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

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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 km². 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 Camitiôn, 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 (Zaráte 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
October 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
marine, Briza ssp., Poa spp., Paspalum dilатatun, Panicum
bergii, Eragrostis ssp., Chloris ssp., and Melica ssp.

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.

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 micromorphological 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 calcrites. 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 volcanioclastic, 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 relics 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
<table>
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<th>Sedimentary unit</th>
<th>Thickness (cm)</th>
<th>Soil Unit</th>
<th>Depth (cm)</th>
<th>Airport profile</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Textural class (SSS, 1993)</th>
<th>Volcanic glass (%)</th>
<th>CaCO₃ (mass %)</th>
<th>Matrix color (dry)</th>
<th>Structure (type, grade)</th>
<th>Pedological Features (textural and amorphous)</th>
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<td></td>
</tr>
<tr>
<td>F</td>
<td>+ 130</td>
<td>5Dtkbb6</td>
<td>960 – 990</td>
<td></td>
<td>51.6</td>
<td>38.3</td>
<td>10.1</td>
<td>clay loam</td>
<td>7.5</td>
<td>7.5</td>
<td>YR 5/4</td>
<td>blocky, strong</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5Ctkbb6</td>
<td>990 – 1090</td>
<td></td>
<td>38.4</td>
<td>48.4</td>
<td>13.2</td>
<td>clay loam</td>
<td>&lt;10</td>
<td>1.8</td>
<td>YR 7/3</td>
<td>blocky, strong</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5Ctkbb6</td>
<td>1090</td>
<td></td>
<td>30.9</td>
<td>51.7</td>
<td>17.4</td>
<td>clay loam</td>
<td>7.5</td>
<td></td>
<td>YR 6/4</td>
<td>blocky, very strong</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Schematic pedostatigraphic column of Airport profile showing soil unit, paleomagnetism, and morphological and micromorphological features.

Depth variation of carbonate morphology: Powdery: S Laminar: H Rizoconcretions P Pseudomycelia: \ Long vertical calcrettes: \ Rounded small nodules: o

Crotovine: C Magnetic polarity: Chron Brunhes [ Chron Matuyama Bidegain (personal communication).

