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Paleoenvironmental reconstruction of Quaternary valley-fill successions in summit paleosurfaces of southern Sierras Pampeanas (Córdoba Province, Argentina)

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ABSTRACT

Climatic and environmental changes were inferred from the study of Late-Quaternary sequences that represent paleo-valleys filling in the summit pampas at the center-South of the Sierra de Comechingones, Córdoba Province, Argentina. A representative sedimentological section (P1) was described and sampled, and sediments age (^{14}C), granulometric characteristics and organic matter content were determined. In the analyzed succession four main stratigraphic units were recognized and interpreted. The stratigraphic and pedological characteristics, diatom levels presence, geomorphological features and altitude conditions of the study area allow us to conclude that: 1) Valley-fill deposits are Holocene (from 8310 ± 110 yr BP to present days) and composed exclusively of loessic/loessoid material from surrounding areas. 2) The dominant transport mechanism could have been laminar and/or hyperconcentrated flows, mainly associated with slope evolution processes (sheet flow and high density flows). 3) Isolated swamps with important biological activity were the dominated environments in to the valleys. These environments suggest an alternating pedogenic cycles, were the most important was the Middle-Late Holocene, indicating a landscape stabilization tendency (4330 ± 130 yr BP). 4) Temperate-wet climatic conditions and high seasonality characterized Middle-Early Holocene (Hypsithermal period). More arid conditions dominated Late Holocene. From 1500 to 1000 BP to the present temperate-wet climatic conditions occurred, and this period was interrupted by the Little Ice Age. 5) In the mountains, both in wet and dry periods, the rainfalls were probably higher as well as the temperature must be lower than the surrounding plain, especially in winters, perhaps reaching periglacial conditions during more arid periods.

1. Introduction

The summit planation surfaces present in the Sierras Pampeanas (locally known as "pampas de altura") correspond to old erosion surfaces generated on Precambrian-Early Paleozoic crystalline basement rocks, which were faulted and tilted during the Andean (Tertiary) orogeny, and subsequently subjected to new denudative cycles.

Some authors interpreted these surfaces as part of a single, unique "peneplain," in the sense of Davis (1899), which is supposed to developed between the Late Paleozoic and the Miocene and was later faulted, tilted, and exhumed during the Andean orogeny (González Díaz, 1981; Jordan et al., 1989; Costa et al., 1999; Beltramone, 2007). Others authors have proposed a polygenetic model, based on the concepts of King (1963), and recognized several planation levels of different origin and age (Rabassa et al., 1996, 1997, 2010; Carignano and Cioccale, 1997, 2008; Carignano et al., 1999; Cioccale and Carignano, 2009; Rabassa, 2010, 2014; Andreazzini and Degiovanni, 2014).

In the Sierras Pampeanas of the Córdoba Province, several levels have been recognized between 2.000 and 500 m a.s.l. These paleosurfaces show a very homogeneous relief, smoothly undulating and minimal internal elevation benches mainly associated with fluvial valleys. The main drainage systems precede the Andean uplift (González Díaz, 1981; Carignano et al., 1999; Degiovanni et al., 2003; Andreazzini and Degiovanni, 2014; among others), and

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started a marked process of incision and headwater erosion, which continues until present times. Longitudinal profiles of stream channels which drain the relict paleosurfaces are unadjusted and preserve features (valley and channel geometry) older than Middle Pleistocene (Degiovanni et al., 2003; Villegas et al., 2006).

The erosion surfaces were covered by loessic/loessoid deposits during the Pleistocene (Manzur, 1995; Tauber, 2006; Tauber and Goya, 2006; Tauber et al., 2008; Krapovickas and Tauber, 2012a,b; Andreazzini et al., 2013). Subsequently, these sediments were partially eroded by gravitational and fluvial processes linked to a reactivation of the drainage network towards the end of the Last Glacial Maximum (ISO2) (Andreazzini et al., 2013). At present, the average loessic thickness is less than 1 m, and exceptionally the cover just exceeds 5 m.

