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Identification and differentiation of Pleistocene paleosols in the northern Pampas of Buenos Aires, Argentina

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Abstract

A combined macromorphological and micromorphological approach was used to identify and differentiate paleosols at a representative exposure of the Pleistocene sedimentary succession in the northern Pampas of Buenos Aires (La Plata area). Five pedological units (Pu), which apparently represent four discrete paleosols plus the surface soil, were initially differentiated on the basis of field-scale morphological properties. The succession was divided into B and C horizon with an A horizon only clearly identified in the surface soil and a weak A horizon at depth. Micromorphology suggests a complex pedosedimentary history of welding, with some degree of water reworking indicated by fragments of sorted layers and the significant grain-size heterogeneity of the parent material. The micromorphological data do not support the field differentiation of Pu4, Pu3, and Pu2 into discrete paleosols. Pedological features (i.e. excrements, secondary carbonate coatings, illuvial clay coatings) occur throughout without any obvious breaks or patterns. Pu4, Pu3, and Pu2 are therefore interpreted as an accretionary and/or welded pedocomplex. The Gorina section does not conform to the simple classical model proposed by other authors in the region of alternating loess and paleosol units associated with arid (loess deposition) and wet (soil formation) intervals, respectively. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Paleosol; Micromorphology; Pleistocene; Pampas, Argentina

Resumen

En una sucesión sedimentaria representativa del Pleistoceno del norte de la Pampa bonaerense (área de la Plata) se utilizó una escala combinada de macromorfología y micromorfología para identificar paleosuelos. En el campo, los paleosuelos se reconocieron a partir de propiedades morfológicas diferenciándose 5 unidades pedológicas, aparentemente representando 4 paleosuelos separados y el suelo actual. Se reconocieron principalmente horizontes B y C, sólo un horizonte A en el suelo actual y un débil horizonte A en profundidad. La información micromorfológica sugiere una compleja secuencia pedosedimentaria de superposición pedogenética con cierto retrabajamiento ácueo, documentado por fragmentos de niveles seleccionados, y heterogeneidad del tamaño de partícula del material parental. Los datos micromorfológicos no avalan la diferenciación de campo de Pu4, Pu3 y Pu2 en paleosuelos separados. Los rasgos pedológicos (excrementos, recubrimientos carbonáticos secundarios, recubrimientos de arcilla iluvial) aparecen a través de la sucesión sin exhibir patrones o cambios obvios que corroboren esa diferenciación. El paquete de Pu4, Pu3 y Pu2 es interpretado como un pedocomplejo acrecional y/o soldado (superpuesto). Así, la resolución de la sección de Gorina como un indicador del modelo clásico de intervalos áridos (depositación de loess) y húmedos (formación de suelos) propuesto por otros autores no es avalado por este estudio. © 2002 Elsevier Science Ltd. All rights reserved.

Palabras clave: Palesuelo; Micromorfiologia; Pleistoceno; Pampas, Argentina

1. Introduction

Kemp and Zárate (2000) followed a micromorphologically based approach to study a Pliocene loess–paleosol sequence in Mar del Plata in the southern part of the Buenos Aires province of Argentina (Fig. 1) and were able to reconstruct the sequence of pedogenic and sedimentary (pedosedimentary) processes responsible for the evolution of the regional landscape during a specified time. They concluded that the balance between sedimentation and pedogenesis varied cyclically; phases of limited deposition and the establishment of relatively stable land surfaces were marked by the development of argillic soil profiles with clearly defined eluvial and illuvial horizons. Intervening periods of more rapid accumulation of coarser material were

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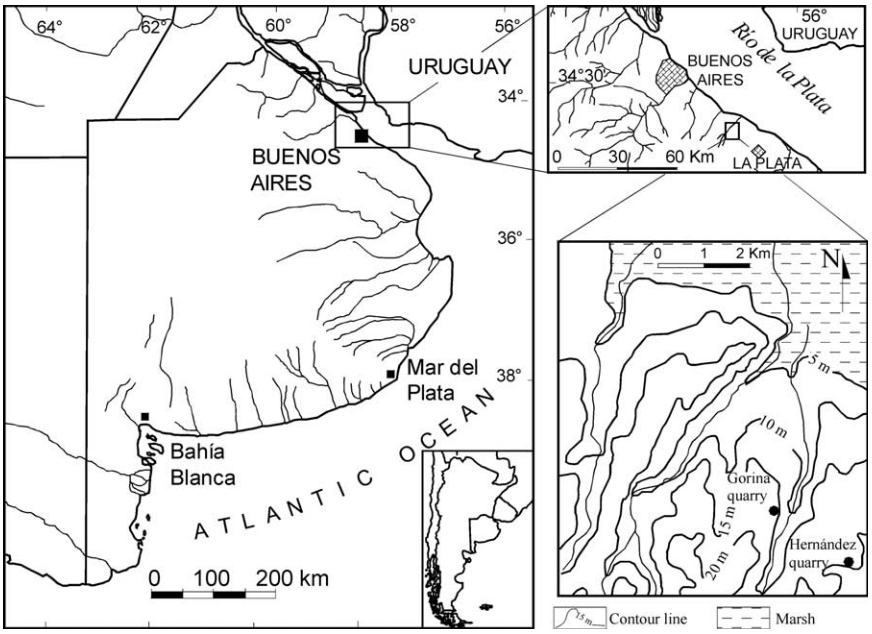

Fig. 1. Map showing location of Gorina.

characterized by accretionary soil development and welding of the new pedological features on preexisting soils as the surface accreted. The study illustrated the general difficulties in recognizing and identifying paleosol horizons in the late Cenozoic record of the Pampean region, particularly where sedimentation is semi-continuous or loess units are insufficiently thick to separate successive paleosol profiles. Further complications may eventuate if textural differences between alternating units primarily reflect cyclical changes in the size of particles deposited rather than the effects of pedogenic translocation processes (Kemp and Zárate, 2000).