# Riggi et al. (1986). *The slickenside is assigned to a b-fabric feature (p. 90, 92) as well as to a pedological feature (p.132), Bullock et al. (1985).
<table>
<thead>
<tr>
<th>Sedimentary Unit</th>
<th>Thickness (cm)</th>
<th>Soil Unit</th>
<th>Depth (cm)</th>
<th>Hernández Profile</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Textural class (SSS, 1993)</th>
<th>Volcanic glass (%)</th>
<th>CaCO₃ (mass %)</th>
<th>Matrix color (dry)</th>
<th>Structure (type, grade)</th>
<th>Pedological features (textural and amorphous)</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>88</td>
<td>Ap</td>
<td>0 – 17</td>
<td></td>
<td>10</td>
<td>33</td>
<td>57</td>
<td>clay</td>
<td>&lt;10</td>
<td>7.5 YR 5/2</td>
<td>blocky, moderate</td>
<td>abundant hypocoatings with porostriated b-fabric*, few clay coatings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17 – 43</td>
<td>Bt1</td>
<td>0 – 17</td>
<td></td>
<td>8</td>
<td>33</td>
<td>39</td>
<td>clay</td>
<td>12</td>
<td>7.5 YR 5/2</td>
<td>blocky, strong</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>43 – 77</td>
<td>Bt2</td>
<td>0 – 17</td>
<td></td>
<td>10</td>
<td>34</td>
<td>56</td>
<td>clay</td>
<td>7.5 YR 5/4</td>
<td>blocky, strong</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>77 – 88</td>
<td>Bck</td>
<td>0 – 17</td>
<td></td>
<td>12</td>
<td>36</td>
<td>52</td>
<td>clay</td>
<td>7.5 YR 5/4</td>
<td>blocky</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>107</td>
<td>Bt1kb2</td>
<td>88 – 140</td>
<td></td>
<td>10</td>
<td>44</td>
<td>46</td>
<td>silty clay</td>
<td>&lt;10</td>
<td>7.5 YR 6/4</td>
<td>blocky, moderate</td>
<td>abundant hypocoatings with porostriated b-fabric, few clay coatings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>140 – 195</td>
<td>Bt2kb2</td>
<td>88 – 140</td>
<td></td>
<td>14</td>
<td>54</td>
<td>42</td>
<td>silty clay</td>
<td>7.5 YR 7/4</td>
<td>blocky, moderate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>205</td>
<td>Btkb3</td>
<td>195 – 255</td>
<td></td>
<td>14</td>
<td>40</td>
<td>46</td>
<td>silty clay</td>
<td>&lt;10</td>
<td>10 YR 7/3</td>
<td>blocky, moderate</td>
<td>abundant hypocoatings with porostriated b-fabric, few clay coatings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>255 – 310</td>
<td>Bck3</td>
<td>195 – 255</td>
<td></td>
<td>14</td>
<td>42</td>
<td>44</td>
<td>silty clay</td>
<td>7.5 YR 7/4</td>
<td>blocky</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 – 360</td>
<td>2Bt1kb4</td>
<td>310 – 360</td>
<td></td>
<td>48</td>
<td>39</td>
<td>13</td>
<td>clay</td>
<td>5</td>
<td>2.5 Y 5/4</td>
<td>blocky, moderate</td>
<td>abundant hypocoatings with porostriated b-fabric, fairly common clay coatings and abundant typic and impregnative nodules</td>
<td></td>
</tr>
<tr>
<td></td>
<td>360 – 400</td>
<td>2Bt2kb4</td>
<td>310 – 360</td>
<td></td>
<td>28</td>
<td>50</td>
<td>20</td>
<td>clay loam</td>
<td>20 – 30</td>
<td>2.5 Y 7/3</td>
<td>blocky, weak</td>
<td></td>
<td></td>
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<td></td>
<td>400 – 450</td>
<td>3Bt1kb5</td>
<td>400 – 450</td>
<td></td>
<td>16</td>
<td>52</td>
<td>32</td>
<td>silty clay loam</td>
<td>&lt;10</td>
<td>2.5 Y 7/3</td>
<td>blocky, strong</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 – 600</td>
<td>3Bt2kb5</td>
<td>450 – 500</td>
<td></td>
<td>42</td>
<td>40</td>
<td>18</td>
<td>silty clay</td>
<td>&lt;10</td>
<td>2.5 Y 6/3</td>
<td>blocky, strong</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>600 – 640</td>
<td>3Bt1kb6</td>
<td>500 – 600</td>
<td></td>
<td>32</td>
<td>46</td>
<td>22</td>
<td>clay loam</td>
<td>&lt;10</td>
<td>7.5 YR 6/4</td>
<td>blocky, strong</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>640 – 685</td>
<td>3Bt2kb6</td>
<td>600 – 640</td>
<td></td>
<td>40</td>
<td>46</td>
<td>14</td>
<td>silty clay</td>
<td>7.5 YR 7/3</td>
<td>blocky, strong</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>685 – 750</td>
<td>4Btkb7</td>
<td>640 – 685</td>
<td></td>
<td>48</td>
<td>38</td>
<td>14</td>
<td>clay</td>
<td>5</td>
<td>5 YR 4/3</td>
<td>blocky, strong</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>750</td>
<td>4Btkb7</td>
<td>685 – 750</td>
<td></td>
<td>54</td>
<td>32</td>
<td>14</td>
<td>clay</td>
<td>10 – 20</td>
<td>5 YR 4.5/4</td>
<td>blocky, strong</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>+110</td>
<td>4Btkb7</td>
<td>750 – 860</td>
<td></td>
<td>56</td>
<td>32</td>
<td>12</td>
<td>clay</td>
<td>5</td>
<td>5 YR 5/4</td>
<td>blocky, moderate</td>
<td>abundant clay and amorphous coatings, abundant typic and impregnative nodules</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Schematic pedostratigraphic column of Hernández profile showing soil unit, paleomagnetism, and morphological and micromorphological features.

