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PARENT MATERIALS, BURIED SOILS AND FRAGIPANS IN NORTHWESTERN BUENOS AIRES PROVINCE, ARGENTINA

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This paper discusses the morphological, physical, chemical, mineralogical and micromorphological properties of two Late Pleistocene-Holocene soil/paleosol sequences. They are located in the NW region (Sandy Pampa) of Buenos Aires province, Argentina. The soil profiles are complex; they are developed on sandy loess and have lithologic discontinuities and buried soils including fragipans. Two buried geosols with argillic horizons and an incipient, recently buried geosol have been found under the surface horizon. The paleosols with Bt horizons reflect humid paleoclimatic conditions similar to those prevailing at present. The deeper one has fragipan properties whose development has been favored by a loamy particle-size class, clay and clay-silt bridges, interlocking grains and a moderate calcification process. © 1998 Published by INQUA/Elsevier Science Ltd. All rights reserved.

INTRODUCTION

Soils with lithologic discontinuities, paleosol horizons and hardened horizons, developed on loessic and sandy materials, have been mentioned and described in the northwestern region of Buenos Aires province ('Sandy Pampa') from a regional, stratigraphic or geomorphological point of view (Bonfils *et al.*, 1960; Dillon *et al.*, 1989; Hurtado *et al.*, 1989; INTA, 1989). However, there is little specific information concerning the physical, chemical, mineralogical, and micromorphological properties of the soils and paleosols of the region (Camilión and Imbellone, 1984; Imbellone and Camilión, 1984).

In the review of the worldwide distribution of fragipans by Witty and Knox (1989), they did not mention their presence in Argentina. However, they have been recognized in the provinces of Buenos Aires, Córdoba, Chaco, Catamarca, Jujuy and Salta. The soils with fragipans have been classified as Fragiaqualfs, Fragiochrepts and Fragiaquepts and occur mainly in low-lying areas. The tops of the fragipans are found at a depth of 40–80 cm and are in the loamy particle-size class, some of them are alkaline and/or saline and may have moderate or low amount of calcium carbonate (INTA, 1990). In the Sandy Pampa of Buenos Aires province, only Fragiaqualfs have been described by INTA (1989) in a small area. However, soils with fragipans are supposed to cover a more extensive area since we have also identified these horizons in Mollisols in the region.

The objective of this paper is to discuss genetic aspects of Late Pleistocene-Holocene soil/paleosol sequences through the analysis of morphological, physical, chemical, mineralogical and micromorphological properties. Particular emphasis has been given to the sequences in which the paleopedogenic cycles include horizons with fragipans.

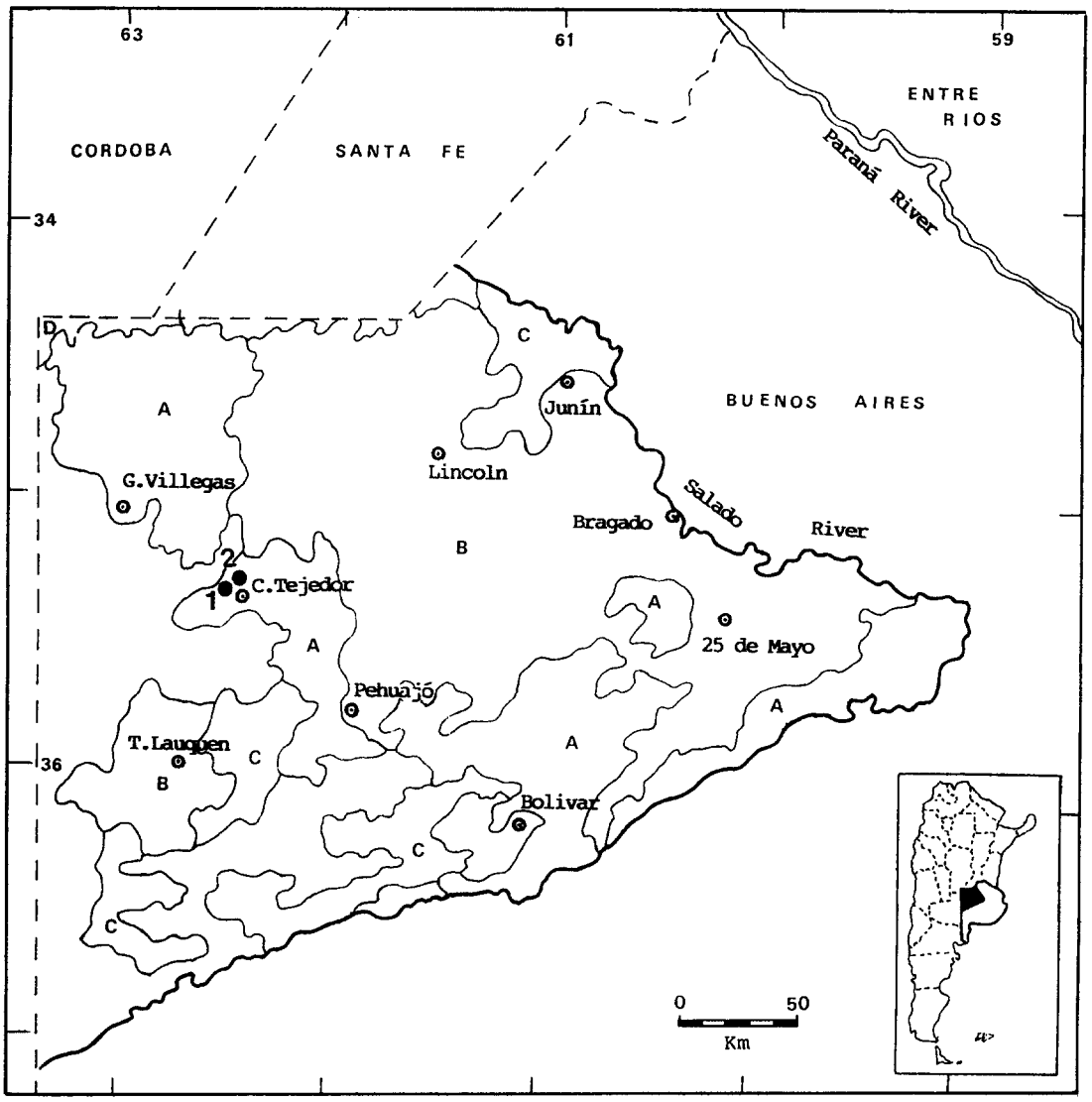
CHARACTERISTICS OF THE STUDY AREA

The province of Buenos Aires is a part of the 'Chaco-Pampean Plain'. This region belongs to an extensive morphologic unit that spans the South American continent, from the Colombian and Venezuelan plains in the north to the Argentine pampas in the south. Its most remarkable feature is its nearly level relief.

