda de los perfiles, indicados por un fuerte grado de estructura y abundantes rasgos pedológicos texturales y amorfos yuxtapuestos y laminados. Los paleosuelos inferiores son indicadores paleoclimáticos de clima húmedo y pueden considerarse como unidades pedoestratigráficas útiles para la correlación en el margen continental del noreste de la Provincia de Buenos Aires, Argentina.

Palabras clave: paleosuelos, micromorfología, loess retrabajado, Argentina.

INTRODUCTION

The Pampean region is the only sedimentary basin in the southern hemisphere where loessial sediments accumulated during the Quaternary, approximately 40–50 m in thickness over an area of about 500,000 km^2. The volcaniclastic nature allows to differentiate it from the loess of the North American prairies, the Russian–Siberian steppes, and the Chinese plains, which are formed from granitic detritus generated by the action of glaciers and redeposited by wind.

Andean volcanism has governed the geologic-sedimentary evolution of a great part of the Argentinean territory. Volcanic dust is deposited far beyond the eruption centers, extending over continental plains, limnic environments, the coastal plain of La Plata River, and the Atlantic Ocean. Numerous Chilean volcanoes, aligned along the subduction zone between the Nazca and South American plates, episodically eject enormous volumes of material to the atmosphere, which are carried by tropospheric winds over very large distances. The eruption of Quizapú volcano, whose ashes reached Rio de Janeiro in 1932, is a well documented example (Larsson, 1937; Imbellone and Camilión, 1988). These volcanic dusts constitute an important part of the Pampean loess, where grasses trap the dust after deposition from direct airfall or redistribution by transport agents.

The Pampean sediments were named “loess y limos pampeanos” (Pampean loess and silts) by Frenguelli (1955), where the word ‘silt’ refers to reworked loess. Teruggi (1957) exposed in a referential paper his fundamental ideas about provenance areas and processes of loess genesis in Argentina, and identified in the loess silt loam to sandy silt textures, with abundant volcanic glass.

Coincident with a growing interest in the study of paleosols, knowledge of the Pampean sediments has increased (Teruggi *et al.*, 1974; Riggi *et al.*, 1986; Imbellone and Teruggi, 1993; Blasi *et al.*, 2001; Imbellone and Cumba, 2003). Other works, while not modifying the classic concepts, have developed a deeper knowledge of provenance areas and transport agents (Zárate and Blasi, 1993; Iriondo, 1999; Morrás, 1999).

As in other loess plains of the world (Busacca, 1989; Chlachula *et al.*, 1997), buried paleosols are stratified in the loess deposits. The east of the Pampean Plain is an ideal and classic area for the study of the paleosols of Argentina. It was a stable continental border during the Quaternary, only affected by very slight epirogenic events. In some places, such as Mar del Plata cliffs on the Atlantic Ocean and Paraná river bluffs, exposures of sedimentary successions with numerous superimposed buried paleosols are observed. Nabel *et al.* (2000) carried out correlations between Baradero and La Plata, utilizing data on paleomagnetism, climate, volcanism and geological evolution. However, no correlations have been performed using micromorphological features of paleosols.

The objectives of this work are: a) to integrate previous and new information on several sedimentary successions, b) to study the micromorphological features of the paleosols, and c) to carry out a regional correlation of paleosols between the localities of San Pedro and La Plata based on field and micromorphological features.

MATERIALS AND METHODS

The study area is located in the eastern part of the so-called "undulating Pampa." It is a gently undulating plain, with 0.5–1.0 % slopes. Elevations range from 5 to 30 m a.s.l. The drainage network is well defined, with numerous rivers and streams which empty into Paraná and La Plata rivers. The climate is temperate–humid (Köppen, 1918), with milder conditions than in similar latitudes of the northern hemisphere due to the moderating effect of the Atlantic Ocean. Since no barriers for the atmospheric circulation exist, the territory is subject to the actions of air masses throughout the year. They are more intense from August to January when E and NE winds prevail in summer due to the Atlantic anticyclone, while in winter a high pressure center established in the continent creates frequent W and SE winds.

Mean annual temperature is 16º C with summer and winter means of 22º C and 10º C, respectively. Precipitation is more abundant in summer, but due to high potential evapotranspiration, soils experience a water deficit during this season. Soil moisture and temperature regimes are udic and thermic according to Soil Survey Staff (1996) (water deficit: less than 90 cumulative days in normal years; mean annual soil temperature: 17º C).

The native vegetation is temperate grassland (Cabrera, 1953), largely modified by agriculture and livestock production since the end of the 19th century. The main species are *Stipa hyalina, Stipa neesiana Piptochaetium* ssp., *Bromus unioloides, Aristida venustula, Aristida murine, Briza* spp., *Poa* spp., *Paspalum dilatatun, Panicum bergii, Eragrostis* spp., *Chloris* spp., and *Melica* spp.

In the continental border of La Plata River, near La Plata city, mainly loess-like sediments of the late–middle Pleistocene outcrop at approximately 20 km from the shoreline. In the coastal plain they are buried to a depth of 2.5 m by Holocene sediments deposited during a regressive sea level stage over the last 6,000 years. No coastal plain sediment exists along the Paraná River, and the Quaternary successions are abruptly exposed on the cliffs

The research was carried out at three quarries (Figure 1) mined for earthy fill materials, where successions of the late–middle Pleistocene and Holocene are exposed. Two of them, near La Plata City, are 10 km apart: Airport quarry (Latitude 34º 55' 00" S, Longitude 57º 57' 30" W; 12.5 m a.s.l.) and Hernández quarry (Latitude 34º 55' 10" S, Longitude 57º 57' 12" W; 13.9 m a.s.l.). San Pedro quarry (Latitude 34º 39' 55" S, Longitude 59º 30' 12" W; 18.5 m a.s.l.), is 200 km distant from the others. Over 90 borrow pits are found in the vicinity of La Plata city. After a careful examination of the exposures, profiles were selected on the basis of features distinctness and their representative character for regional geological and pedological events.