In addition to fluvial reactivation, associated with rainfall increases, tectonic activity should be also regarded as forcing factors on planation evolution during the Quaternary period. Specifically, numerous studies show movements of the main faults in the Sierras Pampeanas during the Upper Pleistocene-Holocene (Costa et al., 2001, 2014; Sagripanti et al., 1998, 2011; among others).

The study of the planation successions allows making inferences about the paleoenvironmental and paleoclimatic conditions that characterized the Sierras Pampeanas during the Quaternary, and comparative analysis with the conditions prevailing in the surrounding plains. The Quaternary evolution of Córdoba Province was recently synthesized by Kröhling and Carignano (2014), illustrating the studies were mainly focus on the lowlands while there are few contributions for the mountain areas. Among the latter can be cited Montes (1958), González (1960), Manzur (1995), Córdoba et al. (2005), Tauber (2006), Tauber and Goya (2006), Tauber et al. (2008), Medina et al. (2008), Medina and Merino (2012), Krapovickas and Tauber (2012a,b) and Andreazzini et al. (2013). Krapovickas and Tauber (2012a) analyzed the paleontology and stratigraphy of Quaternary deposits in several localities along the Sierras Pampeanas of Córdoba Province, where two main units were differentiated and assigned to the Middle-Late Pleistocene and Late Pleistocene-Holocene.

According to the synthesis presented in Carignano et al. (2012) and Kröhling and Carignano (2014), the Quaternary sedimentary sequence of "pampas de altura" in Córdoba Province has a thickness of ca. 4–10 m and is formed by four units separated by discontinuities, deposited on the bedrock. These units have been named: 1- "conglomerados basales", that would be related to the main uplift of the ranges (Early Pleistocene?); 2- "limos arenosos basales", which conform their fossil content are assigned to Middle-Late Pleistocene; 3- "limos de la parte central", that according to lithostratigraphic relationships, and the mineralogical, paleontological and archaeological composition would correspond at Last Glacial Maximum; and 4- "limos eólicos superiores", those lithostratigraphic conditions allows assigned this unit to the Mid-Late Holocene more arid cycle.

The goal of this study was to characterize the Late Quaternary successions that represent the fill valleys at the summit paleosurfaces of the southern Sierra de Comechingones, Córdoba Province, in order to infer paleoenvironmental and paleoclimatic conditions, and to propose a preliminary stratigraphic scheme.

2. Regional geological setting

This study was made on summit planation surfaces located in southern Sierra de Comechingones of the Sierras Pampeanas (Córdoba Province, Argentina), between 32°42′ and 32°50′ S and between 64°52′ and 64°59′ W, near Los Comederos stream (Fig. 1a–c). The Sierra de Comechingones constitutes the southern end of Sierras Grandes, it has about 150 km in length. The elevation decreases towards the south, from 2884 m a.s.l. at the Cerro Champaquí to 650 m a.s.l. at the southern tip.

The loessic deposits of the planation surface are related to a complex geological structure Precambrian-Lower Paleozoic crystalline rocks and a Quaternary cover (Fig. 2). Migmatites and paragneisses of the Monte Guazú Complex (Fagiano, 2007; Rey Ripoll, 2008), mylonites of the Guacha Corral shearing zone (Fagiano and Martino, 2004), and granites of the Cerro Áspero-Alpa Corral Batholith (Pinotti et al., 2002) are the dominant basement rocks. The Quaternary cover includes alluvial, colluvial and aeolian deposits, exposed mainly in the piedmont plains, the fluvial systems and a mantle over some sectors of the summit areas.

The landscape shows three major morphoestructural features: 1) submeridian megablocks of crystalline rocks, 2) a western scarp associated to the Comechingones fault, and 3) a lower eastern structural slope, strongly dissected by the drainage network, which preserves relicts of erosion paleosurfaces in the summit areas (Fig. 1b).