The region is a sedimentary basin where thick sequences of continental and marine sediments have accumulated. They range in age from the Cambrian to the present and rest unconformably on a block-faulted crystalline basement. The main source of sediments are weathered rock outcrops located to the west and southwest in northern Patagonia.

The uppermost Cainozoic deposits of Buenos Aires province comprise the Puelches Formation (very friable, poorly sorted, fine- and coarse-grained sandstones) and the Pampa Formation (reddish to brown, loessial and sandy silt deposits, about 40 m thick) (Russo *et al.*, 1978).

The study area is included in the central part of the Sandy Pampa, a region of about 60,000 km^2 located in northwestern Buenos Aires province (Fig. 1). The central and northern part of that region is characterized by the presence of longitudinal dunes over 100 km long, 2–5 km wide and up to 6 m high. They are arranged as arches in SW–N direction separated by interdune depressions 0.5–5 km wide, which are waterlogged during periods of heavy rains and become the only 'drainageways' since the subregion is totally devoid of streams (Dillon *et al.*, 1989). The original shape and height of the dunes, which are relict forms of a climate much drier than the present, have been smoothed by the action of wind and water and now appear as flat-topped, stabilized landforms which do not have a conspicuous topographic expression. The soils with buried and hardened horizons are found in interdune



LEGEND

Mapping Units	Taxonomic Units		
	Dominant soils	Subordinate soils	Inclusions
A	*Thapto-argic* and *Thapto-natric Hapludolls*	Entic and typic Hapludolls, Aquic Argiudolls	Typic Natralbolls
B	Entic and typic Hapludolls	*Thapto-argic* and *thapto-natric Hapludolls*	Typic Natraquolls and Natraqualfs
C	Entic Hapludolls and Haplustolls	Typic Udipsamments and Ustipsamments	*Thapto-argic Hapludolls*
D	*Typic Fragiaqualfs* and Natralbolls	Entic Hapludolls and Natric Duraquolls	Typic Hapludolls and Natraqualfs

● Location of studied pedons

FIG. 1. Distribution of buried soils and fragipans in NW Buenos Aires province (from INTA, 1989).

depressions and adjacent flat areas where the recent sedimentary cover is thin.

The dominant vegetation is a grassland steppe with *Stipa*, *Piptochaetium*, *Poa*, *Festuca* and *Panicum* as the more common genera. Halophilous communities with *Distichlis*, *Salicornia* and *Atriplex* are common in low-lying areas. However, the native vegetation has been drastically modified in the last 100 yr by pastures (mainly alfalfa) and field crops (wheat, sunflower, corn, oats, rye, etc.).

Mean annual rainfall in most of the area ranges from 900 mm on the east to 700 mm on the west. In the warm season (October–March) rainfall is 450–600 mm, whereas in the cold season (April–September) it is 200–300 mm. The region is characterized by alternations of dry and humid conditions. During the present century the area has suffered from severe droughts and wind erosion, especially between the 1930s and 1950s. Conversely, a humid cycle began in the early 1970s and several years with precipitation far beyond the long-term means have been recorded. The annual potential evapotranspiration is 800–850 mm. Annual water deficit is about 30–80 mm concentrated in summer. The soil moisture regime is udic, intergrading to ustic towards the west. The aquic regime is common in low-lying areas. The mean annual temperature is 15–16°C. The mean temperature of January (mid summer) is 23–24°C and the mean temperature of July (midwinter) is 7–8°C. Extreme temperatures range from +43 to −10°C. The soil temperature regime is thermic throughout the region.

MATERIALS AND METHODS

In order to represent the distribution of buried soils ('thaptoargic' and 'thapto-natric' subgroups) in the Sandy Pampa, a map (Fig. 1) has been elaborated based on information by INTA (1989). Two profiles of buried soils with fragipans, which are representative of the soils of the area, were selected for study near Carlos Tejedor. They are located in flat areas adjacent to two different interdune depressions which are subject to occasional water logging during periods of heavy rain (Figs 1 and 2).

Morphological descriptions of the pedons (Tables 1 and 2) were made according to the U.S. Survey Manual (Soil Survey Staff, 1981) and the soil survey guidelines of Argentina (Etchevehere, 1976). Physical and chemical analyses were made by standard methods. Grain-size distribution was analyzed by the pipette method (Day, 1965) using ½ phi intervals. Pedogenic Fe and Al oxides and silica were analyzed according to Mehra and Jackson (1960). Several samples of each horizon were extracted in Kubiëna boxes for micromorphologic analyses in thin sections. Descriptions were based on Brewer (1964) nomenclature. Total clay was analyzed by X-ray diffractometry in natural, calcinated and ethylene glycol-saturated subsamples, homoionized with Mg. Semi-quantitative estimates were made according to Biscaye's method (1965). Optical microscopic and SEM submicroscopic studies were made on all horizons. Relations between skeletal grains, plasma and voids were described by combined techniques of optical microscopy and scanning electron microscopy, as suggested by Payton (1981).

RESULTS

Characteristics of the Soils

The physical, chemical and mineralogical characteristics of pedons 1 and 2 (Table 3) show evidence for five depositional units and three buried soil units (geosols). Geosols A and B in both profiles consist of Bt and BC horizons. They lack A horizons and underlie a surface horizon in pedon 1 or an incipient, recently buried solum (geosol C) in pedon 2 (Fig. 3). The texture is loam or silt loam in the surface horizons and the A and AC horizons of geosol C. The uppermost Bt and BC horizons are silty clay loam or silt loam and the deeper horizons are clay loam.

The Bt horizons of geosol B have subangular blocky or prismatic structure with a hard or very hard consistence when dry and firm when moist. The Bt horizons of geosol A have prismatic structure and the BC horizons have platy (pedon 2) or weak platy (pedon 1) structure.