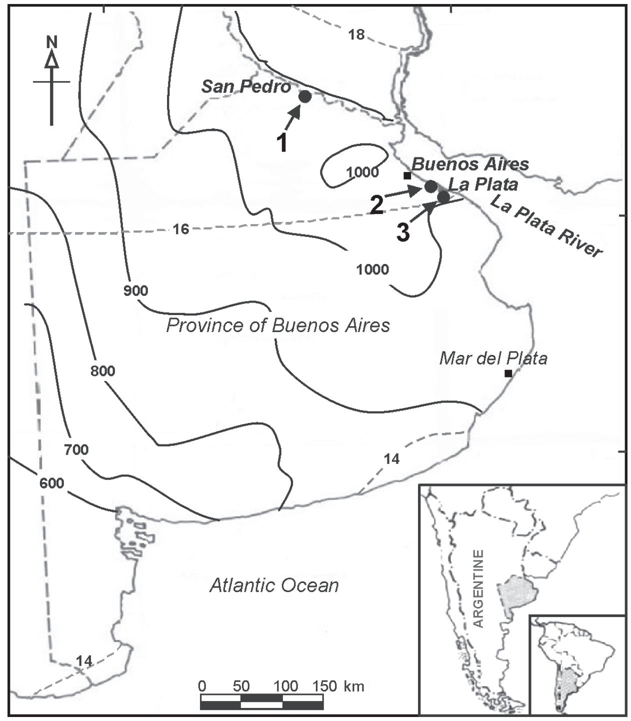


Figure 1. Location map. 1: San Pedro Quarry 33º59´55´´ S, 59º30,12´´ W; 2: Airport Quarry 34º55´00´´ S, 57º57´30´´ W; 3: Hernandez Quarry 34º 55´ 10´´ S, 57º 57´ 12´´ W; — Isohyets (mm); --- Isotherms (ºC).

The paleosols were described in the field paying particular attention to the geologic and sedimentary characteristics and their lateral continuity. They were characterized by conventional macro- and micro-morphological methods (Soil Survey Staff, 1993; Bullock *et al.*, 1985; Catt, 1990). The modern surface soils were classified according to Soil Survey Staff (1996). Samples for thin sections were collected from each sedimentary-pedological unit where these were very well defined and every 15 cm in other cases.

Complementary SEM studies and point chemical analyses were performed on peds with well-defined clay- and sesquioxide coatings, as well as on volcanic glass shards in the very fine sand and coarse silt fraction. As no precise age control is available, paleomagnetic information is used as a temporal reference.

RESULTS AND DISCUSSION

The profiles at Airport and Hernández are located in flat interfluves and the present soils are Argialbolls (A, E, Bt1, Bt2, BC, C), and Vertic Argiudolls (Ap, Btss1, Btss2, BC1, BC2, C), respectively. The San Pedro profile is located on the right bank of the Paraná River, and the surface soil is a Typic Argiudoll (Ap, Bt1, Bt2, BC, C). Superposed buried paleosols have been identified underlying the surface soils (Figures 2, 3 and 4). Each sedimentary unit indicated by a capital letter includes a soil unit indicated by Arabic numerals following the horizon designation.

The thickness of the sedimentary deposits and the associated paleosols are similar in all the profiles (less than 3 m) with only slight variations. The sedimentary-pedological units are separated in the field by more or less evident erosional surfaces, some of them capped with nodular calcretes. In general, the oldest units show well marked 'concave mouldings' (*media caña*) in correspondence with illuvial horizons (soils units: D, E and F in Airport profile; E, F and G in Hernández profile; G in San Pedro profile). The paleohorizons are superposed illuvial horizons and, in some cases, the loess parent material (Airport and San Pedro profile) is identifiably, a fact that would indicate a variable relationship between sedimentation and pedogenesis.

Lithological discontinuities, in the sense of Soil Survey Staff (1993), are indicated by soil units that show differences in clay-free particle size distribution and/or mineralogy. In general, the former are subtle, whereas the mineralogical differences are clearly detected due to the content of volcanic glass (Figures 2, 3 and 4).

The three profiles present textural classes with abundant silt. The Airport and Hernández profiles resemble each other in the fact that the materials are coarser at the bottom and finer at the top. At San Pedro, the inverse situation occurs.

The mineralogical nature of the Pampean sediments was initially established as volcanic-pyroclastic (Teruggi, 1957), but recent studies show a contribution from metamorphic rocks (Blasi *et al.*, 2001). Glass shards are ubiquitous in all paleohorizons, although in extremely variable quantities; this fact allows different sedimentary deposits to be separated in some cases. They are more abundant, though smaller in size, in the 88–125 μm fraction. The surface morphology of vitroclasts is diverse, owing to differences in the degree of viscosity of the magma, rhyolitic to andesitic in composition, at the moment of solidification (Heiken and Wohletz, 1985). Thus, vitroclasts appear completely smooth and unaltered (Figure 5), pitted with very small hollows less than 1 μm (Figure 6), fluidal with 'pipes' of variable diameter and frequency, or affected by etching (Figures 7 and 8). All vitroclast morphologies coexist in the three profiles and are representative of the general morphology of vitroclasts observed in the Pampean sediments.

Although the Pampean loess is characterized as volcaniclastic, no regional correlations based on the tephras have hitherto been carried out. As the volcanic dust is usually incorporated in the soil surface very slowly, due to the large distances from the effusion centers, layers with pure pyroclastic material are seldom found, thus making their regional identification difficult during field-work. Microscopic observations reveal two zones with greater quantity of vitroclasts in the studied profiles (Figures 2, 3 and 4). The deepest zone, the most important for the regional correlation, is found between 4.45 and 7.30 m (D unit) in the Airport profile, between 7.37 and 8.90 m (F unit) in San Pedro profile and from 6.40 m in Hernández profile (G unit). An increase of volcanic glass towards the bottom of the units is observed.

Due to the high content of volcanic shards, the sediment can be readily identified in the field where it appears as massive, loose, or with a weak to moderate structure grade; this allows an easier identification and a regional correlation The presence of zones with higher content of volcanic shards in the Pampean sediments has also been observed in other profiles (González-Bonorino, 1955; Riggi *et al.*, 1986; Teruggi and Imbellone, 1987; Nabel, 1993; Blasi *et al.*, 2001), which indicates more intense volcanic events.