The drainage network above the planation paleosurfaces shows an angular and sub-dendritic pattern and the valleys preserves features previous to Middle Pleistocene. According to the Horton–Strahler classification, the principal streams are of order 3 or 4, and show broad inherited valleys and smooth slope (1.8–3%). The fluvial incision does not exceed 10–15 m, and channel depth is 3–5 m (Andreazzini and Degiovanni, 2014). The present channels are in process of reactivation. In some reaches the valleys attain the metamorphic bedrock, and show a small floodplain. Locally, active rill formation is observed where there are Quaternary sediments.

3. Material and methods

The relicts of planation surfaces covered by Quaternary deposits, especially those areas where there are gullies, were identified and mapped by means of the analysis of topographic maps (scale 1:50.000, Instituto Geográfico Nacional of Argentina), Landsat and Google Earth satellite images, and digital elevation models (DEM) such as SRTM (90 m resolution) (Fig. 1b). Field survey includes the analysis of the landscape morphology, description of stratigraphic sections, and identification of the active geomorphic processes. In particular one sedimentary section (P1) is representative of all the materials that fill the summit valleys, it is located at a tributary gully of Los Comederos stream (Section 1 – 32°45′26.45″S – 64°55′31.65″O) (Fig. 1c). Observations were completed with accessory sections surveyed along the area. The texture, color (according Munsell Color Chart), sedimentary structure, presence and grade of bioturbation, presence of oxides and/or cutans, cementation condition, type of contacts and facies distribution, were examined on each sedimentary unit identified. Sediment samples of different stratigraphic levels were obtained to obtain granulometric data, organic matter content and diatom taxon determinations. These samples were treated in the laboratory by drying at ambient temperature and subsequently were mechanically and chemically disaggregated. The colloidal organic matter was eliminated in cold, by successive applications of small amounts of hydrogen peroxide at 20%. The cements were removed by applications of HCl with buffer NaOAc at pH 5. Then, chemical and ultrasonic dispersion was made. Grain-size distribution were obtained using a Malvern particle laser counter (Mastersizer Hydro 2000 model), then classifying with the USDA (2014) textural proposal. Organic carbon was determined by Walkey Black modified by Jackson (1970) method.