The Pleistocene loess deposits surrounding Buenos Aires and La Plata (Fig. 1) have been the subject of detailed investigations over more than a century. Some of the pioneering contributions to the study of the paleontology and geology of Pampean sediments originated from this type area, where the key stratigraphic units were first defined and characterized (e.g. Ameghino, 1880; Frenguelli, 1957). More recently, the general understanding of the succession has benefited from various specialized studies dealing with its stratigraphy and sedimentology (Riggi et al., 1986), paleopedology (Teruggi and Imbellone, 1987), paleomagnetism (Bidegain, 1991, 1998), and paleontology (Tonni et al., 1999).

Orgeira et al. (1998) and Tonni et al. (1999) used field characteristics to differentiate between paleosol and loess units in the succession and suggested that the loess was deposited under semiarid to arid conditions and the paleosols developed during wetter periods. Although noting that the paleosols vary laterally in terms of thickness, fabric, and horizonation, Tonni et al. (1999) did not describe any of the diagnostic pedological horizons concerned. However, they inferred that paleosol levels are restricted to clay-rich zones with prismatic or blocky structures that contain illuviation (clay coatings), redoximorphic (ferrimanganiferous nodules), and bioturbation features. Other authors, including Riggi et al. (1986) and Orgeira et al. (1998), also differentiated paleosols in Pampean sections on the basis of macromorphological features (structure, bioturbation, textural and color changes). Teruggi and Imbellone (1987) previously identified paleosols around La Plata on the basis of both field and micromorphological features, classifying them as Argiudolls that comprised B (Bt, Btk) horizons. They proposed a polygenetic origin, however, that involved the welding of subjacent paleosols through only shallow thicknesses of intervening sediments. The apparent absence of A or E horizons was attributed to erosion, though they introduced the possibility that these horizons might simply be unrecognizable due to the effects of masking by later episodes of pedogenesis.

Similar issues related to the identification and differentiation of paleosols within loess successions have been highlighted from other parts of the world, including China (e.g. Kemp and Derbyshire, 1998) and the United States (e.g. McDonald and Busacca, 1990). Some of the problems have been successfully addressed by utilizing the micromorphologically based pedosedimentary approach followed by Kemp and Zárate (2000) at Mar del Plata (e.g. Kemp et al., 1994, 1997, 1998). The aim of this paper is to build on the lessons learned from these other projects and the micromorphological study of the Pliocene sequence in Mar del Plata, as well as to apply a similar approach to a typical exposure of the Pleistocene succession in La Plata. It is anticipated that this will provide important insights into the recognition, interpretation, and significance of Pleistocene paleosols in this key region of the Pampas.

Table 1
Pleistocene/Holocene stratigraphy in the area of La Plata

Geochronological unit	Paleomagnetic age Bobbio et al. (1986)	La Plata Riggi et al. (1986)	Hernández Tonni et al. (1999)	Gorina Bidegain (1998)
Holocene to late Pleistocene	Brunhes <30–40 ka	*Buenos aires formation*	*Buenos Aires formation*	*La Postrera formation*
Late to middle Pleistocene	Brunhes		*Buenos Aires formation* *Ensenada formation*	*Buenos aires formation*
Middle to early Pleistocene	Matuyama	*Ensenada formation*	*Ensenada formation*	*Ensenada formation*

2. Geological and stratigraphic setting

The section studied is along the southwestern wall of a 20-m-deep quarry at Gorina (34°54′08″S; 58°01′56″W), 10 km northwest of La Plata (Fig. 1). The original quarry surface is about 17 m above sea level on the upper slope of a wide, low-relief valley, deeply modified by urbanization, that drains to the Rio de la Plata. Whereas, Argiudolls dominate the regional soil cover, vertisols are locally prevalent at Gorina (Instituto de Geomorfología y Suelos, 1992). According to Bidegain (1998), the succession is composed of three lithostratigraphic units (Table 1) that span many loess–paleosol couplets. The lowermost Ensenada Formation is overlain by the Buenos Aires Formation, both of which were formally defined in the area by Riggi et al. (1986). The Brunhes/Matuyama boundary was recorded about 10 m below the surface in this section (Bidegain, personal communication) and taken to mark the upper boundary of the Ensenada Formation (Bidegain, 1998). At the Hernández quarry, 2 km away from Gorina (Fig. 1), the Brunhes/Matuyama boundary was placed within the uppermost part of the Ensenada Formation and correlated with other localities in northern Buenos Aires that show a similar pattern (Tonni et al., 1999). The uppermost 3 m of the exposure at Gorina, including the present soil, was correlated by Bidegain (1998) with the La Postrera Formation (Fidalgo et al., 1973) of Late Pleistocene–Holocene age (Table 1).