The presence of purely eolian loess and water reworked loess (Teruggi, 1982; Pye, 1987) in the Pampean sediments is mentioned by Frenguelli (1955) who established criteria for their differentiation based on field evidences. In the Quaternary successions of the NE continental border of the Pampean plain, many paleochannels and zones with platy stratification produced by water action are observed. In the studied profiles, there is a predominance of reworked sediments with rounded and subrounded clasts consisting of a material similar to the soil matrix; they have variable sizes up to 3 cm in diameter; they are coated with oxide patinas and are harder than the matrix. According to field evidence, the sediments resembling primary loess correspond to the bottom of the D and E units in the Airport profile and to bottom of the F unit in the San Pedro profile. In spite of this, the reworked character of loess is revealed by the presence of clasts observed at microscopic level.

At the micromorphological level, abundant soil matrix intraclasts (Figure 9), pedological features and laminated sediments (Figure 10) embedded in the matrix of the paleohorizons are observed. Clasts are abundant in the very fine sand (63–125 μm) and fine sand (125–250 μm) fractions and are more abundant in the Airport profile and the upper part up to 7.37 m depth in the San Pedro profile. Clasts of pedological origin can be either relicts of the soil matrix, identified by its b-fabric, or fragments of textural features, both clearly embedded in the matrix of younger paleohorizons. Laminae clasts come from sediments with laminar fabric (Figure 11) locally deposited in flooded and intermittently waterlogged areas. Others show alternating thick laminae of coarse and fine material.

The b-fabric of the paleohorizons is mainly stipple-speckled in the C horizons and mosaic-speckled or striated b-fabric in the illuvial horizons. Reticulate striated or parallel b-fabrics are found in the finer textural classes. Crystallitic b-fabric, with impregnative micritic calcite, is irregularly distributed in the paleohorizons and is very abundant in horizons with strong calcification. In paleohorizons corresponding to paleochannel fill materials, masses of barite with radial texture were observed, whose origin could

Sedimentary unit	Thickness (cm)	Soil Unit	Depth (cm)	Airport profile	Sand (%)	Silt (%)	Clay (%)	Textural class (SSS, 1993)	Volcanic glass (%)	$CaCO_3$ (mass %)	Matrix color (dry)	Structure (type, grade)	Pedological Features (textural and amorphous)
A	250	A	0 – 23		8.9	78.9	12.3	clay loam			10 YR 4/2	blocky, weak	
		E	23 – 31		8.8	82.7	10.0	clay loam			10 YR 6/2	blocky, weak	
		Bt1	31 – 57		3.4	43.6	53.1	clay loam			7.5 YR 5/4	blocky, strong	fairly common hypocoatings with porostriated b-fabric*, clay coatings
		Bt2	57 – 80		11.4	37.3	51.2	clay loam	20–30	0.9	7.5 YR 6/2	blocky, strong	
		BC	80 – 160		4.2	57.7	37.5	clay loam			7.5 YR 6/4	blocky, moderate	
		Ck	160 – 210		5.4	61.4	33.2	clay loam			7.5 YR 5/4	massive	
		Ck2	210 – 250		12.3	62.2	25.6	clay loam			7.5 YR 6/4	blocky, weak	
B	120	2Btkb2	210 – 250		11.8	64.2	24.0	clay loam			7.5 YR 6/4	blocky, strong	abundant hypocoatings with porostriated b-fabric,
		2BCkb2	250 – 330		4.7	73.3	22.0	clay loam	<10	2.1	7.5 YR 5/6	blocky, strong	
C	115	2Bt1kb3	330 – 370		4.4	54.1	41.5	clay loam			7.5 YR 6/3	blocky, strong	
		2Bt2kb3	370 – 400		6.3	52.7	40.2	Silty clay	<10	1.5	7.5 YR 6/4	blocky, strong	abundant hypocoatings with porostriated b-fabric, few clay coatings, abundant typic and amorphous impregnative nodules
		2BCkgb3	400 – 445		11.8	60.8	37.4	clay loam			5 Y 7/2	blocky, strong	
D	285	3Btkgb4	445 – 485		6.8	55.6	37.6	silty clay			7.5 YR 7/3	blocky, strong	
		3BCkgb4	485 – 550		13.2	75.4	11.5	clay loam	50–70	2.1	7.5 YR 7/3	blocky, moderate	fairly common hypocoatings with porostriated b fabric, juxtaposed clay and amorphous coatings, abundant typic and amorphousimpregnative nodules
		3Ck1b4	550 – 660		31.9	54.6	13.4	clay loam			7.5YR6/4	massive	
		3Ck2b 4	660 – 730		41.3	54.0	4.7	clay loam			7.5 YR 6/4	massive	
E	230	4Btkb5	730 – 770		39.4	56.0	4.6	clay loam			7.5 YR 5/4	blocky, strong	
		4BCkb5	770 – 810		24.2	56.0	19.9	clay loam			7.5 YR 5/4	blocky, moderate	fairly common hypocoatings with porostriated b fabric, juxtaposed clay and amorphous coatings, abundant typic and amorphous impregnative nodules
		4C1kb5	810 – 860		30.9	60.4	8.65	clay loam	<10	2.9	7.5 YR 6/4	massive	
		4C2kb5	860 – 960		25.3	61.9	12.7	clay loam			7.5 YR 6/4	blocky, strong	
F	+ 130	5Btkb6	960 – 990		51.6	38.3	10.1	loam			7.5 YR 5/4	blocky, strong	
		5C1kb6	990 – 1090		38.4	48.4	13.2	clay loam	<10	1.8	7.5 YR 7/3	blocky, strong	abundant clay, silt an d amorphous coatings, abundant typic and impregnative nodules
		5C2kgb6	+ 1090	Pampean Formation #	30.9	51.7	17.4	clay loam			7.5 YR 6/4	blocky, very strong	

Figure 2. Schematic pedostratigraphic column of Airport profile showing soil unit, paleomagnetism, and morphological and micromorphological features.
Depth variation of carbonate morphology : Powdery: Laminar: Rizoconcretions Pseudomycelia: Long vertical calcretes: Rounded small nodules:
Crotovine: Magnetic polarity: Chron Brunhes Chron Matuyama Bidegain (personal communication).
Riggi *et al*. (1986). *The slickenside is assignated to a b -fabric feature (p. 90, 92) as well as to a pedological feature (p.132), Bullock *et al*. (1985).

