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Pliocene pedosedimentary cycles in the southern Pampas, Argentina

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ABSTRACT

Well-developed Bt horizons of five palaeosols (P1–P5) have been recorded previously within a 20-m-thick succession of Pliocene siltstones and clayey siltstones in the southern part of the Buenos Aires Province of Argentina. This paper reports a detailed field and micromorphological (thin section) investigation of a 6-m portion of the sequence encompassing P2 and P3. Large-scale faunal burrow infillings occur throughout: other bioturbation features in the form of channel and spongy microstructures are mainly confined to the siltstones. The intervening clayey siltstones (Bt horizons) have been affected more by shrink–swell disruption, as evidenced by slickensides and a range of striated b-fabrics in thin sections. Clay coatings, indicative of illuvial accumulation of clay translocated in suspension from overlying A or E horizons, occur in both the siltstones and clayey siltstones. The types, microstratigraphic associations and depth functions of features are interpreted in terms of changing interactions, balances and dominances between sedimentary, pedogenic and erosional processes over time, thus providing the basis for the pedosedimentary reconstruction of landscape evolution in the region during part of the Pliocene represented by the whole P1–P5 sequence (4–5 Ma BP). It is envisaged that this period was dominated by aeolian deposition, although fluvial and mass movement processes probably led to reworking and redistribution of some of the materials. Overall rates of subaerial deposition, however, were not substantial: pedogenic processes were active throughout, the balance between sedimentation and pedogenesis varying over time in a cyclical fashion. Phases of reduced deposition and 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 characterized by accretionary soil development and welding of new pedological features on existing soils as the surface accreted, first transforming existing eluvial horizons into BCt/AE horizons (siltstones) and then encouraging the syndepositional upward extension of these complex horizons. The primary basis of the alternating units of siltstones (BCt/AE horizons) and clayey siltstones (Bt horizons) lies in the cyclical change in size of particles deposited, although pedogenic translocation processes enhanced these textural differences. The underlying driving mechanism behind the pedosedimentary cycle can only be speculated upon, although it is tempting to relate the sedimentation pattern to climatic fluctuations linked to glacial advances and retreats in the Patagonian Andes during the Pliocene.

Keywords Argentina, micromorphology, palaeosols, pedosedimentary, Pliocene.

INTRODUCTION

The Chapadmalal sea cliffs near Mar del Plata (Fig. 1), in the southern part of the Buenos Aires Province of Argentina, provide one of the most complete and laterally extensive exposures of Plio-Pleistocene sediments of the Pampean Formation (Zárate & Fasano, 1989). The succession of siltstones and fine sandstones has a relatively homogeneous mineralogical composition, consisting primarily of plagioclase, quartz and volcanic glass. Amphiboles and pyroxenes dominate the heavy mineral fractions (Teruggi, 1957), with smectite and illite comprising the main clay minerals (Camilión, 1993). Such sediments have generally been regarded as aeolian in origin, being derived from volcaniclastic deposits outcropping in the Andes over 1000 km to the west (Teruggi, 1957), although localized fluvial and mass movement processes probably redistributed the material to a large extent once accumulated in the Pampas (Teruggi *et al.*, 1957). Research to date on the Chapadmalal exposures has mainly concentrated on the abundant remains of vertebrate fossils found throughout the succession (e.g. Ameghino, 1908; Frenguelli, 1928; Kraglievich, 1952; Tonni *et al.*, 1992; Cione & Tonni, 1995). Recent preliminary field mapping and tracing of the units along 30 km of coastal exposures, however, have extended and formalized the stratigraphy, notably by the recognition of a sequence of interbedded palaeosols (Zárate, 1993; Schultz *et al.*, 1998).

This paper is focused on the lowermost stratigraphic interval of the succession comprising nearly 20 m of Pliocene siltstones (Playa San Carlos Alloformation; Zárate, 1993) with up to five well-developed palaeosols (P1–P5). Biostratigraphically, the unit corresponds to the Chapadmalalan stage (Cione & Tonni, 1995). Orgeira (1990) assigned an early Gauss to Gilbert palaeomagnetic age (≈3·6–4 Ma BP), while recent palaeomagnetic and $^{40}Ar/^{39}Ar$ dates of the overlying unit indicate that these siltstones must be older than 4 Ma BP and are likely to be between 4 and 5 Ma BP (Zárate *et al.*, 1998). Burrows and caves of rodents along with burrows attributable to large armadillos and ground sloths are the outstanding features throughout the succession. Fossil remains are abundant in these biogenic structures. At the Los Acantilados section reported here, for instance, remains of the rodents *Actenomys* (Rodentia, Octodontidae), *Paedotherium* (Notoungulata), *Lagostomopsis* (Rodentia, Chinchillidae) have been recovered along with taxa of the Xenarthra order (*Paraglyptodon*, *Scelidotherium*) (Peña, 1997).