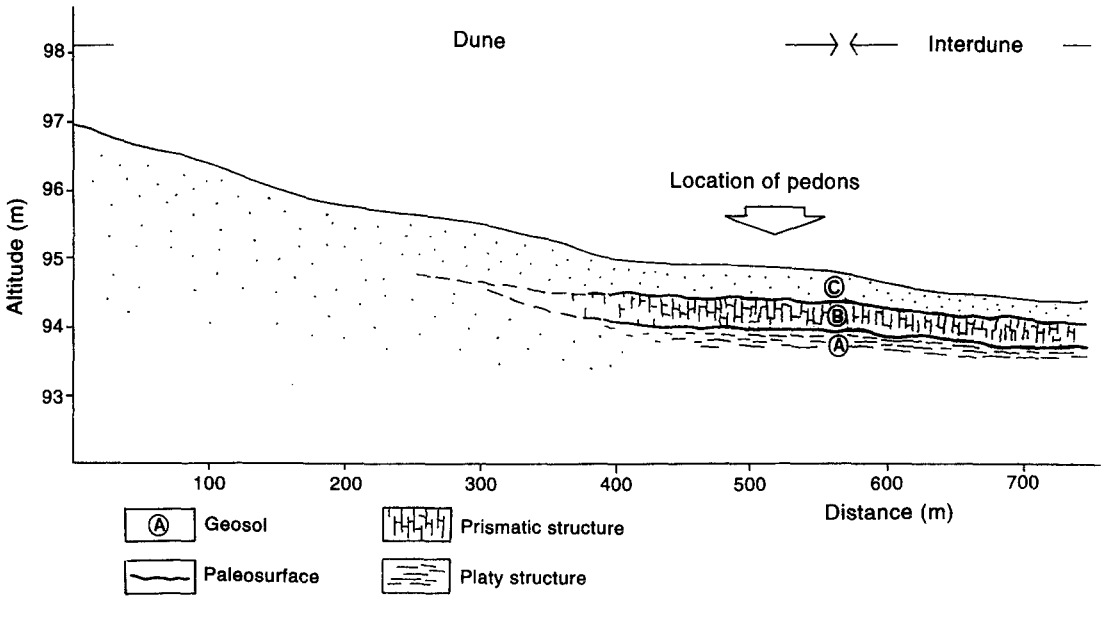


FIG. 2. Generalized catenary relationships of geosols.

TABLE 1. Pedon 1

Geomorphic unit: Flat area adjacent to interdune depression	
Drainage: Imperfectly drained	
Slope: 0.5%	
Altitude: 94 m	
A	0–18 cm; grayish brown to light grayish brown (10 yr 5.5/2) dry, grayish brown (10 yr 3/2) moist; silt loam; weak fine and medium subangular blocky structure; soft, friable, few fine faint mottles; many roots; abrupt smooth boundary
2Btb	18–38 cm; light brown (7.5 yr 6/4) dry, brown to dark brown (7.5 yr 4/4) moist; silty clay loam; moderate medium subangular blocky structure; very hard; common clay-humus skins, few fine faint mottles; many roots; clear smooth boundary
2BCb1	38–53 cm; brown to light brown (7.5 yr 6/3) dry, brown to dark brown (7.5 yr 4/4); silty clay loam; moderate fine platy structure; very hard; common to few clay-humus skins mainly on faces of plates; slight effervescence; common roots; gradual smooth boundary
2BCb2	53–67 cm; brown (7.5 yr 5/4) dry, dark brown (7.5 yr 3/4) moist; silt loam; platy structure
3Btkxb	67–80 cm; light brown (7.5 yr 6/4) dry, brown to dark brown (7.5 yr 4/4) moist; clay loam; moderate medium prismatic structure parting to angular blocky; very hard, brittle; common clay skins; carbonate in old rootlet pores; clear smooth boundary
3CBkxb	80–123 + cm; light brown (7.5 yr 6/4) dry, brown to dark brown (7.5 yr 4/4) moist, clay loam; strong medium platy structure; very hard, brittle; common clay-humus skins mainly on faces of plates; few medium faint mottles; many medium cylindrical and irregular carbonate concretions; very few roots

TABLE 2. Pedon 2

Geomorphic unit: Flat area adjacent to interdune depression	
Drainage: Imperfectly drained	
Slope: 0.5%	
Altitude: 95 m	
A	0–16 cm; grayish brown (10 yr 5/2) dry, dark grayish brown (10 yr 3/2) moist; loam; weak fine subangular blocky structure tending to granular; soft, very friable; common fine distinct mottles; many roots; clear smooth boundary
2Ab	16–30 cm; dark grayish brown (10 yr 4.5/2) dry, very dark brown (10 yr 2/2) moist; loam; weak fine subangular blocky structure; soft, very friable; many roots; clear irregular boundary
2ACb	30–40 cm; pinkish gray to light brown (7.5 yr 6/3) dry, dark brown (7.5 yr 2/2) moist; silt loam; massive; slightly hard, friable; common roots; abrupt smooth boundary
3Btb	40–52 cm; brown (7.5 yr 5/4) dry, dark brown (7.5 yr 3/4) moist; silty clay loam; moderate medium prismatic structure; hard, firm; common clay-humus skins; common roots; abrupt smooth boundary
3BCb	52–64 cm; pink to pinkish gray (7.5 yr 7/3) dry, dark brown (7.5 yr 4/3) moist; silt loam; massive tending to platy; hard, firm, slightly plastic, sticky; few to common clay-humus skins; few fine weak mottles; slight effervescence; common roots; abrupt smooth boundary
4Btkxb	64–96 cm; light brown (7.5 yr 6/4) dry, brown to dark brown (7.5 yr 4/4) moist; clay loam; moderate medium platy structure; very hard, brittle; common clay-humus skins mainly on faces of plates; common fine irregular carbonate concretions; few roots; gradual smooth boundary
4BCkxb	96–118 cm; reddish yellow (7.5 yr 6/6) dry, dark brown (7.5 yr 4/6) moist; clay loam; weak medium platy structure tending to massive; hard, brittle; few to common clay-humus skins mainly on faces of plates; common fine irregular carbonate concretions; some carbonate on rootlet holes and between plates; gradual smooth boundary
5Cb	118–137 cm; pink (7.5 yr 7/4) dry, brown to dark brown (7.5 yr 4/4) moist; loam; massive; abrupt wavy boundary
5Ckm	137–140 + cm; indurated accumulation of calcium carbonate

In both pedons, the older Bt and BC horizons have hard or very hard consistence when dry and are brittle when moist. Clay illuviation cutans are sufficiently expressed in the Bt horizons to consider them argillic horizons, but their sodium adsorption ratios exceed 13, which places them in a natric class. Also, below a depth of about 40 cm the horizons of both pedons are saline.

The deficient drainage of both soils is revealed by hydromorphic features (mottles) in the surface and some subsurface horizons. Calcium carbonate appears mostly in the deeper paleosols as irregular concretions or coating old root channels. In the uppermost paleosols, it appears finely divided in trace amounts.