Sedimentary unit	Thickness (cm)	Soil Unit	Depth (cm)	Hernández profile	Sand (%)	Silt (%)	Clay (%)	Textural class (SSS, 1993)	Volcanic glass (%)	$CaCO_3$ (mass %)	Matrix color (dry)	Structure (type, grade)	Pedological features (textural and amorphous)
A	88	Ap	0 – 17		10	33	57	clay			7,5 YR 5/2	blocky, moderate	
		Bt1	17 – 43		8	33	59	clay	<10	12	7,5 YR 5/2	blocky, strong	
		Bt2	43 – 77		10	34	56	clay			7,5 YR 5/4	blocky, strong	abundant hypocoatings with porostriated b-fabric*, few clay coatings
		BCk	77 – 88		12	36	52	clay			7,5 YR 5/4	block moderate	
B	107	Bt1kb2	88 – 140		10	44	46	silty clay	<10	10	7,5 YR 6/4	blocky, moderate	abundant hypocoatings with porostriated b-fabric, few clay coatings
		Bt2kb2	140 – 195		14	54	42	silty clay			7,5 YR 7/4	blocky, moderate	
C	205	Btkb3	195 – 255		14	40	46	silty clay	<10	0.6	10 YR 7/3	blocky, moderate	abundant hypocoatings with porostriated b-fabric, few clay coatings and fairly typic and impregnative nodules
		BCb3	255 – 310		14	42	44	silty clay			7,5 YR 7/4	blocky, weak	
D	90	2Bt1kb4	310 – 360		48	39	13	clay			5 YR 5/4	blocky, moderate	abundant hypocoatings with porostriated b-fabric, fairly common clay coatings and abundant typic and impregnative nodules
		2Bt2kb4	360 – 400		28	50	20	clay loam	20 – 30	0	2,5 Y 7/3	blocky, weak	
E	100	3Bt1kb5	400 – 450		16	52	32	silty clay loam	<10	0.8	2,5 Y 7/3	blocky, strong	
		3Bt2kb5	450 – 500		42	40	18	silty clay			2,5 Y 6/3	blocky, strong	fairly common, clay coatings, abundant typic and impregnative nodules
F	140	3Bt1kb6	500 – 600		32	46	22	clay loam	<10	0.8	7,5 YR 6/4	blocky, strong	
		3Bt2kb6	600 – 640		40	46	14	silty clay			7,5 YR 7/3	blocky, strong	fairly common clay and amorphous coatings, few impregnative nodules
G	+110	4Bt1kb7	640 – 685		48	38	14	clay			5 YR 4/3	blocky, strong	
		4Bt2kb7	685 – 750		54	32	14	clay	10 – 20	0.7	5 YR 4,5/4	blocky, strong	abundant clay and amorphous coatings, abundant typic and impregnative nodules
		4Bt3kb7	+750	Pampean Formation #	56	32	12	clay			5YR 5/4	blocky, moderate	

Figure 3. Schematic pedostratigraphic column of Hernández profile showing soil unit, paleomagnetism, and morphological and micromorphological features.
Depth variation of carbonate morphology: Powdery: Laminar: Rizoconcretions Pseudomycelia: Long vertical calcretes: Rounded small nodules:
Crotovine: Magnetic polarity: Chron Brunhes Chron Matuyama Tonni *et al.* (1999)
Riggi *et al.* (1986). *The slickenside is assignated to a b-fabric feature (p. 90, 92) as well as to a pedological feature (p.132), Bullock *et al.* (1985).

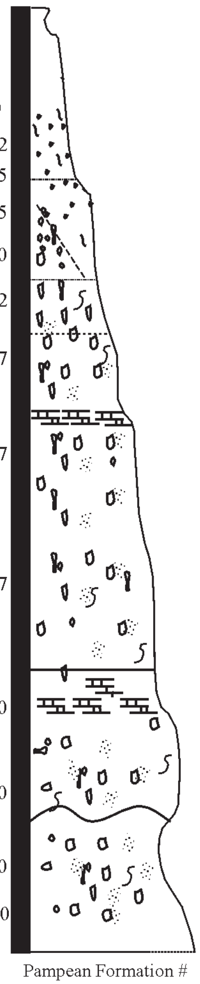
Sedimentary unit	Thinkness	Soil Unit	Depth (cm)	San Pedro profile	Sand (%)	Silt (%)	Clay (%)	Textural class (SSS, 1993)	Volcanic glass (%)	Color matrix (dry)	Structure (type, degree)	Pedological features (textural and amorphous)
A	205	Ap	0 – 25		26.9	59.3	13.1	silt loam		7,5 YR 5/2	block strong	
		Bt1	25 – 50		22.6	57.6	19.9	silt loam		7,5 YR 5/4	prism strong	abundant clay coatings
		Bt2	50 – 75		22.6	66.9	10.4	silt loam	20 – 30	7,5 YR 5/4	prism strong	
		BC	75 – 110		25.1	68.6	5.9	silt loam		7,5 YR 5/4	block moderate	
		Ck1	110 – 122		41.1	50.8	8.1	silt loam		7,5 YR 6/4	massive	
		Ck2	122 – 205		29.4	40.5	30.4	silt loam		7,5 YR 7/4	massive	
B	95	2C3kb2	205 – 245		11.5	52.9	33.5	silt loam	<10	10 YR 7/3	block moderate	fairly common typic and amorphous nodules
		2C4kb2	245 – 300		24.8	47.6	27.5	loam		7,5 YR 7/4	block strong	
C	62	3Btkb3	300 – 362		27.8	51.5	20.7	silt loam	<10	5 YR 5/4	prism strong	fairly commun clay and amorphous coatings, scarse typic and amorphous nodules
D	75	4C5gkb4	362 – 437		9.03	42.1	48.8	loam	<10	2,5 Y 7/3	block moderate	fairly common typic and amorphous nodules
E	300	5C6gkb5	437 – 587		24.1	38.4	37.6	loam		2,5 Y 7/3	block moderate	fairly common typic and amorphous nodules
		5C7gkb5	587 – 737		14.3	50.1	35.5	silt loam	<10	2,5 Y 6/3	block moderate	
F	153	6C8kb6	737 – 810		13.8	80.1	6.06	silt loam	50 – 70	7,5 YR 6/4	massive	fairly common typic and amorphous nodules
		6C9kb6	810 – 890		17.9	60.7	24.6	silt loam		7,5 YR 7/3	massive	
G	+160	7Bt1gkb7	890 – 960		28.6	58.1	12.3	silt clay loam		5 YR 4/3	prism strong	
		7Bt2gkb7	960 –1050		28.6	58.1	12.3	silt loam	<10	5 YR 4,5/4	prism strong	plentiful juxtaposed clay, silt and amorphous coatings, plentiful typic and impregnative nodules
		7Bt3gkb7	+1050		28.7	48.9	22.2	clay loam		5 YR 5/4	prism strong	

Figure 4. Schematic pedostratigraphic column of San Pedro profile showing soil unit, paleomagnetism, and morphological and micromorphological features.