The palaeosols comprise strongly developed Bt horizons (clayey siltstones) displaying a well-defined prismatic and blocky structure with abundant coatings of clay and Fe/Mn oxides (and/or oxyhydroxides) on channel and aggregate surfaces. These horizons grade upwards and downwards into more massive siltstone beds, which were originally regarded as C horizons, any A or E horizons assumed to have been removed by erosion (Zárate & Fasano, 1984). More recently, however, Zárate & Imbellone (1998) have suggested that at least some of these surface horizons remain, yet are difficult to recognize in the field because of pedogenic welding of subjacent palaeosols. They emphasized the need to view such successions in terms of cycles or phases of sedimentation and pedogenesis, and advocated the use of micromorphology to decipher the nature and order of events

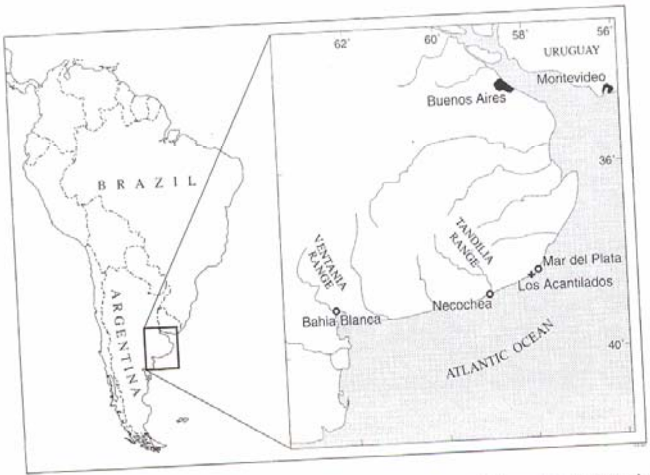


Fig. 1. Location of Los Acantilados near Mar del Plata, east-central Argentina.

recorded within the polycyclic or welded horizons.

This paper aims to reconstruct landscape evolution in this Pampean region during the Pliocene by following a micromorphologically based 'pedosedimentary' approach developed for Quaternary loess–palaeosol sequences in Germany (Kemp *et al.*, 1994), China (Kemp *et al.*, 1995, 1996, 1997) and the United States (Kemp *et al.*, 1998). Not to be confused with the pedofacies concept of Bown & Kraus (1987) considering spatial changes in degrees of soil development, this approach is based upon the description of thin sections spaced at close vertical intervals throughout a single laterally confined sequence. The form, microstratigraphic associations and depth functions of micromorphological features are interpreted in terms of changing interactions, balances and dominances between sedimentological, pedogenic and erosion processes over time. For the detailed micromorphological analyses, we selected a 6-m-thick interval representative of the Playa San Carlos Alloformation encompassing palaeosols P2 and P3 at Los Acantilados, located 18 km south-west of the city of Mar del Plata in the distal south-east piedmont of the Tandilia range (Fig. 1).

METHODS

The 600-m coastal section at Los Acantilados was logged, and a representative profile described in detail. Undisturbed samples taken in Kubiena tins (7 × 5 × 4 cm) at ≈25-cm vertical intervals from this profile were air dried, impregnated with polyester resin and made into large thin sections (7 × 5 cm) according to standard procedures (Lee & Kemp, 1992). The thin sections were described at 10–400× magnification under a petrographic microscope using the terminology of Bullock *et al.* (1985). The microstratigraphic relationships and estimated proportions of key micromorphological features in each thin section were recorded and used to provide the basis for pedosedimentary reconstruction of the profile. Particle size analysis, following standard pipette/sieving techniques, of bulk samples collected 40 cm above and below the upper boundary of the Bt horizons in three palaeosols (i.e. six samples in total) was also undertaken in order to determine sand/silt ratios for the assessment of sediment uniformity.

FIELD DESCRIPTION

Bt horizons of four different palaeosols (P1–P4) can be traced within the Playa San Carlos Alloformation at Los Acantilados, although they are laterally discontinuous as a result of the uneven erosional contact with the overlying Punta Martinez de Hoz Alloformation (Fig. 2). Diagenetic platy accumulations of calcium carbonate, related to groundwater circulation, occur