TABLE 3. Physical, chemical and mineralogical properties of pedons 1 and 2

Geosol	Horizon	Depth (cm)	Sand	Silt (%)	Clay	Bulk dens. ($Mg\,m^{-3}$)	pH (paste)	E.C. ($dS\,m^{-1}$)	Org. C (%)	$CaCO_3$ (%)	Free oxides SiO_2	Free oxides Fe_2O_3 (%)	Free oxides Al_2O_3	Clay mineralogy I	Clay mineralogy I/S (%)	Clay mineralogy K
Pedon 1																
	A	0–18	31.4	52.1	16.4	1.44	7.3	—	2.3	—	0.33	0.09	0.48	80	15	5
B	2Btb	18–38	17.8	46.7	35.4	1.41	7.6	2.87	0.83	—	1.63	0.03	0.27	65	35	t
B	2BCb1	38–53	15.2	51.6	33.2	1.38	7.9	9.40	0.66	1.51	2.88	0.02	4.34	65	30	t
B	2BCb2	53–67	19.2	55.1	25.8	1.54	7.6	17.23	0.35	2.36	0.54	0.03	0.79	85	10	t
A	3Btkxb	67–80	21.1	45.0	33.9	1.49	8.0	6.29	0.43	2.57	0.32	0.13	0.21	40	60	t
A	3BCkxb	80–123 +	24.6	43.3	32.0	1.62	8.1	4.81	0.30	4.88	0.66	0.04	1.60	60	40	t
Pedon 2																
	A	0–16	40.9	41.5	17.6	1.37	6.3	—	3.83	—	0.33	0.21	0.57	80	10	10
C	2Ab	16–30	30.6	46.7	22.7	1.18	7.3	—	2.80	—	0.28	0.10	0.31	85	10	5
C	2ACb	30–40	27.7	52.9	19.4	1.32	8.0	1.50	0.82	—	0.47	0.04	0.56	75	20	5
B	3Btb	40–52	17.6	46.5	36.0	1.56	7.8	5.74	0.68	—	0.98	0.04	0.39	70	30	t
B	3BCb	52–64	18.7	62.8	18.6	1.47	8.2	6.46	0.52	0.47	0.31	0.04	0.29	60	40	t
A	4Btkxb	64–96	20.4	50.8	28.9	1.47	7.9	1.46	0.42	2.05	0.46	0.05	0.90	60	40	t
A	4BCkxb	96–118	24.0	47.0	29.0	1.42	8.1	—	0.17	1.52	0.04	0.08	0.08	60	40	t
	5Cb	118–137	37.4	46.2	16.4	1.46	8.1	—	0.10	0.56	0.65	0.03	2.11	50	50	t

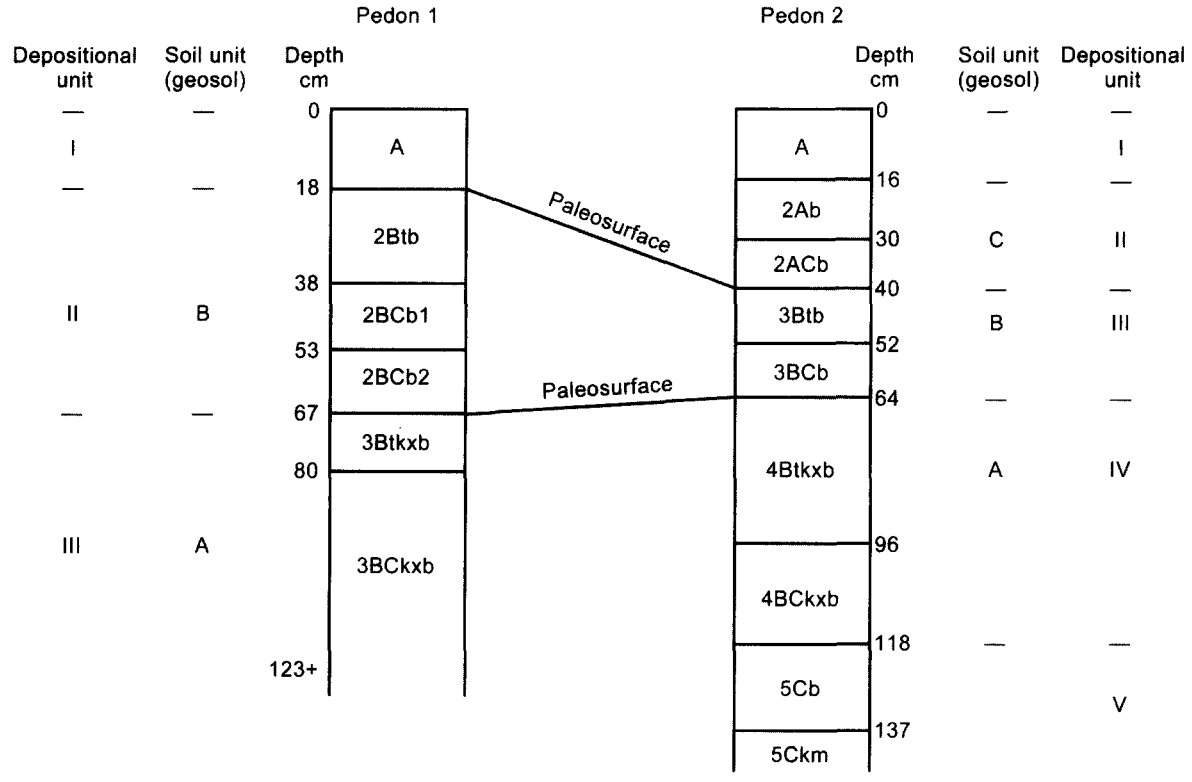


FIG. 3. Correlation of depositional units and soil horizons.

Using all available information, the soils have been classified as Udolls. The classification at lower levels was difficult because the studied pedons have a combination of horizon characteristics (mollic, natric, and fragic), buried horizons and a udic moisture regime not contemplated by Soil Taxonomy. For example, the presence of fragipans in Mollisols and natric horizons in Udolls are not recognized (Soil Survey Staff, 1975, 1994). Creating new taxonomic units is beyond the objectives of this paper.

Characteristics of the Parent Materials

The parent material of the soils in the Pampean region has been generically considered as loess. The dominant particle-size is mainly silt, but the sand content significantly increases towards the western part of the Buenos Aires province (Imbellone and Teruggi, 1993). In this area textural variations along toposequences are found; for example, in the higher positions, sand content varies from 40 to 60%, whereas in the low-lying sectors it ranges from 15 to 40% (INTA, 1989). These relationships indicate that variations in the grain-size distribution are due to variations in the parent materials and pedogenic processes.

In pedon 1 the parent material is unimodal in the uppermost horizon with a mode between 3 and 4 ϕ. It corresponds to a very fine sand and is dominated by the 62–88 μm fraction. The subsurface horizons are bimodal; the main mode is between 4 and 5 ϕ (coarse silt) with the maximum varying between 22–31 and 31–44 μm. In the illuvial horizons another mode is in the finest fraction (>11 ϕ or fine clay).

Pedon 2 exhibits greater textural variations than pedon 1. The surface and C horizons have a main mode between 3 and 4 ϕ (very fine sand, 62–125 μm). The illuvial horizons have a main mode between 3 and 6 ϕ, with maxima in the 22–44 μm interval. In the Bt horizons the mode between 11 and 12 ϕ is very strong.