Depth variation of carbonate morphology: Powdery: Laminar: Rizoconcretions Pseudomycelia: Rounded small nodules:

Crotovine: Magnetic Polarity: Chron Brunhes Nabel (1993) # Riggi *et al*. (1986)

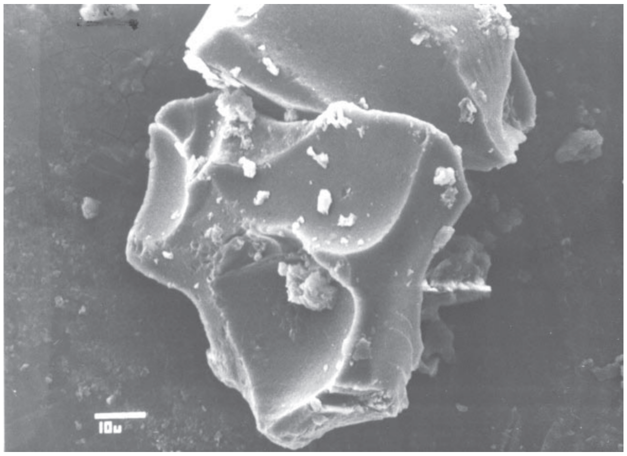


Figure 5. Blocky glass shard with curved surfaces of large original vesicles. It is a fragment from a wall between several vesicles; vesicle walls are curved and smooth whereas fractures are conchoidal. Hernández profile; unit G, 4Bt1kb7; SEM x 1,000; bar 10 µm; fraction 88-125 µm.

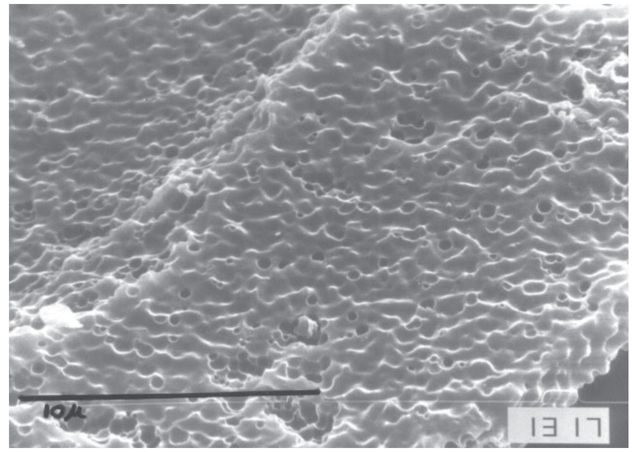


Figure 6. Spongy, highly vesicular glass shard. Note the fresh aspect of surfaces and abundance of small vesicles. Hernandez profile; unit G, 4Bt2kb7;SEM x 5,000; bar 10 µm; fraction 88-125 µm.

not be determined. Excremental fabric (Figure 12) is observed mainly at the upper part of the profiles (A, B and C units in Airport, Hernández and San Pedro profiles) and at the upper part of the oldest units (D, E and F units in the Airport profile; D, E, F and G units in Hernández profile and G unit in San Pedro profile).

Textural pedofeatures are abundant and strongly expressed in illuvial horizons of the lower paleosols in the Airport (units D, E and F), Hernández (units E, F and G) and San Pedro (unit G) profiles. In the former, they diminish and then disappear in the C horizon; in the Hernandez profile they are almost regularly distributed in the superposed B horizon. They appear as simple clay coatings (Figure 13) with limpid clay or microlaminated clay; and more abundant as compound layered textural coatings with clay and silt, juxtaposed clay and amorphous coatings (Figure 14), and hypocoatings of iron and manganese. Some of them are true coatings of neoformed birnessite with a characteristic sponge-like morphology (Figures 15 and 16). In areas with crystallitic b-fabric, calcification features overlie illuviation features. All of them coat ped faces and voids of the matrix, as well as pedotubules, cavities, and channels generated by faunal activity. The juxtaposition of clay–silt, clay–oxide and clay–calcium carbonate coatings indicates complex pedological processes in a single paleosol and the influence of one pedological cycle on the other (Ruhe and Olson, 1980; McDonald and Busacca, 1990; Wright, 1992).

The overlapping of pedofeatures indicates variable ecological conditions both in the studied profiles and regionally between an Pedro and La Plata. Simple and

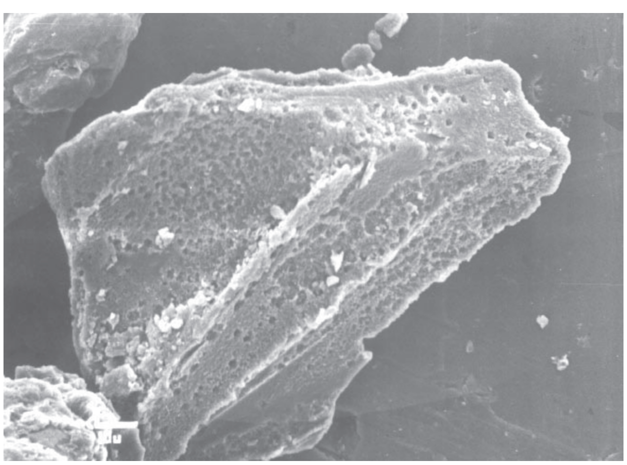


Figure 7. Altered glass shard. Numerous pits and rough surfaces formed by dissolution. Hernández profile; unit G, 4Bt2kb7; SEM x900; bar 10 µm; fraction 63-88 µm.