3. Methods

The upper 11 m of the section of the Gorina quarry, mostly included within the Brunhes chron (0–10 m) and the youngest part of the Matuyama chron (10–11.3 m), was logged and sampled at approximately 25-cm intervals. Paleosols were identified and differentiated on the basis of morphological properties (i.e. color, texture, structure, consistency, boundaries) following the approach applied by other authors in the region (Riggi et al., 1986; Orgeira et al., 1998; Tonni et al., 1999).

Forty undisturbed blocks collected within Kubiena tins (7 cm × 5 cm × 4 cm) were air dried, impregnated with polyester resin, and made into mammoth thin sections (7 cm × 5 cm), according to the procedures of Lee and Kemp (1992). Thin sections were described at 10–400 × magnification under a petrological microscope, following the terminology of Bullock et al. (1985), with the estimated proportions of key micromorphological features recorded in the form of a depth function.

4. Results

4.1. Macromorphology

Five pedological units (Pu), apparently representing four discrete paleosols plus the surface soil, were differentiated on the basis of recognized horizon sequences and lateral traceability across the quarry, then numbered from top to bottom (Pu1, Pu2, Pu3, Pu4, and Pu5) (Fig. 2). Following the stratigraphic interpretation of Bidegain (1998), Pu5 developed in the uppermost portion of the Ensenada Formation; Pu2, Pu3, and Pu4 are included in the Buenos Aires Formation; and Pu1 is in the La Postrera Formation.

At a field scale, the sequence is divided mostly into B and C horizons (Table 2, Fig. 3). A true A horizon was only identified in the surface soil (Fig. 3a), though a weak A horizon was designated at 7.50–8.00 m on the basis of its bioturbation features, texture, and relationship with the underlying B horizon. The main diagnostic features of the B horizons are generally darker colors (10YR 4/6, 5/4), clayey textures, clay coatings on ped surfaces, bioturbation structures, and moderately to well-developed blocky and prismatic structures (Fig. 3c). C horizons form massive and light-colored layers (10YR 6/4, 6/6) (Fig. 3a, b and d). Carbonate nodules and redoximorphic features occur in both B and A horizons (Table 2, Fig. 3c and d).

The lower and upper boundaries of Pu5, between 10 and 12 m, are sharp and horizontal in the logged section; 2–3-m-wide paleochannels are traced at the lower contact elsewhere in the quarry (Fig. 3b). The Pu4/Pu5 boundary coincides with the position of the Brunhes/Matuyama boundary (Bidegain, personal communication). The Bt horizon is darker than the overlying and underlying horizons and has clay coatings on the surfaces of its well-developed blocky aggregates. It grades downward into transitional horizons (BC, BCk) characterized by common invertebrate bioturbations and mottles, few Mn coatings, and decoloration haloes along the root traces. Carbonate content increases progressively from top to bottom of the unit. Fine carbonate concentrations occur along the root channels

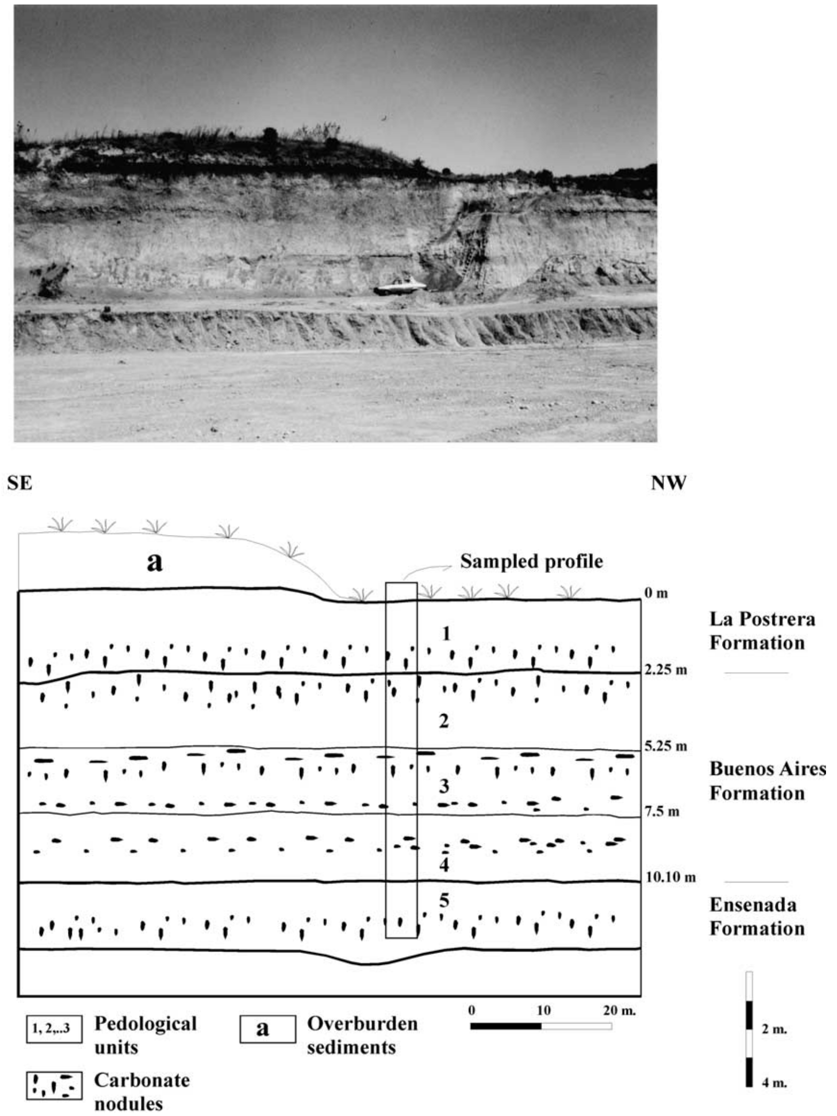

Fig. 2. Stratigraphic log of the SW wall of the Gorina quarry and panoramic view of the section.

in the lower part of the BC horizon, and medium rounded carbonate nodules are common in the BCk horizon.