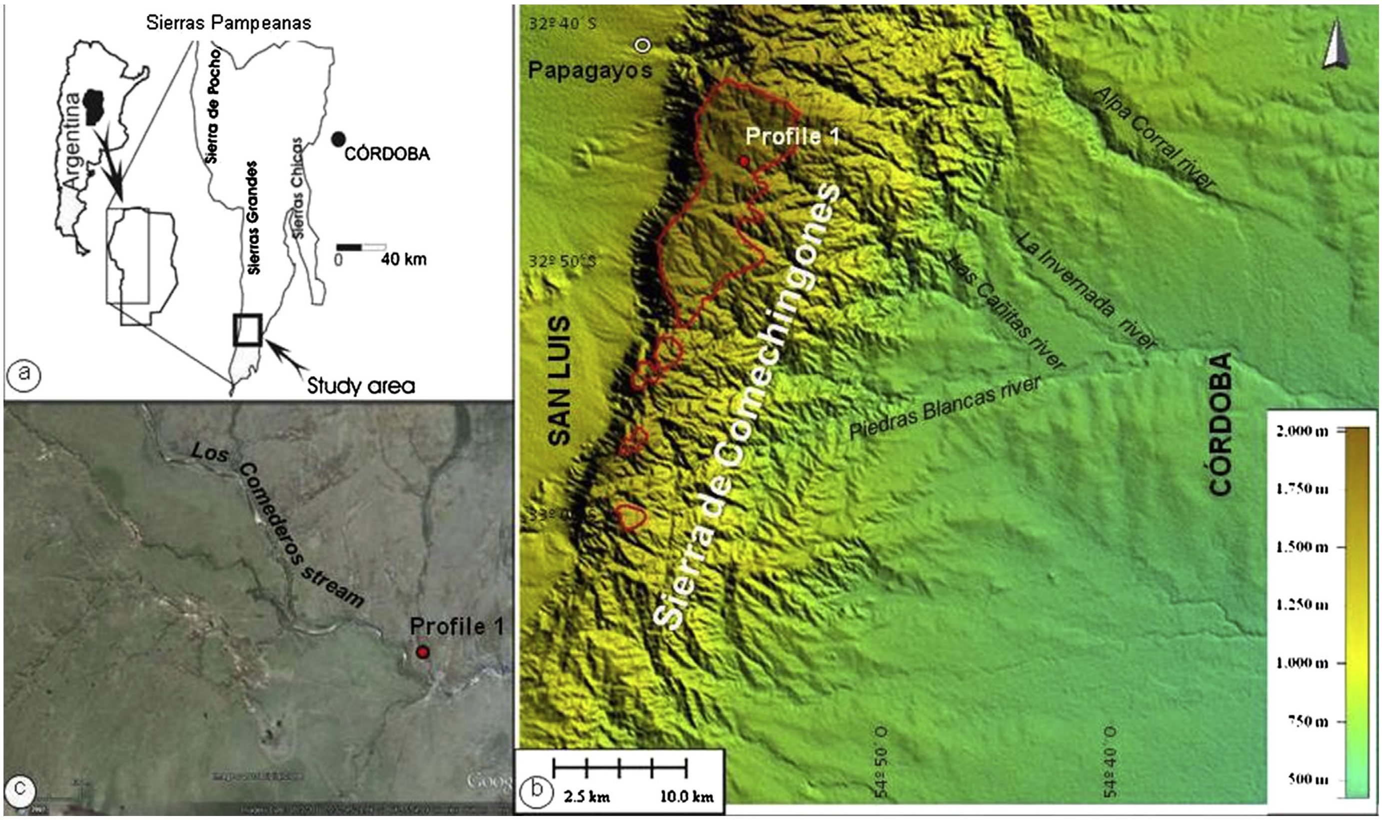

Fig. 1. a) Location of the study area at the southern zone of the Sierras Pampeanas. b) Digital elevation model from SRTM (Shuttle Radar Topography Mission) of 90 m resolution, the study Quaternary deposits in the summit plains are indicated by the red dot. c) Landsat image (courtesy of Google Earth) of the study area and location of the section P1 section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The successions were chronologically constrained by means of conventional radiocarbon dating, carried out at the Tritium and Radiocarbon Laboratory (Universidad Nacional de La Plata).

A microscopic qualitative analysis of diatoms was made on three samples, using a Zeiss standart 16 microscope. The material was firstly dissolved in water and the observation was made at 40x. The identification and ecological information of the diatoms were taken mainly from the literature (e.g., Patrick and Reimer, 1966; Patrick, 1977; Germain, 1981; Archibald, 1983; Krammer and Lange Bertalot, 1986; Krammer and Lange Bertalot, 1988; Round et al., 1990; Krammer and Lange Bertalot, 1991a,b; Round and Bukhtiyarova, 1996; Stoermer et al., 1999; Lange Bertalot, 2001; Metzeltin et al., 2005).

4. Results

4.1. Description and interpretation

Four main stratigraphic units, I to IV from base to top, were recognized in the analyzed succession at Section 1, showing 3.20 m of sediments overlying the metamorphic bedrock (Fig. 3 and Table 1).

Table 1
Analytical data of the units of the P1 section. References: ++ (many), +++ (very many).