The difficulty in recognizing lithologic discontinuities in loessial sequences has been mentioned (Wang and Arnold, 1973). In the loessic deposits of Argentina it is difficult to distinguish depositional units because the differences are very subtle in the field and laboratory data. Previous work in the area found the particle-size distribution to be the best parameter to detect lithologic discontinuities (Camilión and Imbellone, 1984).

The grain-size distribution on a clay-free basis (Table 4) likely reflects the original grain-size composition of the sediments. In both pedons the largest sand fraction is between 3 and 4 ϕ (very fine sand); the modal fraction is between 4 and 5 ϕ (coarse silt), with a distinctive sand content at the top and bottom of the profiles.

The sand/silt ratio (62–125 μm/31–62 μm) indicates subtle but discernible differences which permit the identification of depositional units (in Roman numbers) separated by lithologic discontinuities and the relation they have with geosols (in capital letters) in both profiles (Fig. 3). The ratios help establish boundaries and correlate parent material units between profiles (Table 4). The grain-size differences mark lithologic discontinuities that separate depositional

TABLE 4. Clay-free grain-size distribution, percent of total sand and silt

Geosol	Horizon	1000–500 (μm)	500–250	250–125	125–62	62–31	31–16	16–8	8–4	<4	Sand/silt ratio*
Pedon 1											
	A	0.0	0.2	9.6	27.8	25.1	17.5	12.1	7.8	16.4	1.11
B	2Btb	0.3	0.3	6.0	21.1	26.1	17.5	16.4	12.6	35.4	0.81
B	2BCb1	0.0	0.1	5.0	17.6	25.0	18.6	17.6	16.1	33.2	0.70
B	2BCb2	0.5	0.5	5.4	19.3	28.2	19.8	14.3	11.0	25.8	0.68
A	3Btkxb	0.2	0.6	6.9	24.2	26.8	16.3	13.4	11.7	33.7	0.90
A	3BCkxb	0.1	0.4	8.4	27.4	28.9	14.5	10.7	9.7	32.0	0.95
Pedon 2											
	A	0.2	1.2	13.0	35.2	21.6	13.4	9.8	5.6	17.6	1.63
C	2Ab	0.1	0.7	8.8	30.0	15.7	15.7	11.8	10.2	22.7	1.32
C	2ACb	0.2	0.7	6.8	26.6	25.5	17.1	13.3	9.8	19.4	1.05
B	3Btb	0.2	0.5	4.8	21.9	28.2	18.5	17.2	10.4	36.0	0.77
B	3BCb	0.1	0.4	3.8	18.7	26.8	21.1	16.7	12.4	18.6	0.70
A	4Btkxb	0.1	0.4	4.8	23.0	28.4	16.7	13.2	13.1	28.8	0.81
A	4BCkxb	0.2	0.5	5.4	27.7	33.4	15.7	8.7	8.4	29.0	0.83
	5Cb	2.5	2.3	6.2	33.7	25.7	13.4	9.2	7.1	16.4	1.31

*125–62 μm/62–31 μm.

units and correspond with morphological boundaries and paleosol characteristics observed in the field.

In pedon 1, three depositional units (I, II, III in order of increasing age) are distinguished. They correspond to a horizon sequence that is visible in the field and interpretable as a paleosol complex. Unit I forms the surface horizon, whereas units II and III correspond to geosols B and A, respectively.

In pedon 2, five depositional units could be distinguished. Unit I forms the surficial horizon. Unit II contains weakly developed paleosol characteristics and appears to be a separate unit. The paleosols in units III and IV correlate with geosols B and A in pedon 1. Unit V is differentiated on the basis of grain-size characteristics.

On the basis of the common loess-paleosol relationships in the region, we deem that a clear correlation exists between depositional units II and III of pedon 1 and depositional III and IV of pedon 2. The correlation between unit I of pedon 1 and units I and II of pedon 2 is not so clear. The clay mineralogy reveals that both profiles have qualitatively and quantitatively homogeneous materials. Illite is the dominant clay mineral, associated with smectites and very small quantities of kaolinite (Table 1). The more recent materials have the highest content of illite. In general, illite contents are progressively lower in the older depositional units.

Buried Soils

The horizonation and combination of features such as texture, structure (type and grade), consistence, brittleness, illuviation cutans (type, quantity and expression) and voids (root/worm channels) have permitted the identification of paleosols. The micromorphological study shows that the soils and paleosols have a mineralogical composition similar to that of the Pampean loess. According to the terminology of Brewer (1964), the surface horizon and the most recently buried soil horizons have granular and massive microstructures, relative intertextic porphyroskelic distribution and silasepic plasmic fabric with punctual extinction due to the abundance of silt particles. The most remarkable feature is the presence of biorelicts and abundant irregular voids which are interconnected and randomly distributed.

In geosols B and A, the fabric is porphyroskelic with silasepic, argilsilasepic or insepic plasmic fabric in some parts. The intrapedal matrix is dense with few or common voids. In the upper part of the B horizons rows of vughs are interconnected. The plasma in the soil matrix is light brown under plain light and has low birefringency under the optical microscope. Observations with SEM indicate the presence of lattice clays randomly arranged in the material.

The plasma concentrations appear mainly as simple and/or compound cutans on voids (vughs and/or plane fissures). The mesovoids are more abundant in the lower part of geosol B. Geosol A differs from the overlying geosol B in its lower porosity in vughs and abundant craze planes, some of them subhorizontal. A large part of the porosity is infilled by argillans and calcitans (Fig. 4). The upper part of geosol B has fragipan characteristics.

Characteristics of the Fragipan

Horizons with fragipan characteristics range in depth to the top of the pan from 64 to 67 cm and range