Pu4 has a transitional upper boundary and comprises A, Bt, BC, and Ck horizons extending from 7.5 to ca. 10 m. The A horizon is massive, of relatively coarser texture than the underlying Bt horizon, and has common root traces. It grades into a Btk with a few discontinuous clay coatings, frequent ferrimanganiferous mottles or nodules, and diffuse concentrations of carbonates. Through a transitional horizon (BCk), it passes into an indurated layered Ck1 horizon and then into a more friable Ck2, both of which include many invertebrate bioturbation structures, root traces, and abundant fine carbonate nodules. The lowermost part of Ck2 contains diffuse and discontinuous horizontal bedding structures, which suggests that this material was partially reworked by water when at the surface.

There are several stratigraphically superposed Bt horizons between ca. 2.2 and 7.5 m, differentiated according to the changes in the relative abundance of clay coatings, ferrimanganiferous concentrations, and carbonate nodules. Two pedological units (Pu2 and Pu3) are separated on the basis of the sharp upper boundary of the Btkg horizon at approximately 5.2 m (Fig. 2). This horizon protrudes in vertical exposure as a massive layer with fine, discontinuous horizontal fractures. Carbonate nodules are common here and form 5- to 10-cm-long platy concentrations, though they are absent in the underlying Bt1 and Bt2 horizons. Medium, rounded carbonate nodules, however, are present in the lowermost Btk horizon. Ferrimanganiferous nodules and mottles occur throughout but become less common with depth. Pu2 consists of a 2.2 m sequence of Bt horizons separated by gradual to diffuse boundaries. Redoximorphic features (ferrimanganiferous nodules and mottles) are common below 4.25 m (Btg horizon), whereas, the upper 1.3 m is dominated by rounded and elongated carbonate nodules of 2–3 cm diameter.

Table 2
Main macromorphological features of the pedological units

Pedological unit (Pu)	Depth (*m*)	Pedological horizon	Color	Texture	Structure	Main morphological features
Pu1	0 0.30	A	10YR3/2, very dark grayish brown	clS	B	Common bioturbations; common roots; many very fine to fine macropores
	0.60	Bt1	10YR 3/4, dark yellowish brown	sCl	P	Continuous clay coatings; common roots
	0.90	Bt2	10YR 4/6, dark yellowish brown	sCl	P	Continuous clay coatings; common roots
	1.20	BC	10YR 4/6,dark yellowish brown	sCl	P	Discontinuous clay coatings; few calcareous nodules (<0.5 cm); common roots and channels
	1.60	Ck1	10YR 6/6, brownish yellow	clS	M/B	Common very fine to fine macropores and channels; few roots; common calcareous nodules
	2.20	Ck2	10YR 4/6,dark yellowish brown	clS	M/B	Few Fe mottles; few Fe–Mn nodules; calcareous to very calcareous matrix; common calcareous nodules
Pu2	2.90	Btk1b	10YR 5/4, yellowish brown	clS	B	Discontinuous clay coatings; common Fe mottles; common calcareous nodules
	3.10	Btk2b	10YR 5/3,brown	clS	P/B	Less development than horizons above and below; common Fe mottles; common calcareous nodules
	3.35	Btk3b	10YR 5/4, yellowish brown	clS	P/B	Clay coatings; common Fe mottles, common Fe/Mn nodules; many calcareous nodules; very slightly calcareous matrix
	3.60	Btkgb	10YR 5/3,brown	sCl	P/B	Many Fe mottles; common calcareous nodules
	4.20	Btkb	10YR 5/34, yellowish brown	clS	P/B	Discontinuous clay coatings; common Fe mottles; clay coatings along channels
	5.25	Btgb	10YR 5/4, yellowish brown	clS	P/B	Continuous clay coatings; many Fe mottles; common pedotubules; few to common macropores and channels; few calcareous rhizoconcretions
Pu3	5.90	Btkgb	10YR 5/4, light yellowish brown	clS	P/B	Many Fe mottles; very common macropores and clay coatings along channels; many calcareous nodules
	6.30	Bt1b	10YR 5/4, yellowish brown	clS	P/B	Discontinuous clay coatings, common Fe mottles; common macropores and channels with clay coatings
	6.90	Bt2b	10YR 5/4, yellowish brown	clS	P/B	Discontinuous clay coatings; common Fe mottles; clay coatings along channels
	7.50	Btkb	10YR 5/4, yellowish brown	clS	P/B	Discontinuous clay coatings; common Fe mottles and channels with clay coatings; common calcareous nodules
Pu4	8.00	Ab	10YR 5/6, yellowish brown	S	M	Common calcareous nodules; common Fe mottles; matrix: slightly calcareous; common channels with clay coatings