Unit sub-unit (suffix)	IV	III$_2$	III$_1$	II$_4$	II$_3$	II$_2$	II$_1$	I
Depth from the top (cm)	0–20	20–50	50–54	54–79	79–114	114–174	174–264	264+
Color (matrix)	10YR 4,5/1	10YR 4,5/1	10YR 6/1	10YR 4,5/1	10YR 5/1	10YR 6/2	10YR 6/2	10YR 6/3
Cutans					++	++	++	
Bioturbation	++	+++	+++	++	++	++	++	++
% Organic carbon	2.23	4.85	2.05	2.75	1.23	1.48	1.48	0.63
% Organic matter	3.53	8.09	3.41	4.58	2.05	2.47	2.47	1.06
Texture (%)								
Clay (0–3.9 μm)	13.7	14.96	15.85	13.03	15.34	13.84	14.71	9.97
Silt (3.9–31 μm)	61	59.98	60.09	64.67	59.06	60.18	60.6	41.18
Coarse silt (31–62.5 μm)	18.78	17.26	16.48	18.14	18.94	17.95	17.41	19.24
Very fine sand (62.5–125 μm)	4.8	6.49	5.6	4.15	5.23	6.15	5.18	14.91
Fine sand (125–250 μm)	1.68	1.18	1.28	0.02	1.28	1.43	1.71	7.8
Medium sand (250–500 μm)	0.04	0.14	0.65	0	0.15	0.4	0.38	5.21
Coarse sand (500–1000 μm)	0.00	0	0.04	0	0	0.05	0	1.68
Very coarse sand (1000–2000 μm)	0.00	0	0	0	0	0	0	0.01