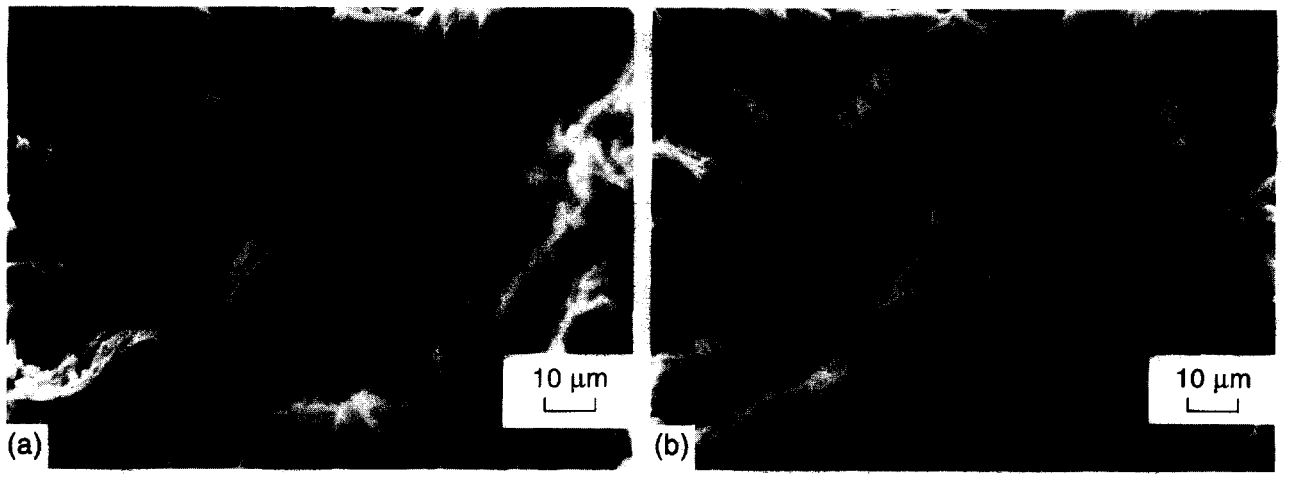


FIG. 4. Illuvation features on mesovughs (30–75 μm). Pedon 2, 4BCkxb horizon. (a) Simple argillan, SEM × 1000. (b) Microlaminated argillan. SEM × 1000.

in thickness between 54 to more than 66 cm. They are loamy in texture and have very little organic matter; they are very hard when dry and brittle when moist and slake in water. They have mottles and clay-humus skins, an abrupt upper boundary and a gradual lower boundary.

The term 'fragipan' and the suffix 'x' are used here in a general sense denoting a horizon with reversible induration. According to Soil Taxonomy (Soil Survey Staff, 1994) the brittle horizons in this study do not meet all the classification criteria for a fragipan. In particular, they lack the large prisms defined by vertical streaks arranged in a polygonal pattern on a horizontal exposure; in addition, the bulk density is not significantly different compared with the overlying horizons.

Because these horizons slake in water they cannot be considered duripans or petrocalcic or petroferric horizons, which are horizons with irreversible induration. Besides, their contents of silica, calcium carbonate and iron oxides are not significantly different with respect to other horizons (Table 3). Although the parent materials of both pedons are rich in volcanic materials, only a few glass shards with etched surfaces were found and no silica cementation was observed.

The fragipans generally have a well-expressed platy structure with plates about 1–3 cm thick. In one area, surficial layers with a conspicuous platy structure (about 10 cm thick) was observed at the bottom of blowout dunes in the southern part of the Sandy Pampa. This could suggest a depositional origin of the platy structure of the fragipans, but further investigations to elucidate the causes are necessary.

The fragipans are virtually devoid of roots, except along vertical fractures, generally more than 10 cm apart, and between platy peds. However, many pores of old rootlets can be observed within the plates, which suggests that these horizons were originally near the surface and were not hard enough to restrict root penetration.

S-matrix characteristics

Skeleton grains predominate in the S-matrix of the materials; they have angular-subangular shapes and their size ranges from 125 to 31 μm (3–5 ϕ). These shapes and sizes favor a close packing, have many points and surfaces of contact between grains. The macroporosity is low, with a prevalence of mesopores consisting of planes and few vughs.

The plasma is clayey and is strongly linked to sand and silt grains. Observations with SEM show that sand and silt grains are linked by clay bridges without forming a continuous mass where grains are imbedded. The plasma separations are very scarce, although zones with birefringent plasma around and between skeleton grains are observed with optical microscopy.

Plasma forming bridges has been observed. Some of them have the shapes described by Wang *et al.* (1974) and Payton (1981). These shapes are:

(a) *Clay bridges* linking skeleton grains or fine cutans of oriented clay particles (Fig. 5). Although this orientation is locally strong, it changes within short distances, thus preventing the development of an oriented plasmic fabric in the soil matrix. These bridges can partially infill packing voids and are randomly distributed. When the thickness and continuity of these cutans and bridges increase, the plasmic fabric is observed more skelsepic or masepic at small magnifications (Payton, 1981).

(b) *Bridges of fine microvesicular matrix*, consisting of clay and fine silt bound by skeleton grains and other bridges. Particles of moderately oriented clay is observed within the bridges (Fig. 6).

DISCUSSION

The parent materials of the soils have the characteristics of Pampean loess. The main mode lies in the 3 to 5 ϕ range (sandy loess, according to Pye, 1987). The mineralogical composition is pyroclastic (volcanic) in nature. In the study area there has been an important contribution of volcanic ash, either concentrated in tephra layers or mixed with the soil material. The shape of the clasts is angular to subangular. This and the great angularity of the volcanic glass shards, appearing