(*continued on next page*)

Table 2 (*continued*)

Pedological unit (Pu)	Depth (*m*)	Pedological horizon	Color	Texture	Structure	Main morphological features
	8.50	Btb	10YR 6/4, light yellowish brown	saS	B	Discontinuous clay coatings; common Fe mottles; few calcareous nodules, few calcareous rhizoconcretions; very slightly calcareous matrix; abundant macropores and channels with clay coatings
	9.00	BC	10YR 6/4, light yellowish brown	saS/sSa	B	Common Fe mottles; few calcareous nodules
	9.90	Ck1	10YR 6/4, light yellowish brown	saS/sSa	M/B	Common Fe mottles; common calcareous nodules; many macropores and channels; stratified indurated horizon
	10.10	Ck2	10YR 6/4, light yellowish brown	saS/sSa	M/B	Few Fe mottles; many macropores and common channels; common calcareous nodules; more friable than Ck1
Pu5	10.35	Bt	10YR 5/4, yellowish brown	saS	B	Clay coatings; common Fe mottles; few calcareous nodules
	11.00	BC	10YR 5/4, yellowish brown	saS	M/B	Discontinuous clay coatings; common Fe mottles; few calcareous nodules; decoloration haloes; common macropores and channels
	11.30 +	BCk	10YR 6/4, light yellowish brown	saS	M/B	Common calcareous nodules; calcareous to very calcareous matrix

Depth (DEP); Texture: saS = sandy silt, sCl = silty clay, sSa = silty sand, clS = clayey silt, and S = silt. Structure: M = massive, B = Blocky, and P = prismatic

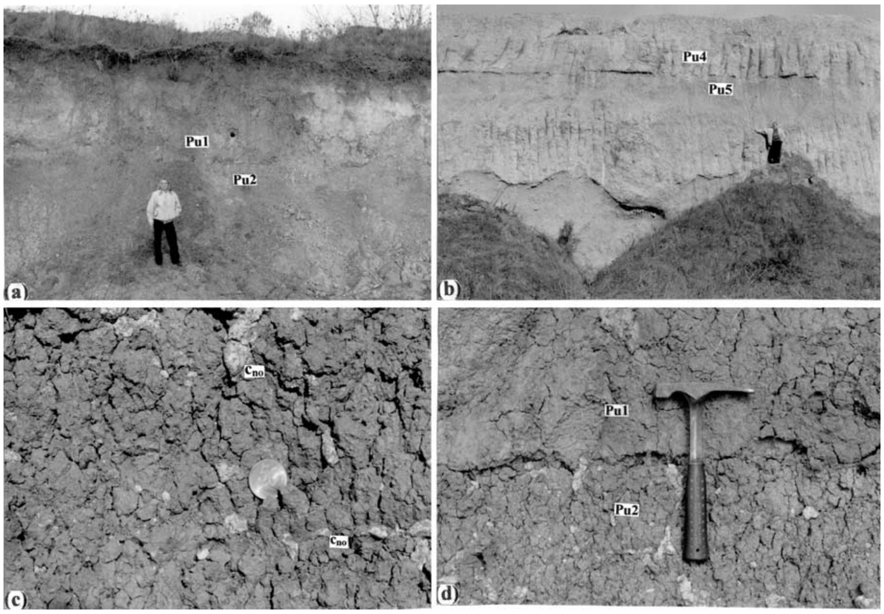

Fig. 3. Macromorphological features of the studied section. (a) Pu1/Pu2 boundary; (b) Pu4/Pu5 boundary; (c) Close up of a Btk horizon (Pu2) with blocky structure and carbonate nodules (cno), coin: 2.2 cm; and (d) Pu1/Pu2 boundary between Ck2 and Btk horizons.

The surface soil (Pu1), classified as an Hapludert (Instituto de Geomorfología y Suelos, 1992), consists of an A horizon (mollic epipedon) overlying a.70-m-thick Bt horizon that grades downward through a transitional horizon (BC) into the Ck horizons. Large, discrete carbonate nodules, up to 4 cm in diameter, are present in Ck1; the lower Ck2 has diffuse carbonate accumulations around the root traces. A discontinuous series of fine, horizontal stratified lenses and the abrupt and horizontal to slightly irregular lower contact suggest an erosional boundary between Pu1 and Pu2 (Fig. 3a and d).

4.2. Micromorphology

Key micromorphological characteristics and features of the profile are illustrated in Figs. 4 and 5, and semi-quantitative estimates of their abundances are recorded in Fig. 6. The ratios of coarse to fine material (c:f), which provide a micromorphological record of textural variations down the section, show that the grain size of the parent material is not uniform with the coarser ratios that dominate in Pu4 and the lower section of Pu1, mainly intermediate ratios in Pu2, and fine ratios in Pu5 and the middle portion of Pu3. Moderately impregnated segregations and nodules of Fe and Mn oxides (and/or oxyhydroxides), reflective of fluctuations in redox potential associated with periodic water saturation, occur in small quantities throughout the sequence (Fig. 4a), though they are generally more prevalent in horizons (often assigned a ‘g’ suffix), where distinct mottles are noted in the field descriptions. Discrepancies, however, occur between the field and micromorphological data and presumably are a function of the size of features and differences in scales of observations. Thus, though the three main zones of secondary carbonate accumulation ([i] bottom of Pu1 and top of Pu2, [ii] most of Pu4, and [iii] the bottom of Pu5) are clearly demarcated in the depth distribution of calcitic nodules and coatings (Fig. 4b), thin sections from other calcic horizons identified in the field do not contain secondary carbonate features, because large nodules were not sampled within the relatively small blocks collected for micromorphological analysis.