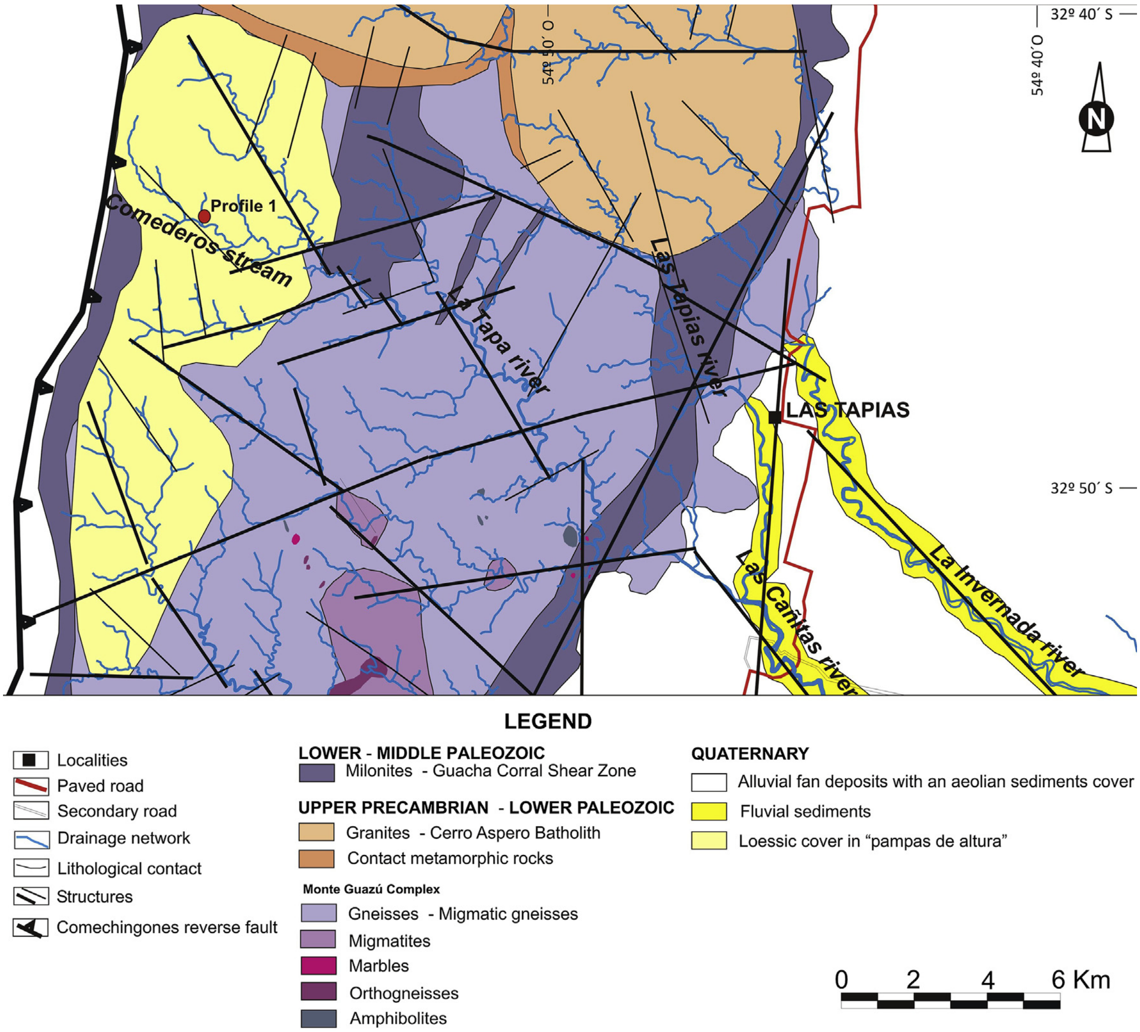

Fig. 2. Geological map of the study area (modified of Fagiano, 2007 and Rey Ripoll, 2008).

4.1.1. Unit I

At the base of the succession there is unit I, formed by 0.90 m of poorly sorted, silt loam with scattered fine gravels, and pale brown color (10YR 6/3) (Fig. 3a). It is a finely (1 mm), horizontally laminated to massive, with sets of up to 5 cm thick, tabular geometry and laterally traceable for several meters. Bioturbation is moderate. Frequent stains of Fe-oxides are associated to conduits/roots (Fig. 3b). The ^{14}C dating of a sample from Unit I at 45 cm above the base yielded an age of 8310 ± 110 yr BP (Table 1).

This unit is interpreted dominated by allochthonous loessic materials, with subordinated autochthonous sand coming from the weathered crystalline rocks. The sedimentary structure suggests depositation by low energy currents (Abdullatif, 1989; Miall, 1996), likely related to ephemeral water flows, which reworked the loessic sediments and mixed with the local sandy material. Fe-oxides, bioturbation and organic matter content suggest higher pedogenesis than sedimentation processes, possibly associated to more water availability attained seasonally.

4.1.2. Unit II

Unit II overlies through a sharp contact Unit I (Fig. 3c), and shows 2.20 m of massive, well/very well sorted, silt loam with scattered, less than 3 mm, pale brown, clay-silty nodules. This unit is light brownish gray (10YR 6/2) in the base and turns to dark gray/gray to the top (10YR 4,5/1). The upper 60 cm of Unit II is interpreted as a buried soil due to the presence of a dark color, intense bioturbation, pedogenic structure, in addition to moderate to high organic matter content and presence of cutans. This unit is then subdivided into four subunits (II_1, II_2, II_3 and II_4, Fig. 3a) based on pedogenic features, with transitional boundaries among them, and interpreted as buried soil horizons. The buried soils presents a moderate prismatic and blocky structure, breaking in angular and sub-angular small blocks, and clay-humic cutans mainly in the lower three subunits (more coarse and humic in II_3). A ^{14}C dating on organic matter from subunit II_4 yielded an age of 4330 ± 130 yr BP.

Unit II is interpreted as formed due to subaqueous current remobilization of loessic sediments previously accumulated on the summit planation surfaces of the Sierras Pampeanas. The lack of sedimentary structure can be related to deposition by hyperconcentrated flows (Harms et al., 1982; Martin and Turner, 1998). The deposition occurs rapidly from suspension with reduced turbulence inhibiting the formation of bedforms; the high sediment concentrations result in dampening of turbulence (Middleton and Southard, 1978; Lowe, 1982). The presence of some massive layers of silt deposited directly by wind can not ruled out.