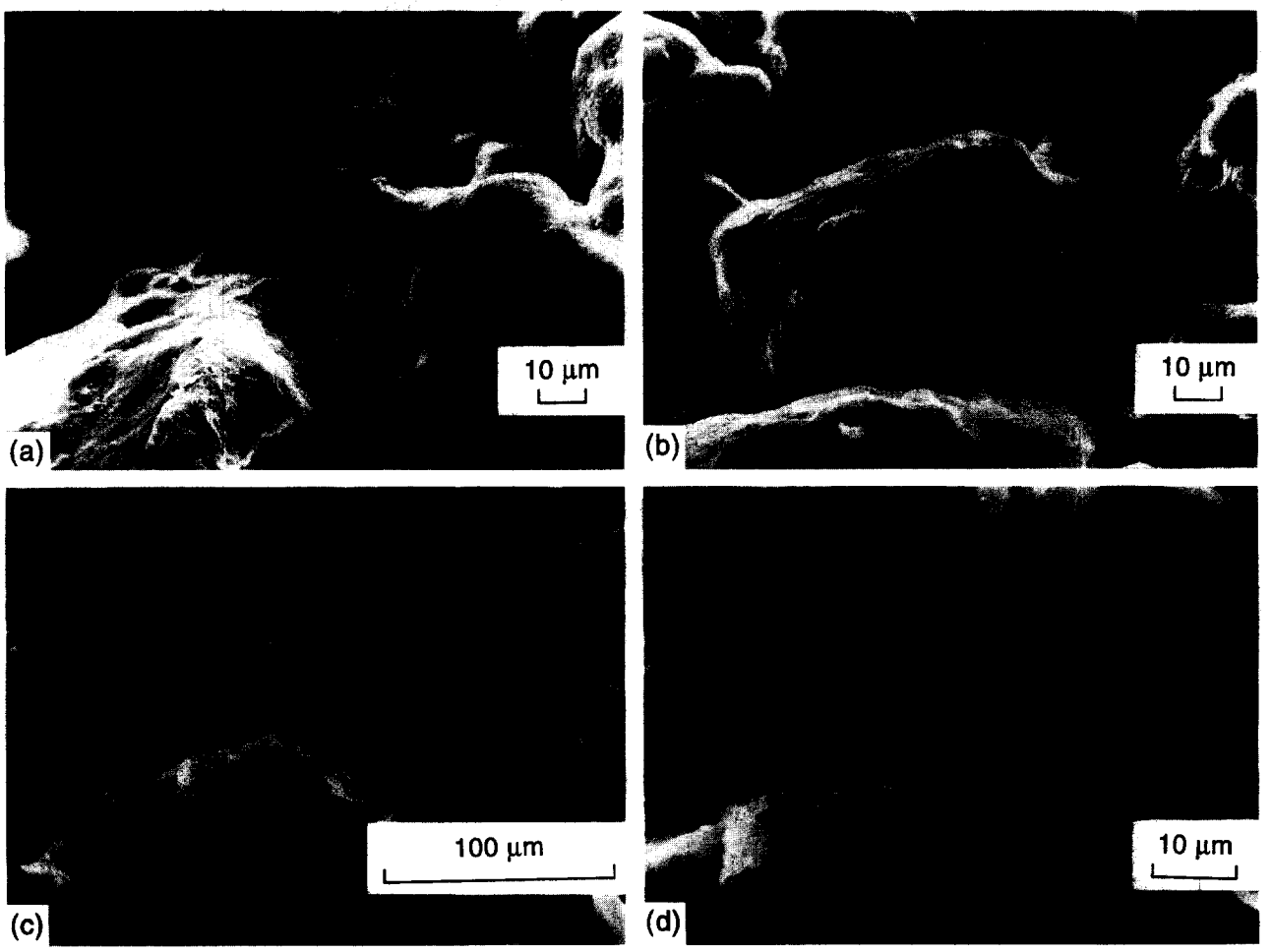


FIG. 5. Clay bridges. Pedon 2, 4BCkxb horizon. (a), (b) Illuvial clay coating very fine sand grains and forming bridges 2–15 μm thick. SEM × 1000. (c) Grain argillan forming a partial bridge, SEM × 500. (d) Detail of (c) SEM × 1500.

in all the fractions (Imbellone and Camilión, 1984, 1988), favor a close packing of the soil material.

The soils under study have macro- and micromorphological characteristics which can favor the formation of hardened horizons; namely, loamy particle-size (Petersen *et al.*, 1970), presence of lithologic and pedologic discontinuities (Smeck *et al.*, 1989) and clay bridging (Wang *et al.*, 1974; Payton, 1981).

The silt content is high (42–63%) in both pedons; in the fragipans it ranges from 43 to 51%. Clay content ranges from 16 to 36% and from 29 to 34% in the fragipans. The contents of silt and clay have an influence in the presence of the brittle and hard properties. For example, silt promotes a close packing, whereas a high clay content of over 30% (Ransom *et al.*, 1987) or 35% (Soil Survey Staff, 1975) preclude fragipan formation.

The paleopedologic features are well marked and permit the determination of the presence of paleosols. There is a correlation between the trends of clay-depth functions and the amount of clay cutans. The pedons contain evidence of two geosols (B and A) with argillic horizons. In geosol A the clay illuviation process is better expressed at the micromorphological level than in geosol B because the grain-size composition of the former is coarser. The illuviation has possibly affected not only the conduction voids but also the soil matrix. This has favored the formation of clay bridges and modified the initial distribution of the clastic components, promoting the development of the fragipan properties.

Geosol A is slightly calcareous. Post burial calcification is a common process in paleosols buried by loess in Argentina where redistribution of calcium carbonate has occurred (Zárate, 1989; Pazos, 1990; Imbellone and Teruggi, 1993). However, the presence of calcium carbonate in the horizons with brittle properties deserves some further consideration. Its origin is associated with the poor drainage in interdune depressions. Observations with optical microscopy show that the calcitans appear to coat and disrupt the clay illuviation features, infill voids and cause the cementation of the soil matrix. This appears to be a current process and would contribute to the hardening of the materials.

The brittleness of fragipans can be explained by microfabric features. The horizons with fragipan characteristics have bridges of fine materials (clay or clay plus silt) acting as links between clastic particles. There are also zones where the skeletal grains are closely packed. In this type of packing, volume changes are less likely because swelling is resisted by the intergrain bridges, as discussed by Payton (1981).