Depth variation of carbonate morphology: Powdery: 🌾 Laminar: 🌾 Rizocretions 🌾 Pseudomyelia: 🌾 Long vertical calcrites: 🌾 Rounded small nodules: 🌾

Crotovine: 🌾 Magnetic polarity: Chron Brunhes 🌾 Chron Matuyama 🌾 Tonni et al. (1999)

# Riggi et al. (1986). *The slickenside is assigned to a b-fabric feature (p. 90, 92) as well as to a pedological feature (p. 132), Bullock et al. (1985).
<table>
<thead>
<tr>
<th>Sedimentary unit</th>
<th>Thickness (cm)</th>
<th>Soil Unit</th>
<th>Depth (cm)</th>
<th>San Pedro profile</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Textural class (SSS, 1993)</th>
<th>Volcanic glass (%)</th>
<th>Color matrix (dry)</th>
<th>Structure (type, degree)</th>
<th>Pedological features (textural and amorphous)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>205</td>
<td>Ap</td>
<td>0 – 25</td>
<td></td>
<td>26.9</td>
<td>59.3</td>
<td>13.1</td>
<td>silt loam</td>
<td>22.6</td>
<td>57.6</td>
<td>19.9</td>
<td>7.5 YR 5/2</td>
</tr>
<tr>
<td>B</td>
<td>95</td>
<td>2C3kb2</td>
<td>205 – 245</td>
<td></td>
<td>11.5</td>
<td>52.9</td>
<td>33.5</td>
<td>silt loam</td>
<td>24.8</td>
<td>47.6</td>
<td>27.5</td>
<td>7.5 YR 7/4</td>
</tr>
<tr>
<td>C</td>
<td>62</td>
<td>3Btkb3</td>
<td>300 – 362</td>
<td></td>
<td>27.8</td>
<td>51.5</td>
<td>20.7</td>
<td>silt loam</td>
<td>9.03</td>
<td>42.1</td>
<td>48.8</td>
<td>2.5 Y 7/3</td>
</tr>
<tr>
<td>D</td>
<td>75</td>
<td>4C5gkb4</td>
<td>362 – 437</td>
<td></td>
<td>9.03</td>
<td>42.1</td>
<td>48.8</td>
<td>loam</td>
<td>14.3</td>
<td>50.1</td>
<td>35.5</td>
<td>2.5 Y 6/3</td>
</tr>
<tr>
<td>E</td>
<td>300</td>
<td>5C6gkb5</td>
<td>437 – 587</td>
<td></td>
<td>24.1</td>
<td>38.4</td>
<td>37.6</td>
<td>loam</td>
<td>17.9</td>
<td>60.7</td>
<td>24.6</td>
<td>7.5 YR 6/4</td>
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<td>F</td>
<td>153</td>
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<td>737 – 810</td>
<td></td>
<td>13.8</td>
<td>80.1</td>
<td>6.06</td>
<td>silt loam</td>
<td>28.6</td>
<td>58.1</td>
<td>12.3</td>
<td>5 YR 4/3</td>
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<tr>
<td>G</td>
<td>160</td>
<td>7Bt1gkb7</td>
<td>890 – 960</td>
<td></td>
<td>28.6</td>
<td>58.1</td>
<td>12.3</td>
<td>silt clay loam</td>
<td>28.6</td>
<td>58.1</td>
<td>12.3</td>
<td>5 YR 4/5/4</td>
</tr>
</tbody>
</table>

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:  
Rizocorretions  
Pseudomycelia:  
Rounded small nodules:  

Crotovine:  
Magnetic Polarity:  
Chron Brunes  
Nabel (1993)  
Riggi et al. (1986)
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
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 litoral 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
Micromorphology of paleosols at the continental border of the Buenos Aires province, Argentina

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, which 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 hypococatings 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,
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).

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

The authors are very grateful to Ing. Jorge Giménez for her constructive comments.

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