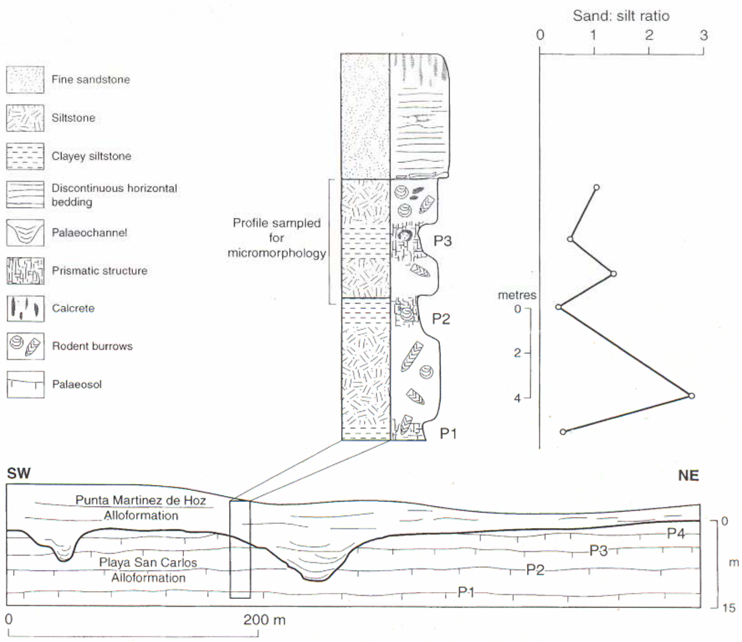
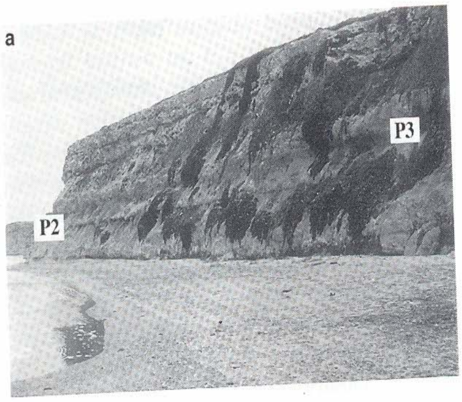


Fig. 2. Field log of the Los Acantilados section showing location of sampling profile and depth function of sand:silt ratios through main units.



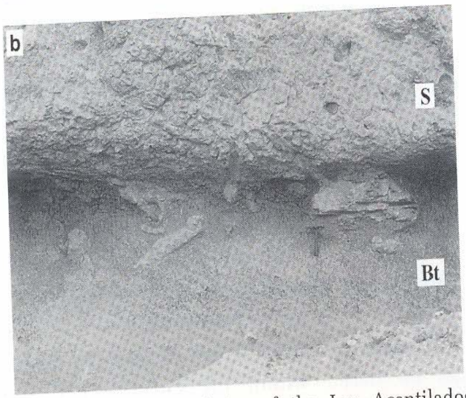


Fig. 3. Field characteristics of the Los Acantilados section. (a) South-western end of the section beyond the sampling profile, partially overgrown by vegetation, yet clearly showing lateral extent of the Bt horizons of P2 and P3 picked out by shadows beneath overhangs. Section is ≈15 m thick here. (b) Bt horizon of P2 beneath overhang of more resistant siltstone (S). Both contain evidence for substantial bioturbation in the form of individual or complex associations of vertebrate burrows and invertebrate pedotubule structures. Note hammer for scale.

Table 1. Field description of units sampled at Los Acantilados.

Above Bt horizon of P3 Dark yellowish brown (10YR 3/6) siltstone; massive to weakly developed fine/medium angular blocky structure; non-calcareous except for few platy carbonate accumulations at upper boundary; frequent nodules and coatings of Fe/Mn (oxyhydr)oxides and few discontinuous clay coatings around channels; common invertebrate pedotubule structures and many vertebrate burrows; smooth, gradual/diffuse lower boundary.
Bt horizon of P3 Dark brown (7·5YR 3/4) clayey siltstone; strongly developed medium prismatic and angular blocky structure; few slickensides; non-calcareous except for few calcareous coatings around channels; abundant nodules and coatings of Fe/Mn (oxyhydr)oxides and very abundant continuous clay coatings around channels and on aggregate surfaces; common invertebrate pedotubule structures and vertebrate burrows; smooth, gradual/diffuse lower boundary.
Above Bt horizon of P2 Dark yellowish brown (10YR 3/6) siltstone; massive to weakly developed fine/medium angular blocky structure; non-calcareous; common nodules and coatings of Fe/Mn (oxyhydr)oxides and few discontinuous clay coatings around channels; common invertebrate pedotubule structures and many vertebrate burrows; smooth, diffuse lower boundary.
Bt horizon of P2 Dark brown (7·5YR 3/4) clayey siltstone; strongly developed fine prismatic and angular blocky structure; common slickensides; non-calcareous; common nodules and coatings of Fe/Mn (oxyhydr)oxides and very abundant continuous clay coatings around channels and on aggregate surfaces; common invertebrate pedotubule structures and vertebrate burrows.

along this erosional surface and around the walls of vertebrate burrow infillings (Zárate & Camilión, 1992; Zárate, 1993). The majority of the section, however, is non-calcareous. The Bt horizons are easily recognizable in natural cliff sections, as they are less resistant than intervening horizons to current erosion and therefore tend to occur beneath more resistant overhangs (Fig. 3). All horizons show an apparent dip of ≈1° towards the south-west, presumably a reflection of the slope of the palaeosurfaces.