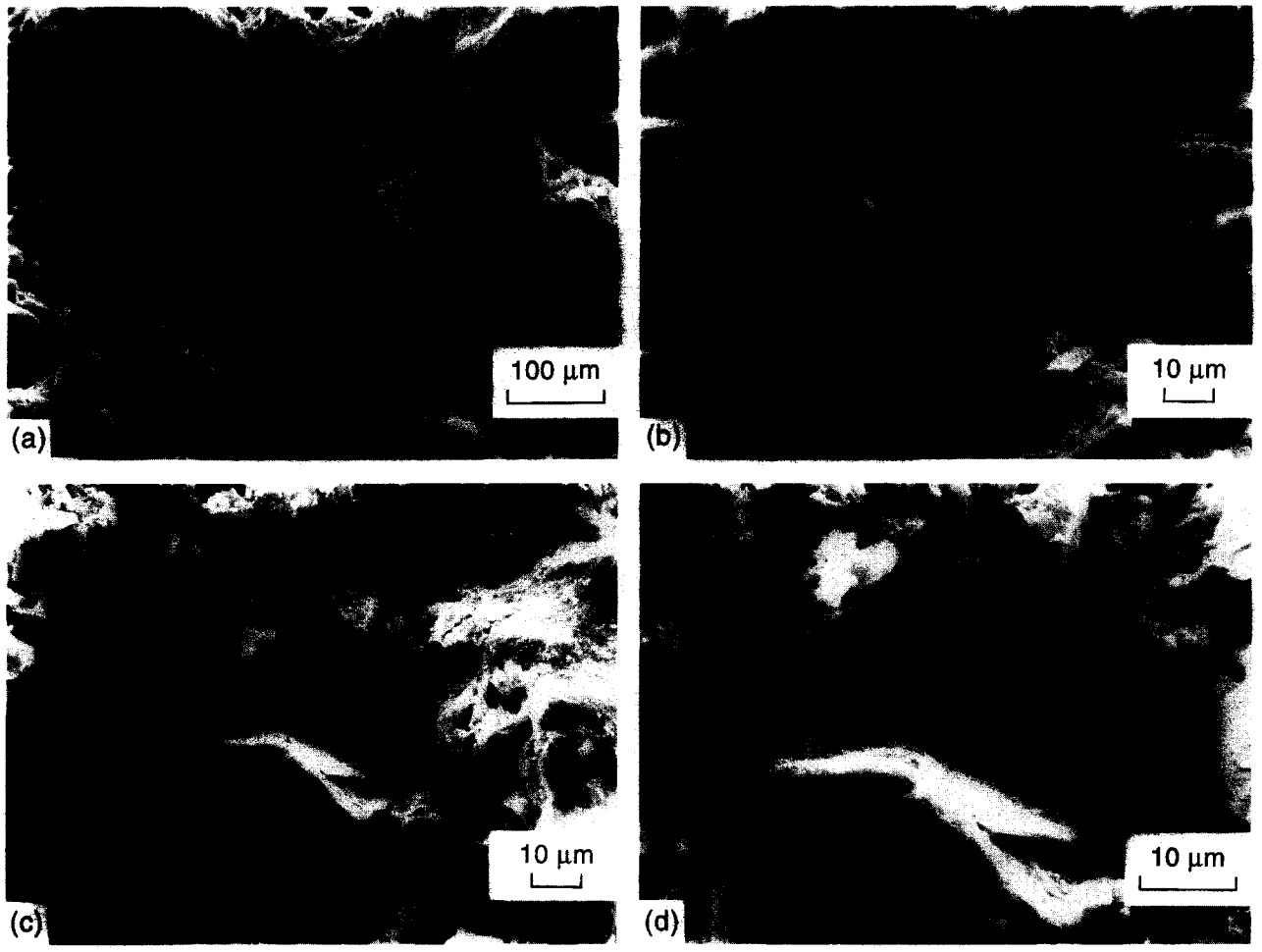


FIG. 6. Clay and fine silt bridges. (a) S-matrix showing skeletal grains, mesovughs and clay-silt bridges. Pedon 2. 4BCkxb horizon. SEM × 200. (b) Detail of (a). SEM × 1000. (c) S-matrix showing skeletal subangular grains and clay-silt bridges. Pedon 2. 3Btb horizon. SEM × 1000. (d) Detail of (c) showing interlocked grains. SEM × 2000.

Landscape evolution

The northwest region of Buenos Aires province presents many complex soil profiles which reflect a succession of sedimentary and pedogenic events in the recent geologic history. At this point in our analysis we assume that each paleopedologic cycle started in a new depositional unit. The ages of the soils or sediments are not known because no direct or indirect dating of the soils has been made and no fossils have been found. However, some possible paleoclimatic conditions can be deduced based mainly on paleontological studies carried out in other parts of the Pampas.

During the Late Pleistocene arid conditions prevailed, which were accompanied by temperatures at least 10°C lower than the present. The Early Holocene was a more humid interval with higher temperatures. The Late Holocene was characterized by a drier climate, but not so severe as that of the Late Pleistocene and without major temperature fluctuations (Tonni and Fidalgo, 1978).

The possible succession of events in the study area can be outlined as follows: the sediments underlying geosol A (depositional unit V) were deposited in dry conditions, possibly similar to those that gave rise to the longitudinal dunes, which form the surface of the original relief. These relationships agree with Fairbridge (1972) who found that during the last Full Glacial (Pleniglacial) immense dune fields were initiated in the foothills of the Argentine Andes that spread northeastwards over Paraguay and Brazil.

Subsequent moist conditions favored the reworking of sediments from the higher parts of the dunes to the depressions forming depositional unit IV. The moist conditions promoted the development of geosol A with a clay-enriched B horizon. Then arid conditions followed which promoted loss of vegetative cover and deflation that caused truncation of the geosol and the subsequent burial of its Bt horizon by unit III. The platy structure found in the top of geosol A appears to be related to the reworking process.

A succession of humid and dry conditions permitted the development of geosol B in unit III of pedon 2. Then widespread erosion exposured the Bt horizon across a large area. In some places a very thin (2–3 mm thick) platy, vesicular crust has been observed overlying the Bt horizon and underlying AC and C horizons. Because these crusts have properties similar to surface crusts or seals (Bresson and Valentine, 1994), they are evidence for exposure of the Bt horizons for a period of time, which were subsequently buried by a unit II. So,

for mapping purposes, the top of geosol B can be used as a stratigraphic marker that indicates a paleosurface. This relationship establishes a correlation of unit III in pedon 2 with unit II of pedon 1.

The different characteristics in pedon 1 and 2 indicate that the history of this paleosurface has been different. In pedon 2 there are two depositional units (I and II) overlying geosol B. In unit II of pedon 2 there is evidence of an incipient paleosol (geosol C) and in some places, this geosol is covered by a tephra layer, 1–2 cm in thickness. The tephra was deposited in 1932 (Larsson, 1937; Imbellone and Camilión, 1988) and serves as a stratigraphic marker bed in the region. This surface horizon of pedon 2 has formed in the eolian sediments (depositional unit I) deposited after the ashfall, mainly during the 1930s and 1940s, a period characterized by frequent droughts. In pedon 1, only one sediment unit is found overlying the Bt horizons, in which the modern A horizon formed.

In the eastern Pampas, Quaternary sequences with several superposed paleosols have been described, but no A horizons have been identified (Teruggi *et al.*, 1974). This is an unresolved issue of paleopedology in Argentina. Teruggi and Imbellone (1987) point out that the systematic truncation of eluvial horizons by wind or water erosion is difficult to explain in all cases. They conclude that in some cases A horizons might have been overlooked due to oxidation of organic matter and overprinting by younger pedogenic processes. However, we deem that the deflation processes in the northwestern region of Buenos Aires province have been more effective in truncating the A horizon of geosol B than in the eastern Pampas. In the western region the climatic fluctuations have been greater (Forte Lay *et al.*, 1989) and the sediments are coarser.

The relief also had an influence on the different development of the soils. In a landscape modeled by wind with dunes and interdunes, a marked pedogenic differentiation has occurred in the low-lying areas. The paleohorizons can be traced in paleocatenas that cut across the longitudinal dunes and interdune areas. Maximum thickness and pedogenic development of horizons occur in interdune depressions; the Bt horizons thin laterally and are not found in the dunes (Fig. 2), where only soils with A–AC–C horizons are found.

CONCLUSIONS

Two well-developed buried paleosols recognized as geosols A and B were studied at two pedon sites. They have argillic horizons but lack eluvial horizons nearly everywhere examined. The pedon profiles are polygenetic and geosol B is superposed on geosol A. This indicates a succession of depositional, erosive and pedogenic processes, which reflect an alternation of dry and humid paleoclimatic conditions. Geosol A and B show variations in soil development along toposequences and are interrupted by younger dunes. The best expressed argillic paleohorizons are found in interdune depressions and they pinch-out in the direction of dune crests.

Geosol A, the deepest paleosol, includes a horizon considered to be fragipan in a general sense, although it does not meet some of the requirements of Soil Taxonomy. The textural and mineralogical nature of the materials, the clay illuviation and calcification processes and, possibly the depositional process, have contributed to the development of the fragipan properties. Micromorphology has been instrumental for the identification of geosols and fragipans. This is the first detailed study relating the presence of buried soils and fragipans in Argentina. However, at the present stage, many aspects are still unknown and need further investigations.

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