Excremental fabrics, reflective of faunal turbation processes, are not confined to the surface A horizon. They occur throughout the sequence, particularly in the Ck horizons of Pu1, the Bt horizons of Pu2 and Pu3, the A and BC horizons of Pu4, and the BC horizons of Pu5 (Fig. 4c). Non- or weakly bioturbated fabrics are very rare and restricted to only a few levels (Fig. 4d). Illuvial clay also does not display a classical depth distribution; some Bt horizons have rare (Pu1, Pu5) or even no (Btk1, Pu2) clay coatings in thin sections, whereas greater amounts occur in the A and BC horizons than in the Bt horizon of Pu4.

Many micromorphological features display clear micro-stratigraphic relationships with one another, which thus enables the order of events to be reconstructed. For example, secondary carbonate features often engulf and therefore postdate clay coatings (e.g. in Btk horizons of Pu2), which indicates a pedosedimentary sequence of welding involving clay translocation, sediment accretion and build up of land surface, and leaching of new surface horizons and precipitation of secondary carbonate in the previously formed Bt horizons. Clay coatings around excremental aggregates (e.g. in the Btg of Pu2) (Fig. 5a) provide further evidence for complex pedosedimentary development, with transformation of A horizons into Bt horizons as surfaces become progressively buried to greater

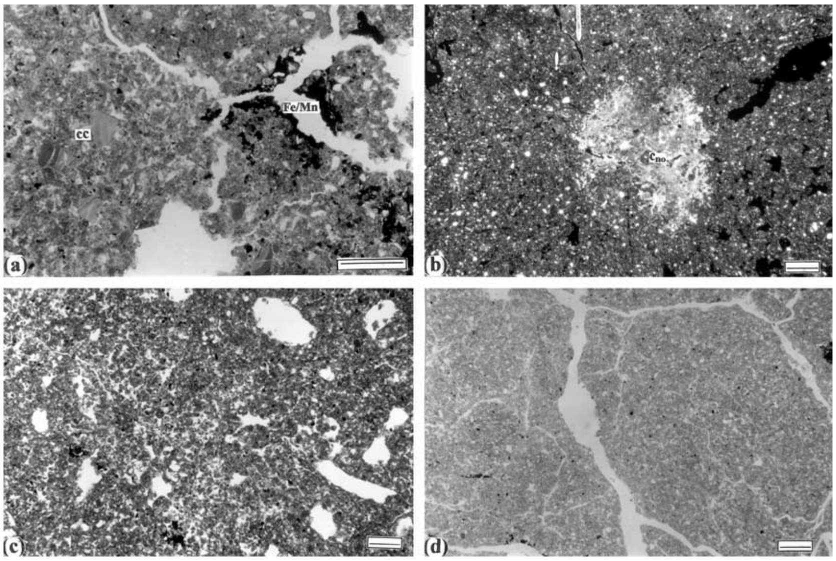

Fig. 4. Photomicrographs of key micromorphological features from Gorina. Plane polarised light. (a) Fragmented clay coating (cc) embedded in groundmass (centre) plus Fe/Mn concentrations (Fe/Mn) (A horizon, Pu4); (b) irregular calcitic nodule (c_{no}) (BC horizon, Pu5); (c) bioturbated (excremental) fabric (BCk, Pu5; and (d) nonbioturbated fabric (Btk horizon, Pu2). Scale bar 500 μm.

depths within the solum. The relationships, however, are not simple, as there are examples (e.g. Bt horizons of Pu3) in which the clay coatings are disrupted and incorporated in the excrements.

At the base of Pu4, and to a limited extent in the Bt1 horizon of Pu1, are concentrations of rounded aggregates that contain deformed clay coatings and have textures different from the adjacent groundmass (Fig. 5b). In places, these aggregates are themselves coated by illuvial clay (Fig. 5c). Interpreted as fluvial rip-up clasts, they indicate that the soil was eroded and then redeposited as parent material for a subsequent phase of pedogenesis. Supporting evidence for some degree of water reworking of these loess sediments is provided by the ubiquitous fragments of sorted layers that compose thin subhorizontal layers of different c:f ratios (Fig. 5d).

5. Discussion

The micromorphological data provide important insights into the pedosedimentary development of the Gorina sequence, such that its initial field differentiation into discrete pedological (paleosol) units needs to be reevaluated. Although