The profile sampled for micromorphology extends from 2 m above the top of the Bt horizon in P3 down into the upper part of the Bt of P2, thus providing coverage through more than one complete palaeosol unit (Fig. 2 and Table 1). Both Bt horizons are dark brown (10YR 3/6) clayey siltstones with strongly developed blocky and prismatic soil structures and slickensides associated with the aggregate surfaces (Fig. 4). These horizons have abundant Fe/Mn oxide nodules and coatings, clay coatings, vertebrate burrows and invertebrate pedotubule structures throughout. The more massive dark yellowish-brown (10YR 3/6) siltstones between the Bt horizons of P3 and P2 and above P3 contain these same Fe/Mn, clay and bioturbation features, indicating that they have also been pedogenically altered, albeit to different extents (Fig. 3b). Sand/silt ratios (Fig. 2) suggest that the textural differences between the siltstones and clayey siltstones are depositional, at least in part, and presumably reflect cyclical changes in depositional energy conditions.

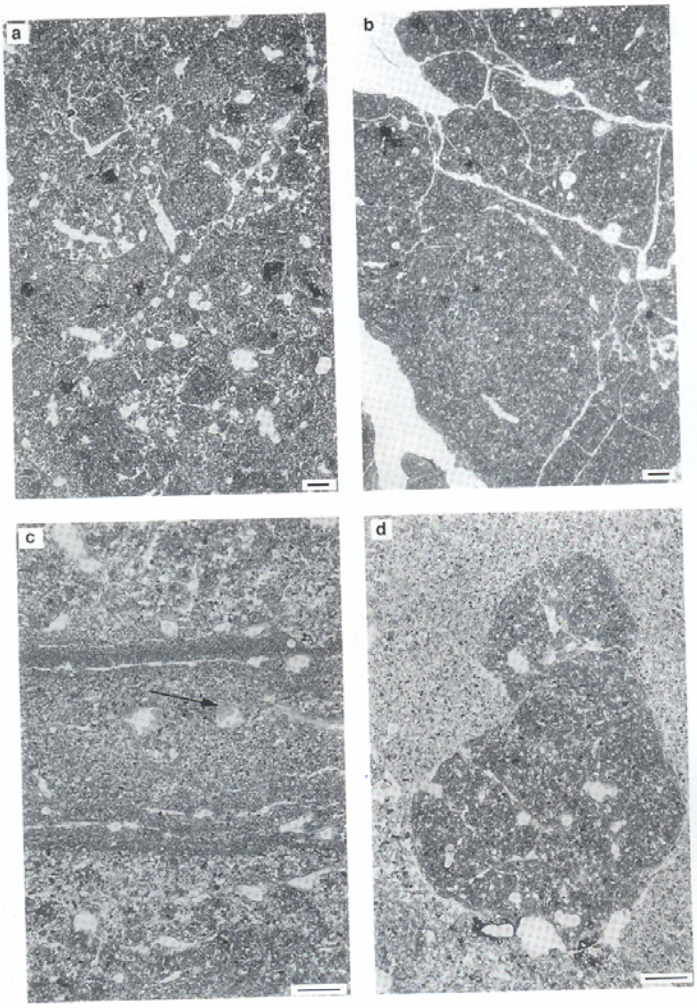


Fig. 5. Photomicrographs of key features from Los Acantilados; plane polarized light; scale bar = 500 μm. (a) Channel and spongy microstructures. (b) Blocky aggregates separated by planar voids. (c) Sorted layers partially disrupted by channels coated by clay (arrow). (d) Aggregate of fine-textured material embedded within coarser textured groundmass.

downwards from overlying A or E (eluvial) horizons (McKeague, 1983), abound in every thin section. The majority comprise limpid/speckled, flecked continuous to continuous, laminated and microlaminated clay coatings (50–2500 μm) around channels (Fig. 6b), some of which bisect embedded aggregates (LA13, LA21 and LA22), or around partially welded granular aggregates (Fig. 6c) or sorted layers (Fig. 5c) (LA20). These microstratigraphic relationships are crucial, as they demonstrate unequivocally that bioturbation and water reworking predated clay illuviation at any one level. The most logical explanation for this pattern is that surface A or E horizons were buried by sediment and therefore 'moved' some distance below the land surface, where they were transformed into Bt (clayey siltstone) or BCt/AE (siltstone) horizons by the accumulation of clay translocated from eluvial horizons newly created in the overlying sediments.

Some thin sections also contain coarser (impure), discontinuous clay coatings (100–1000 μm), occasionally with limpid/speckled, flecked continuous microlaminations. Generally, but not always, these predate the limpid layers within compound features (Fig. 6c and d). Although the exact environmental significance of different textures within illuvial coatings is not universally accepted, there is general consensus that coarser clay (and silt) components probably result from translocation under more turbulent flow commonly associated with