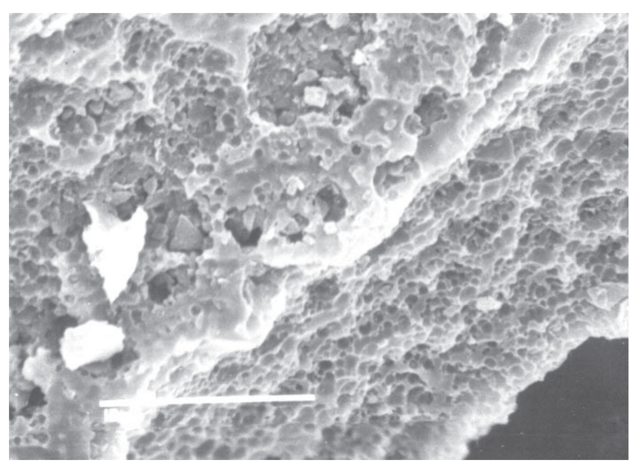


Figure 8. Close up of Figure 7. The original vesicle hollows have been pitted by dissolution. Hernández profile; unit G, 4Bt2kb7; SEM x 4,600; bar 10 µm; fraction 66-88 µm.

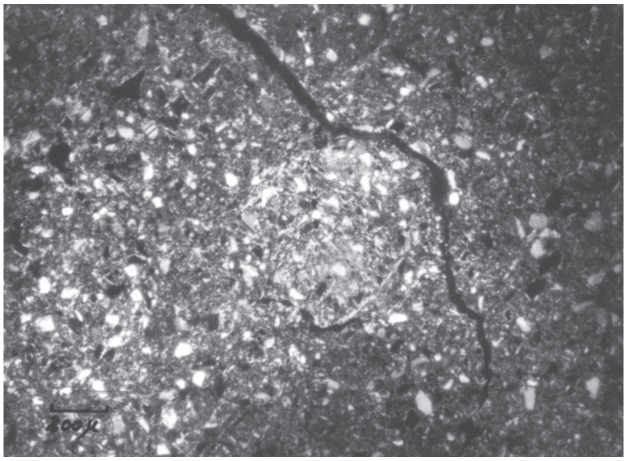


Figure 9. Matrix soil relict only identifiable by stipple-speckled b-fabric embedded in the soil matrix with stipple b-fabric. Airport profile, unit B, 4Btkb4; PPL x 5; bar 200 μm.

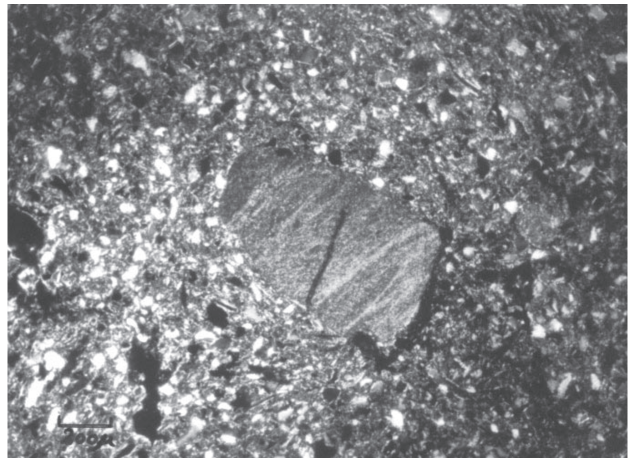


Figure 10. Sedimentary relict with laminar fabric embedded in the soil matrix. Airport profile; unit A (Ck, 1.60–2.10 m); PPL x 5; bar 200 μm.

juxtaposed coatings (*c.f.* Bullock *et al.*, 1985, p. 98) are generated by single or paired processes such as illuviation and hydromorphism.

The clay and amorphous coatings originate under moist conditions, and the juxtaposition of amorphous over textural coatings reveals a period of increasing moisture. Although calcitic pedofeatures indicate a relatively drier period, there is evidence of clay illuviation in calcareous environments (Wieder and Yaalon, 1978).

Since juxtaposed coatings are abundant and very well developed at the bottom of the three profiles (D, E, F units; E, F, G units; G unit in the Airport, Hernández and San Pedro profiles, respectively), they can be used for regional correlations in the northeastern littoral of the Pampean region (Figure 17), and can be possibly assigned to El Tala and Hisisa geosols established by Nabel *et al.* (2000).

The most widespread post-burial process is calcification, represented by different kinds of calcretes originated by the precipitation of micritic and sparitic calcite in voids and fissures from groundwater circulating through the buried soils (Imbellone and Teruggi, 1986). In some cases, textural coatings within the calcretes are found, which indicates a diagenetic, impregnative calcification process. It should be emphasized that the surface soils of the three studied profiles show powdery calcium carbonate pseudomycelia corresponding to micritic zones and/or acicular calcite formed during periods of high evapotranspiration.

Intensive post-burial gleying may be difficult to distinguish from pedological gleying (Catt, 1990). The former

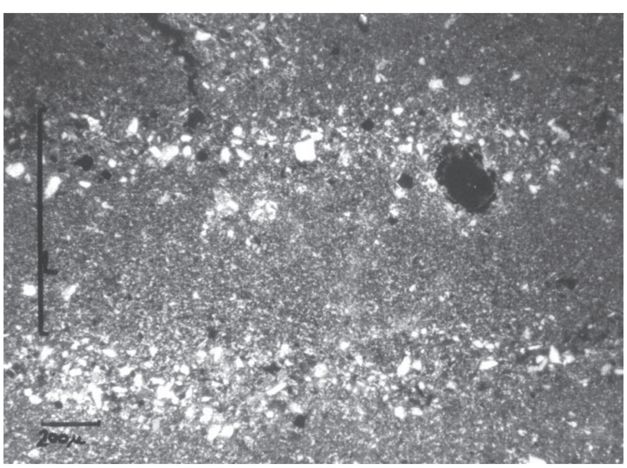


Figure 11. Sorted laminar microstructure locally produced in areas subject to ephemeral waterlogging. Airport profile; unit B, 2Btkb2; XPL x 5; L: 2,000 μm; bar 200 μm.