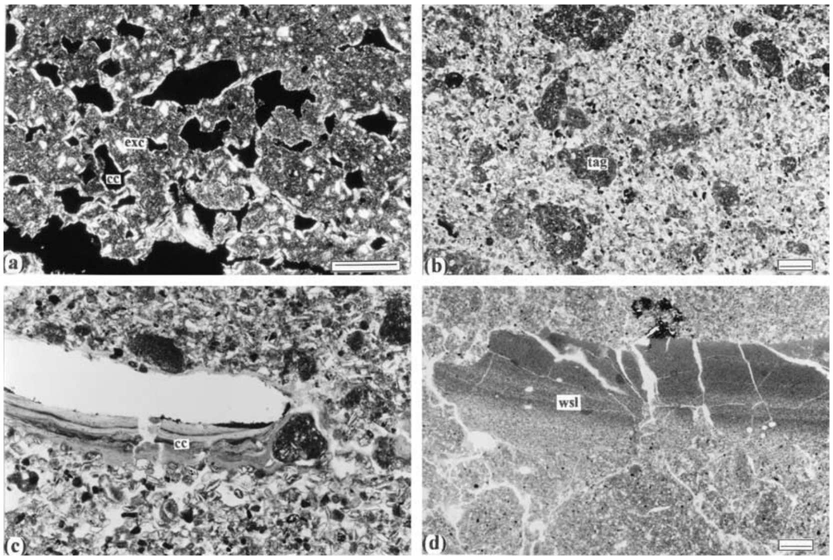

Fig. 5. Photomicrographs of key micromorphological features from Gorina. All plane polarised light except (a), which is cross-polarised light. (a) Clay coating (cc) (postdating) around excrements (exc) (Bt horizon, Pu4); (b) incorporated transported aggregates (tag) (Ck2 horizon, Pu4); (c) clay coating (cc) around a channel cutting through groundmass containing transported aggregates (Ck1 horizon, Pu4); and (d) water-sorted layer (wsl) postdated by clay coating around a channel (bottom left-hand corner) (Btg horizon, Pu2). Scale bar 500 μm.

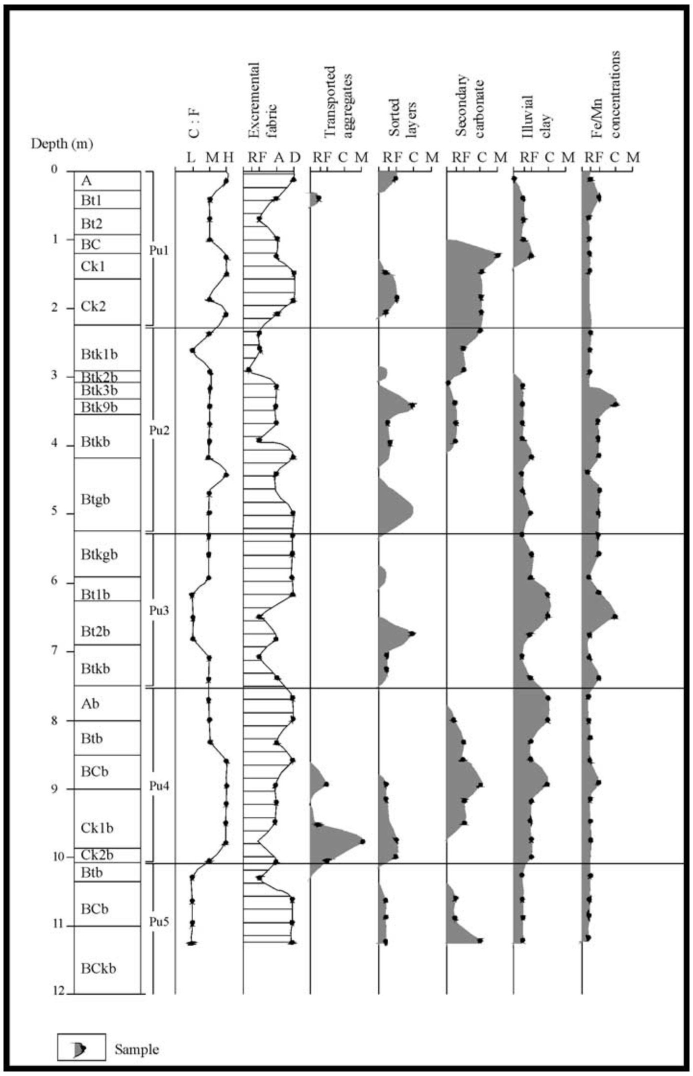

Fig. 6. Depth function of micromorphological features at Gorina. c:f$_{20\ \mu\mathrm{m}}$ coarse:fine ratio of mineral grains: L = low (< 1 : 2); M = medium (2 : 1–1 : 2), H = high (> 2 : 1). Excremental fabric: R = rare (< 10%); F = frequent (10–25%); A = abundant (25–50%); D = dominant (> 50%). Transported aggregates, sorted layers, secondary carbonate, illuvial clay, and Fe/Mn concentrations: R = rare (< 1%); F = few (1–2%); C = common (2–10%); M = many (> 10%).

clearly defined A horizons are not preserved below the surface soil, the presence of excremental fabrics throughout the vertical column suggests that bioturbation processes were active as the sediment accreted, with build-up of the surface resulting in conversion of A into B and C horizons and any humic material presumably lost by oxidation. Removal of A horizons by erosion may also have occurred at some levels, notably the top of Pu5. This latter paleosol initially developed at a relatively stable land surface, and leaching and clay translocation processes encouraged the formation of Bt and underlying BCk horizons. Evidence for truncation and erosion of A and upper Bt horizons is provided by the rip-up clasts of Bt-horizon material in the Ck horizons of Pu4, a fluvial cause being supported by the channel macrostructures evident at this level elsewhere in the quarry. Fragments of sorted layers in thin sections in the basal part of Pu4 further substantiate the role of water reworking, though the presence of these features throughout the sequence suggests that the accumulating aeolian sediments were continually subjected to some degree of redistribution by surface processes.