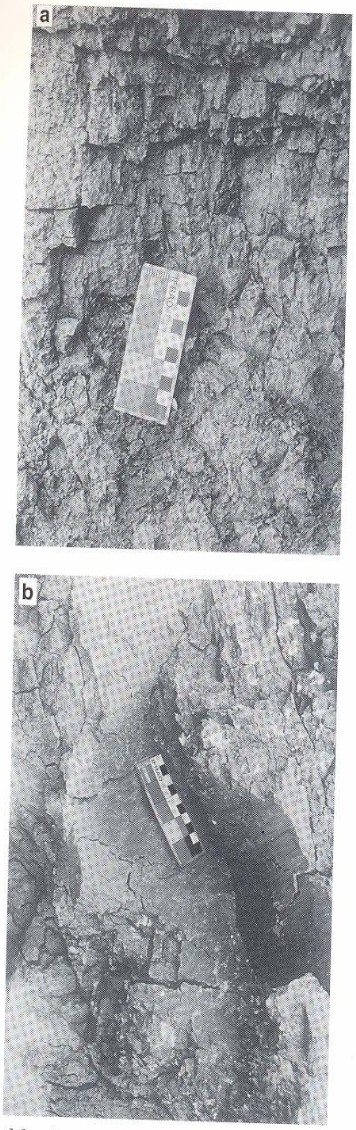


Fig. 4. Field characteristics of the Los Acantilados profile. (a) Strongly developed blocky and prismatic (soil structural) aggregates within the Bt horizon of P3. (b) Slickensides on the surfaces of prismatic aggregates within the Bt horizon of P2.

MICROMORPHOLOGY

Key micromorphological characteristics and features of the profile are illustrated in Figs 5 and 6. Semi-quantitative estimates of the abundances and microstratigraphic relationships of these features are recorded in Fig. 7.

Microstructure and groundmass

Channel and spongy microstructures (Fig. 5a), reflective of root and faunal activity, are typical of the siltstones. The Bt horizons (clayey siltstones) also retain the imprint of bioturbation processes, yet their microstructure is dominated more by the presence of blocky aggregates separated by planar voids (fissures) that were created by shrink–swell pressures (Fig. 5b). Deformed, irregular, unconnected voids (vughs) predominate in the thin section (LA13) taken from within a large burrow infilling and also occur in other thin sections, normally in association with sorted layers (Fig. 5c). The latter, comprising thin (1–5 mm) subhorizontal layers of different $c{:}f_{20\,\mu m}$ [ratio of coarse (>20 μm) to fine (<20μm) particles] ranging from 2:1 to 1:5, probably reflect some degree of water transport and sorting.

The overall $c{:}f_{20\,\mu m}$ of the groundmass varies between 2:1 and 1:3, the finer-textures mainly confined to the Bt horizons. These clay-rich zones tend to be dominated by striated birefringence (b-) fabrics, reflecting shrink–swell stress-induced zones of parallel orientation of clay mineral domains, and contrast markedly with the less developed stipple- and mosaic-speckled b-fabrics of the siltstones. The porostriated b-fabrics are the micromorphological equivalents of the slickensides recognized in the field.

Embedded aggregates

Many thin sections contain irregular aggregates (0·2–8 mm) distinguishable by differences in b-fabric and c:f ratio or porosity from the adjacent groundmass in which they are embedded. In LA16, for instance, clay-rich aggregates with striated b-fabrics (typical of the Bt horizons) are enclosed within the predominantly speckled b-fabric of the coarse-textured siltstone (Fig. 5d). The groundmass of LA12, on the other hand, generally has a striated b-fabric, yet contains aggregates with speckled b-fabrics (Fig. 6a). Taking into account the amalgam of different aggregates in LA13 from the large burrow infilling, it would appear reasonable to interpret these features in terms of bioturbative mixing of horizons. In some cases, however, they may be rip-up clasts associated with surface water flow and reworking, particularly where associated with sorted layers (e.g. LA16).

Clay concentrations

Clay concentrations, resulting from the illuvial accumulation of clay translocated in suspension