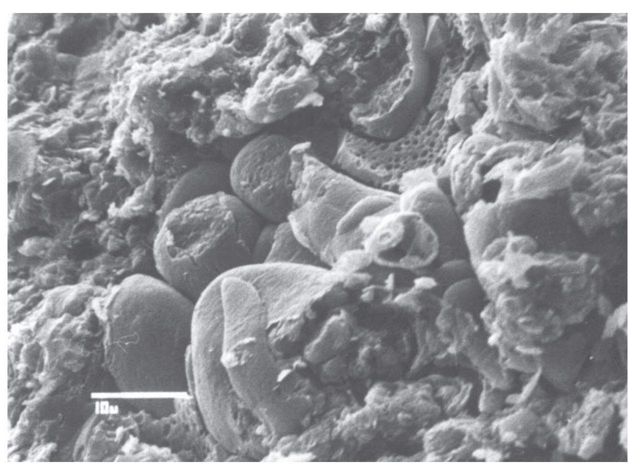


Figure 12. Biofeatures (excrement) in the matrix of the soil. Hernández profile; unit D; 2Bt1kb4; SEM x 2,000; bar 10 μm.

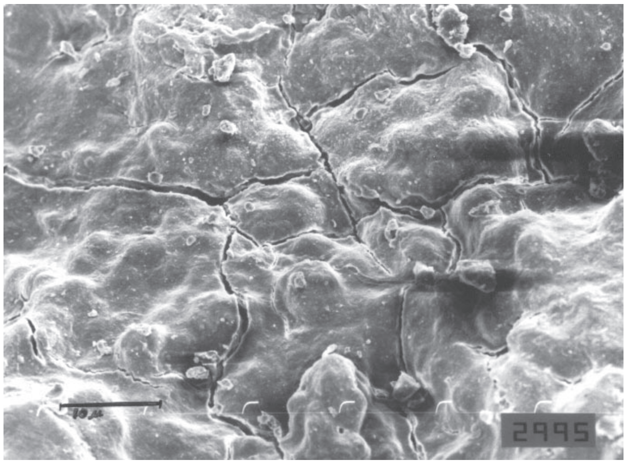


Figure 13. Ped surface showing thick clay coating. Airport profile; unit E, 4Btkb5; SEM x 2,000; bar 10 µm.

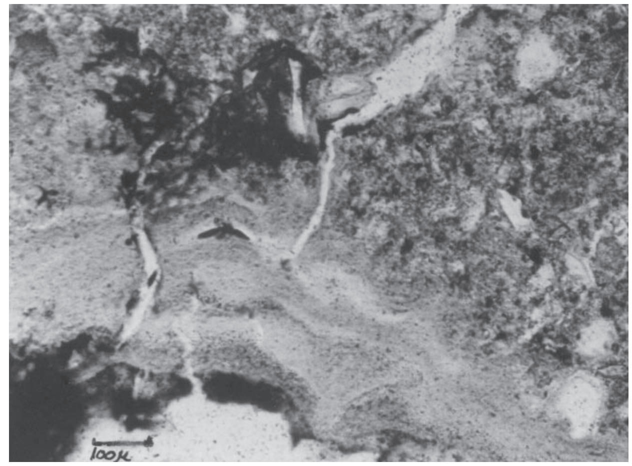


Figure 14. Partial view of a juxtaposed layered textural and amorphous coatings in a void. Note sharp boundary with the soil matrix and a composition of microlaminated clay and silt. San Pedro profile; unit G, 7Bt1kgb7; PPL x 20; bar 100 µm.

may give rise to some mottling or nodules, but in field recognizable paleochannel fills, extensive gray mottling or almost uniform gray colors, and some isotropic micromass fabric in thin sections, would correspond to original gleying. Bioturbation processes are inferred by the presence of pedotubules and channels crossing through the original sedimentary microstructure. Moreover, some biological voids are lined with coatings and hypocoatings indicating superposed processes.

In the upper paleosols (B and C units of Airport profile; B and C units of Hernández profile and B, D and E units of San Pedro profile), Bt horizons have been initially identified in the field due to the lustrous and generally discontinuous aspect of ped faces. However, the microscopic study revealed that the lustrous surfaces correspond to zones of micromass orientation (striated b-fabric) produced by stress, which allowed us to determine the operating pedogenic process.

Most of the loessial sediments deposited during a semiarid climate have been modified by pedogenesis. In a few cases, C horizons probably belonging to loess sediments barely affected by pedogenesis have been identified. All the paleosols have evolved under a humid climate, with pedological processes of clay illuviation, hydromorphism, pedoturbation, and calcification similar to those acting in the surface soils of the studied profiles and in many soils of the undulating Pampa.

A common pattern is the presence of amorphous and cryptocrystalline features which are prominent, both macro- and micromorphologically, in the lowermost part of the profiles. This suggests a more humid paleoenvironment that modified the oxidation–reduction conditions of the soils,

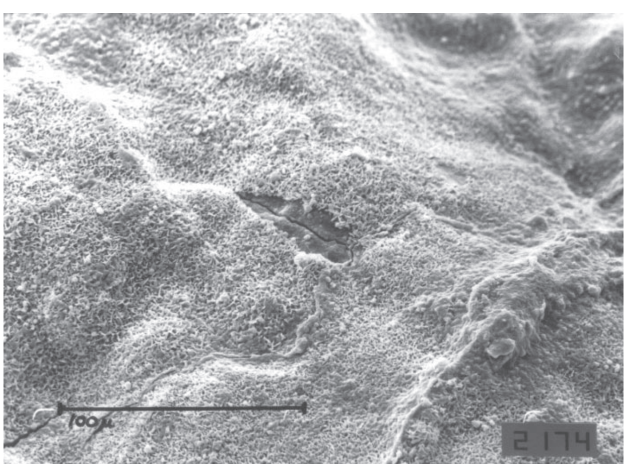


Figure 15. Compound juxtaposed clay and microcrystalline birnessite coating on a ped surface. Airport profile; unit D, 3Btkgb4; SEM x 500; bar 100 µm.