The micromorphological and particle size data do not support the field differentiation of separate paleosols for Pu4, Pu3, and Pu2. Pedological features (e.g. excrements, secondary carbonate coatings, illuvial clay coatings) occur throughout these paleosols without any obvious breaks or patterns that might warrant separation into discrete paleosols. Although relatively stable land surfaces that mark significant depositional hiatuses may have been present, conclusive and unambiguous evidence has not survived at the microscale. Thus, we can only conclude that this ca. 8 m sequence is an accretionary and/or welded pedocomplex with a superimposition of secondary carbonate on illuvial clay features and illuvial clay coatings on excrements as the surface built up and horizons became transformed. Periodic water reworking may also have been involved, as discussed.

The macroscale differentiation of this pedocomplex into three distinct units (Pu4, Pu3, and Pu2) appears to reflect sedimentological and possible diagenetic factors. For example, the transitional boundary between Pu4 and Pu3 is sedimentological and simply marks a change in size of the material deposited (Blasi et al., 2001) rather than any kind of major hiatus. Bt horizons above tend to have formed in finer textured sediments, their field morphology and apparent advanced degree of development possibly a reflection of sedimentological more than pedological controls. The relatively low abundance of illuvial clay in thin sections from some Bt horizons may be a consequence of disruption and incorporation into the clay-rich groundmass by shrink–swell pressures. However, some of the coatings identified in the field may be stress features. The upper boundary of Pu4 coincides with an important sedimentological change that causes the morphological differences observed at field scale and recorded by the A horizon designation. The upper surface of a zone of platy carbonate accumulations (Btkg horizon) was designated in the field as the boundary between Pu3 and Pu2. However, this carbonate accumulation may represent a groundwater concentration and therefore has no real pedogenic significance.

The truncation of Pu2, clearly shown by the erosional unconformity identified in the field, involved the stripping of the uppermost horizon. The truncated pedocomplex was later buried by sediment that has provided the parent material for the present surface soil (Pu1). This latter soil shows some accretionary features yet has been forming at the present surface sufficiently long for development of an A, Bt, and Ck profile, with secondary carbonate associated with this phase of leaching extending down into the upper horizons of Pu2.

In summary, the Gorina succession predominantly reflects the changing balance between loess deposition and pedogenesis, though fluvial redistribution and even erosion of the sediments have had significant impacts. Pu5 marks the first major depositional hiatus, during which time a soil developed at a relatively stable land surface. This was followed by truncation and a period of renewed sediment accumulation and pedogenesis, though there are no clear hiatuses associated with discrete phases of soil development at stable surfaces recognizable within the resultant pedocomplex, apart from that at the top of Pu2. Following truncation of Pu2, there was renewed accretion to the surface at which the present-day soil has developed.

6. Conclusions

This study, along with micromorphologically based investigations from other parts of the world (e.g. Kemp et al., 1994, 1997, 1998), emphasizes the potential complexity of loess–paleosol sequences. The systematic micromorphological approach applied here shows that some of the pedological units differentiated on the basis of field morphological features at Gorina are not discrete paleosols, but instead reflect the overriding influence of sedimentological and possibly even diagenetic processes. Furthermore, some of the morphological properties frequently used to infer the extent of soil development (e.g. clay content, structure) rather may be a (direct or indirect) reflection of changes in particle size of the parent material. Notwithstanding these complications, pedogenic processes have had a major impact on the character and properties of this sequence. The full significance of the succession can be appreciated only by considering the effects of changing balances of pedosedimentary processes over time, particularly when vertical migration of components may lead to the superimposition of different age features.

The Gorina section does not conform to the simple classical model proposed by other authors in the region (e.g. Tonni et al., 1999) of alternating loess and paleosol units associated with arid (loess deposition) and wet (soil formation) intervals, respectively. The parent materials of the paleosols are not homogeneous. The two erosional surfaces recorded in the succession mark the boundaries between the three main depositional units, each associated with either a soil (paleosol) or pedocomplex (i.e. the lower Pu5, the intermediate Pu4–Pu3–Pu2, and the upper Pu1). In addition, a third hiatus is suggested by the occurrence of common sorted layers on top of Pu3. Although its absolute age is unknown, the 8-m-thick intermediate pedocomplex developed very likely over several interglacial–glacial cycles within the last 0.7 Ma. It is interesting to note that a cyclical sedimentation pattern was also proposed for the Pliocene loess–paleosol sequence at Los Acantilados, with the textural differences between the alternating siltstone and clay-like siltstones enhanced by pedogenesis (Kemp and Zárate, 2000). This cyclicity was hypothetically related to glacial–interglacial fluctuations in the source areas. At Gorina, the grain-size heterogeneity of the accumulated material might indicate changes in the source areas and/or the dynamic of transport agents (winds) under the Pleistocene climatic fluctuations, but more investigations are needed to understand the environmental significance of the pedosedimentary changes identified.

This case study, representative of Late Cenozoic Pampean loess sequences throughout the Buenos Aires province, has demonstrated the value of employing a combined approach at both the macro- and micromorphological scales. The identification of paleosols exclusively on the basis of field morphology should be cautioned against, as it may lead to an oversimplification of the pedogenic and sedimentary balances and interactions that are responsible.

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