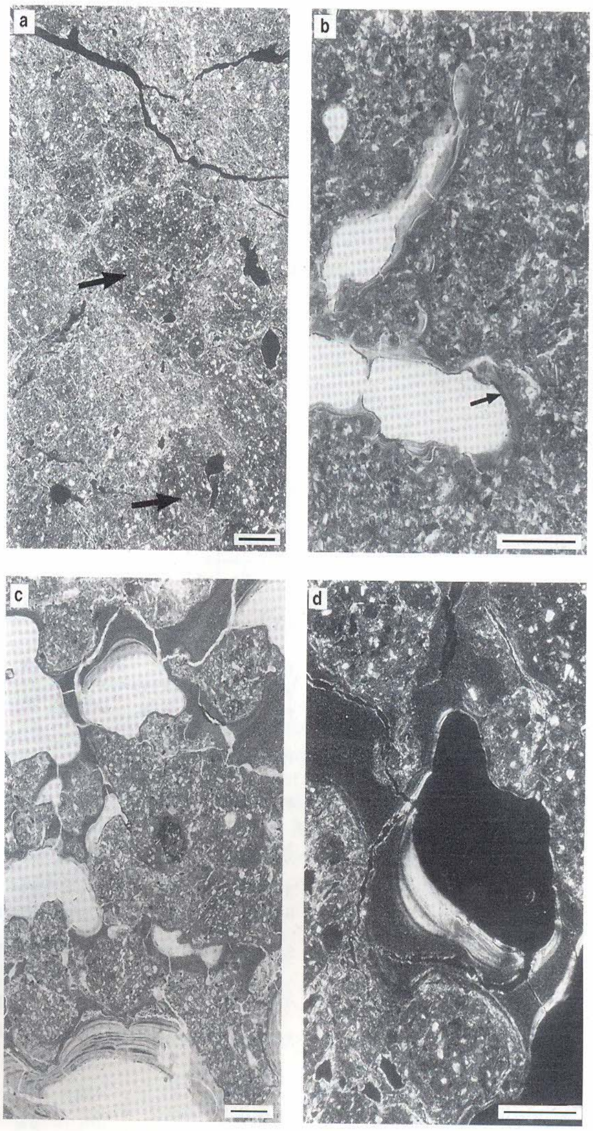


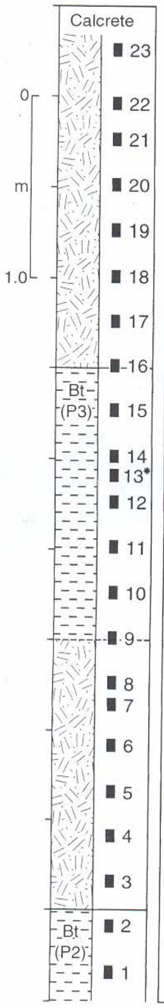
Fig. 6. Photomicrographs of key features from Los Acantilados; plane polarized light (PPL); crossed polarized light (XPL); scale bar = 500 μm. (a) Aggregates of stipple-speckled b-fabric (dark area arrowed) embedded within a groundmass of striated b-fabric (XPL). (b) Channels with clay coatings, some with superimposed coatings of Fe/Mn oxides and/or oxyhydroxides (arrow) (PPL). (c) Compound impure and limpid clay coatings around partially welded granular aggregates (PPL). (d) Compound impure and limpid clay coating (XPL).

unstable or sparsely vegetated surfaces (Kemp, 1999).

Deformed or disrupted clay coatings, normally in the form of flecked continuous concentrations unassociated with voids, occur in the Bt horizons. These often grade into zones of striated b-fabric, suggesting that shrink–swell pressures led to the disruption and ultimate incorporation of some illuvial clay into the groundmass, thus providing an explanation for the lack of a significant difference in amounts of illuvial clay distinguishable in thin sections from Bt (clayey siltstone) compared with coarser textured BCt/AE (siltstone) horizons (Fig. 7). On the basis of the micromorphological data, it appears therefore that the number of 'true' *in situ* illuvial clay coatings (particularly on aggregate surfaces) may have been overestimated in the field descriptions of the Bt horizons. This probably reflects the frequently reported difficulty in field differentiation of stress reorientation (slickensides) and illuvial concentration of clay in fine-textured horizons (Bullock & Thompson, 1985).

Fe/Mn concentrations

Concentrations of Fe and Mn oxides (and/or oxyhydroxides), mainly in the form of strongly impregnated nodules (<250 μm) and hypocoatings or coatings (<100 μm), are present in all thin



Thin section	Microstructure (1)	C:f20µm (2)	B-fabric (3)	Sorted layers (4)	Embedded aggregates: Speckled b-fabrics (5)	Embedded aggregates: Striated b-fabrics (6)	Embedded aggregates: Dense (7)	Clay concentrations: Limpid / speckled coatings (8)	Clay concentrations: Impure coatings (9)	Clay concentrations: Deformed / disrupted coatings (10)	Fe / Mn concentrations: Sharp nodules (11)	Fe / Mn concentrations: Diffuse nodules (12)	Fe / Mn concentrations: Hypocoatings and coatings (13)
23	SC	1:1	Sp	–	–	–	•	•• 9	•	–	–	•••	•
22	SC	1:1	Sgp	–	–	–	•	••• 7,9	•	–	–	••	• 8
21	SC	3:2	Sg	–	•	–	••	••• 7	–	–	–	••	• 8
20	VCs	3:2 - 1:3	Sgp	••••	–	–	–	••• 4	–	–	–	•	• 8
19	CVs	1:1	SGp	–	–	–	••	••	–	–	–	–	•• 8
18	Cps	3:2	Smgp	–	–	–	–	•••	–	–	–	•	•• 8
17	Cs	1:1	Spr	–	–	–	–	•• 9	•	–	–	•	•• 8
16	Vcs	2:1	Sg	••	–	•••	••	••	–	–	•	•	•• 8
15	BC	2:3	SPmr	–	–	–	–	•	–	••	–	•	••
14	Bc	1:1	MSPr	–	•	•	–	••	–	••	–	•	•• 8
13*	VCs	2:1 - 2:3	SMg	–	••••	••••	•••	••• 5,6,7,9	•• 8	••	–	•••	•• 8
12	Bc	1:2	RPM	–	•••	–	–	•	–	••	•	••	••
11	BCs	1:1	Smpg	–	–	•••	–	••••	–	•	–	••	•• 8
10	SC	1:1	SMg	–	•	•	•	•••• 9	•••	••	–	•	••
9	Csb.	1:1	Smp	–	•	•	–	••• 9	•	•	–	•	••
8	SC	3:2	Sgpm	–	•	•	–	••• 9	•	–	–	•••	•
7	SCb	3:2	Sgp	•	–	–	•	••	–	–	–	••	••
6	SC	3:2	SP	•	•	•	•••	••• 9	• 8	–	–	••	–
5	Cs	3:2	SPg	–	–	–	••	•••	–	–	•	••	–
4	SC	1:1	SPgm	–	••	••	–	•••	•	–	•	••	–
3	SCb	1:1	Spg	–	–	–	–	••	–	–	••	•	–
2	Scb	2:3	Mspg	–	–	–	–	••	•	•	••	•	–
1	BC	2:3	RPMs	–	•	–	–	••	–	–	•	••	•