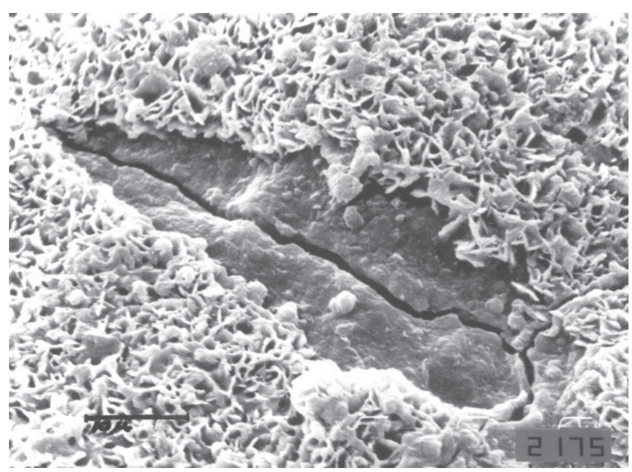


Figure 16. Close-up of Figure 14. Note the spongy surface texture of birnessite coating and smooth surface texture of clay coating. Airport profile; unit D, 3Btkgb4; SEM x 2,000; bar 10 µm.

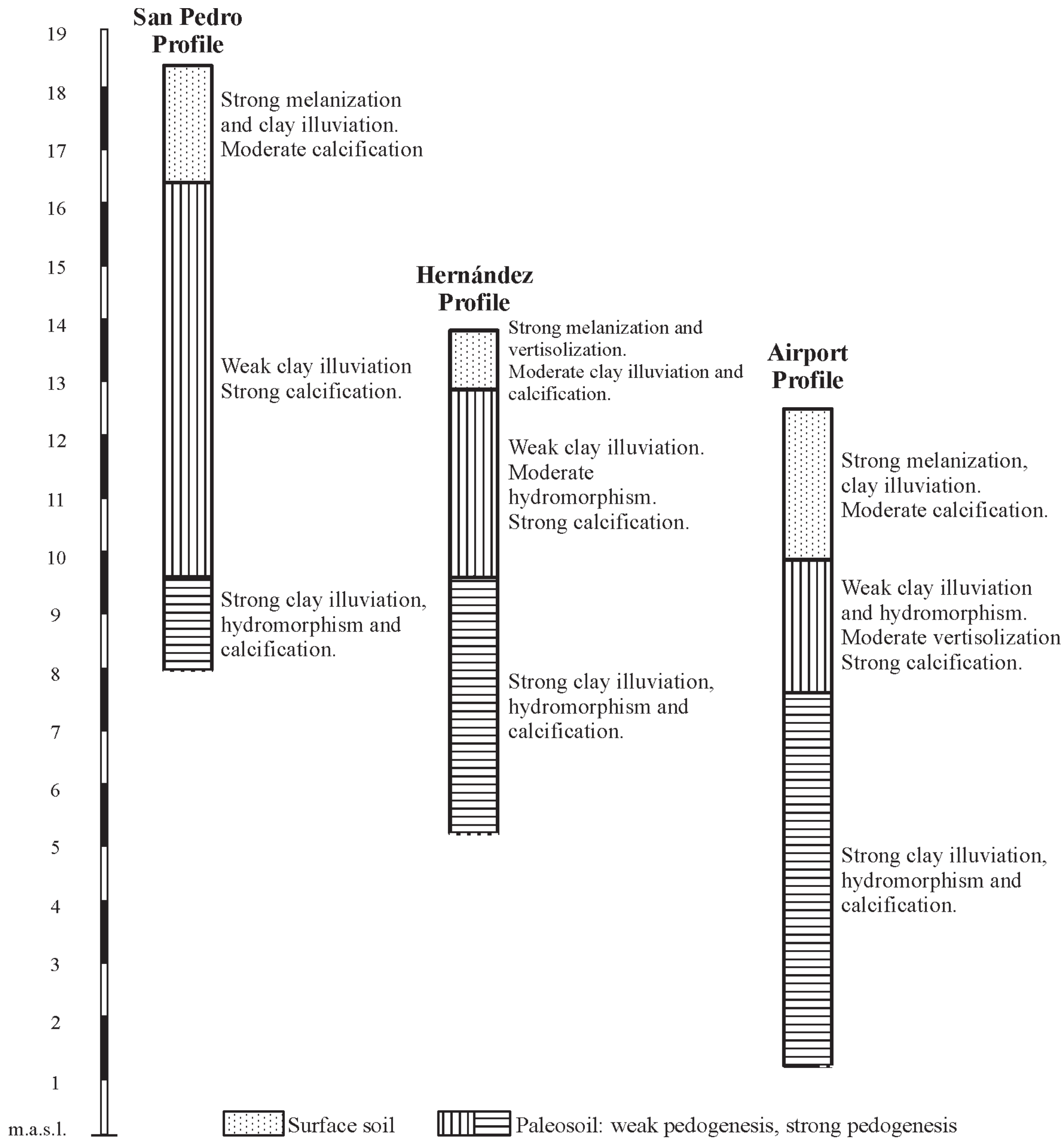


Figure 17. Schematic relationship between soil-paleosol profiles illustrating the type and intensity of pedogenic processes interpreted from morphology and micromorphology.

mobilizing soluble forms of iron and manganese. Mobilization of iron and manganese gives rise to reduced colors, depleted zones in the matrix, different kinds of nodules, and thick and continuous coatings. Stronger redistribution of manganese at the bottom of the profiles indicates that the climate was more humid than the present one, but not enough to solubilize large quantities of iron. The presence of opal phytoliths supports evidence of paleosols formed under grassland vegetation (Bertoldi de Pomar, 1975).

The macro- and micromorphological analysis of the studied profiles allows a sedimentation–pedogenesis model for the study area to be established. In climatic conditions with appreciable moisture fluctuations, two great sedimentary-pedological cycles with variable rates of sedimentation and pedogenesis should be considered. At the bottom of the profiles, strong pedological development is due to either: a) episodic sedimentation and soil development when sedimentation decreased to low rates or during non-sedimentation pauses (Airport and San Pedro profile); or b) development of superposed pedogenesis with overlapping of illuvial horizons (Hernández profile) in an accretional landscape with more or less continuous sedimentation. On the other hand, the upper part of each profile is more variable, which in some cases formed in an environment with a lower rate of soil formation (San Pedro profile) and in others with slow and continuous pedological processes in an up-building landscape (Airport, Hernández profile).

ACKNOWLEDGEMENTS

The authors are very grateful to Ing. Jorge Giménez for the English version and the reviewer Dr. Elizabeth Solleiro for her constructive comments.

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Manuscript received: April 8, 2002
Corrected manuscript received: November 7, 2002
Manuscript accepted: February 6, 2003