■ Thin section

* Thin section 13 is within a large burrow infilling

Microstructure
B Blocky
C Channel
S Spongy
V Vughy
P Prismatic

B-fabric
S Stipple - or mosaic-speckled
M Monostriated
P Porostriated
G Granostriated
R Reticulate striated

Dominant forms shown with capitals

– Not detected
• Rare (< 0.2%)
•• Very few (0.2 - 2.0%)
••• Few (>2 - 5%)
•••• Common (>5%)

Numbers beneath abundance values in data columns refer to the features which are postdated. For instance, Thin Section 22, Fe/Mn hypocoatings and coatings: " • 8 " indicates that there are rare Fe/Mn hypocoatings and coatings which sometimes postdate limpid/speckled clay coatings (8)

Fig. 7. Depth functions of the main micromorphological features from Los Acantilados.

sections. While some of the sharply bounded nodules might be inherited and have been transported within the sediment, the majority of the features (diffuse nodules and coatings/hypo-coatings) are *in situ*. They are generally regarded as forming in soils by redistribution of Fe and Mn oxides and oxyhydroxides in response to fluctuations in redox potential associated with periodic water saturation (Vepraskas *et al.*, 1994). The common superimposition of these features on illuvial clay (Fig. 6b), however, suggests that many may have formed relatively late in the pedosedimentary cycle and are probably associated with groundwater circulation (in a similar manner to the calcium carbonate concentrations higher in the section) occurring sometime after complete burial and isolation from pedogenic processes.

PEDOSEDIMENTARY RECONSTRUCTION

The field log and depth functions of these micromorphological characteristics provide the basis for the separation of the pedosedimentary evolution of the section at Los Acantilados into four successive stages (Fig. 8). Although these stages are unlikely to have been discrete events with clearly defined boundaries, their identification enables recognition of a cycle of pedosedimentary change that has general applicability throughout these Pliocene sequences.

Pedosedimentary stage 1 followed a period of aeolian sedimentation and water/mass movement reworking, and represents a phase of relative landscape stability with minimal sedimentary inputs. Upper horizons were bioturbated, resulting in the development of spongy aggregates; clay was translocated from these AE horizons into underlying Bt horizons (Fig. 8). Shrink–swell activity in this clay-enriched horizon led to disruption and incorporation of some illuvial clay coatings into the groundmass and generation of striated b-fabrics and slickensides.

Rates of sedimentation and modal size of accumulated particles increased markedly during the initial part of pedosedimentary stage 2. Pedogenic processes, however, continued to be active as the land surface accreted. Initially, this resulted in the translocation of clay from new surface horizons into the existing Bt and AE horizons of the stage 1 soil, thus transforming the AE into a welded BCt/AE horizon (Fig. 8). As more material accumulated and syndepositional

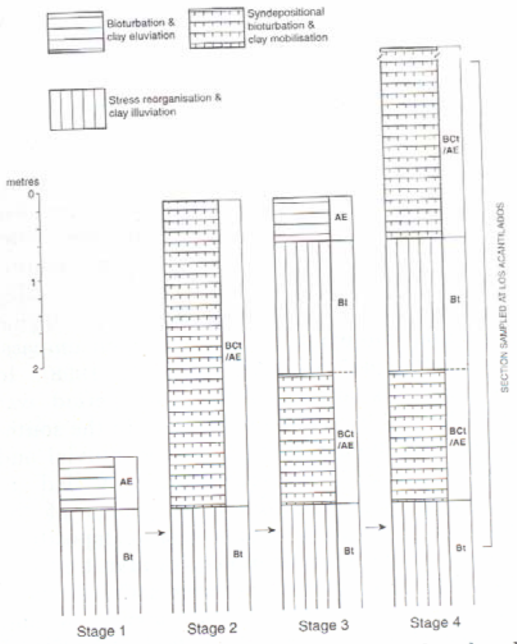


Fig. 8. Reconstruction of the sequence of pedosedimentary stages responsible for the development of the P2/P3 complex at Los Acantilados. Stage 1: minimal sedimentation, relative landscape stability, development of AE and Bt horizons. Stage 2: increased sedimentation, transformation of AE into BCt/AE horizon, upwards extension of BCt/AE horizon by syndepositional pedogenic alteration. Stage 3: reduced sedimentation, relative landscape stability, development of AE and Bt horizons. Stage 4: increased sedimentation, transformation of AE into BCt/AE horizon, upwards extension of BCt/AE horizon by syndepositional pedogenic alteration.

pedogenic alteration proceeded, this complex welded horizon was extended upwards as ephemeral eluvial and bioturbated horizons became successively buried and partially transformed into illuvial horizons.

Particle size (and probably accumulation rate) of the sediments began to decrease towards the end of pedosedimentary stage 2. Eventually, a relatively stable land surface was established, allowing pedogenic translocation and bioturbation processes to dominate (pedosedimentary stage 3) and resulting in modification of the upper part of the BCt/AE complex and the development of an AE horizon overlying a Bt horizon, i.e. a repeat of pedosedimentary stage 1 (Fig. 8). Renewed sedimentation and syndepositional pedogenic alteration during stage 4, mirroring the activities of stage 2 (Fig. 8), reinforces the cyclical nature of the pedosedimentary development of the sequence.

DISCUSSION AND CONCLUSIONS

The detailed field and micromorphological study outlined here has concentrated on the genesis of the P2–P3 palaeosol complex, but the wider significance of the pedosedimentary reconstruction lies in the fact that it also provides a working model for landscape development in this region throughout the whole time sequence encompassing P1–P5 (4–5 Ma; Zárate *et al.*, 1998). In essence, it is envisaged that this period was characterized by aeolian deposition in the southern part of Buenos Aires Province. Fluvial and mass movement processes probably led to reworking and redistribution of some of the materials. Overall rates of subaerial deposition, however, were not substantial (≈12 m in 1 million years?); pedogenic processes were active throughout, the balance between sedimentation and pedogenesis varying over time. Phases of reduced deposition and the establishment of relatively stable land surfaces were marked by the development of argillic soil profiles. Intervening periods of more rapid accumulation of coarser material were characterized by accretionary soil development and welding of new pedological features on existing soils as the surface accreted.

The basis of the alternating units of siltstone and clayey siltstone lies in the cyclical changes in the size of particles deposited, although pedogenic translocation processes enhanced these textural differences. There is no evidence of any obvious hiatuses within the sequence. Erosional phases, however, cannot be discounted, particularly in view of the occurrence of isolated water-sorted structures and extensive networks of faunal burrows and caves. As well as being directly responsible for moving and mixing material between horizons or units, the rodents, armadillos and ground sloths may have made available significant quantities of unconsolidated material for erosion and redistribution during the course of their excavations.

The underlying driving mechanism behind this pedosedimentary cycle can only be speculated upon. There is some dispute over the climate prevalent in the region at the time of the formation of the P1–P5 palaeosols. Pascual (1984), on the basis of palaeontological remains, for example, suggested that warm humid (subtropical) conditions dominated, whereas Cione & Tonni (1995) cited the large number of rodent caves as evidence for a cold, arid environment. Whatever the exact climatic conditions, it is clear that the same basic pedogenic and sedimentological processes were active throughout the time sequence encompassing P1–P5, the main variation being in sedimentation rate and size of particles deposited. While recognizing the possible complications brought about by fluvial or mass movement reworking, it is tempting to relate the cyclical sedimentation pattern to changing speeds and capacities of transporting winds and to varying vegetation covers and availability of sediment in the aeolian source areas. Perhaps these were in turn controlled by climatic fluctuations associated with the glacial advances and retreats that have been inferred in the Patagonian Andes during the Pliocene (Mercer, 1983; Clapperton, 1993).

Using the last Quaternary glaciation as an analogue, it might be that Pliocene glacial advances were marked by increased transport of sediment from the high Andes by meltwater rivers into floodplains, whence winds redistributed sediments onto the southern Pampas. Reduced aeolian inputs and development of soils with AE and Bt horizons at relatively stable land surfaces on the Pampas would have occurred during periods of glacial retreat in the Andes when supplies and transfers of sediments were diminished. Testing or confirming such linkages requires further investigation. Establishment of tighter chronological controls should be a particular priority, not least because it might afford the opportunity to compare the Pampean pedosedimentary record with marine oxygen isotope curves (Schultz *et al.*, 1998).

The need to consider and unravel the relative roles of pedogenic, erosional and depositional processes within many alluvial, colluvial and aeolian depositional systems is increasingly being realized by sedimentologists and pedologists alike (Bown & Kraus, 1987; Kemp, 1999). Studies of pre-Quaternary sequences, however, have not always taken such interactions into account. One notable exception is provided by Marriott & Wright (1993), who used field criteria to identify different degrees of pedogenic development within Silurian and Devonian alluvial suites from South Wales and interpreted the vertical changes in terms of temporal fluctuations in geomorphic stability. The pedosedimentary approach followed in this Argentinian example, based upon interpretation of the form, microstratigraphic associations and depth functions of micromorphological features that have good preservation potential, allows an additional means of deciphering such sequences and may have wider applicability to other parts of the geological record.

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