Considering the ^{14}C ages obtained in Unit I and on the top of Unit II, this last succession is here interpreted as the result of discontinuous sediment aggradation and superimposed pedogenic processes.

Fig. 3. a) Sedimentological scheme and field view of P1 section, showing the identified four main units (Roman numbers) and sub-units (suffix). b) Detail of iron-oxides and bioturbation features in unit I. c) Sharp contact between units I and II. d) Close-up of the diatoms level (III$_2$) at the top of the section.

The different recognized horizons allow infering successive overlap pedogenesis periods (forming pedocomplexes). Thus, as the upper unit is deposited, the A horizon of lower unit receives translocation of colloids (clay and humus) from upper level, changing gradually to an argillic horizon (Bt). Level II$_4$, with high organic matter content (4.58%, Table 1) and lack of cutans corresponds to A horizon, associated to the most important pedogenetic cycle. The increase of organic matter on the top of Unit II indicated that rate production was higher than rate decomposition, favoring accumulation. In addition, the important clay translocation (Bt) suggests a moderate-wet environment, with a significant thermal amplitude, and a longer stabilization landscape period.

4.1.3. Unit III

Above a sharp and undulating boundary there is Unit III, composed of massive, 5–8 cm thick and horizontally laminated silt loam. This unit presents a moderate prismatic structure and important bioturbation (Fig. 3a–d). Within this unit, it was recognized a lower subunit (III$_1$) of gray/light gray color, rich in diatoms and lenticular geometry, and an upper subunit (III$_2$) of dark gray/gray color and with diatoms. In subunit III$_1$ 19 diatom taxa were identified: *Nitzschia sp*, *Pinnularia sp*, *Achnanthidium helveticum*, *Achnanthidium minutissimum*, *Diatoma vulgaris*, *Diploneis smithii*, *Gomphonema parvulum*, *Hantzschia virgata*, *Navicula mutica*, *Navicula radiosa*, *Nitzchia dissipata*, *Nitzchia frustulum*, *Nitzchia perminuta*, *Pinnularia borealis*, *Pinnularia braunii*, *Pinnularia maior*, *Pinnularia viridis*, *Planothidium lanceolatum*, *Rhopalodia gibba* and *Cymbella minuta*. *Pinnularia borealis* and *Achnanthidium minutissimum* were among the more abundant specimens. In subunit III$_2$ 9 diatom taxa, mostly broken and in lower numbers than in subunit III$_1$, were recognized: *Denticula sp*, *Navicula sp*, *Achnanthidium minutissimum*, *Cymbella minuta*, *Gomphonema acuminatum*, *Gomphonema parvulum*, *Hantzschia amphioxys*, *Pinnularia borealis* and *Pinnularia maior.*

Unit III, similarly to the lower two units, correspond to loessic sediments deposited from high density flows in subaqueous environments. The presence of diatoms frustules in the lower subunit III$_1$ indicates the existence of a lentic shallow and restricted water body, possibly formed in abandoned channel or isolated depressions in the floodplains. The determinated diatom taxa, especially *Pinnularia borealis* and *Achnanthidium minutissimum*, can be associated with shallow water environments with restricted water circulation, cool to cold clean waters, low salinity and nutrients content, and neutral to slightly alkaline pH.

Subunit III$_2$ represents the accumulation by hyperconcentrated flow deposits, with some reworking of previously deposited sediments rich in diatoms. The high organic matter content (approx. 8%, Table 1) and moderate structure to the top of Unit III indicate pedogenetic processes (A horizon).

4.1.4. Unit IV

This unit includes the uppermost sediments of Section 1, covering through a sharp and irregular contact Unit III (Fig. 3a). Unit IV is composed of 0.20 m of massive gray/dark gray, silty-loam in tabular beds and showing moderate irregular blocky structure and abundant roots.

The contact between units III and IV is interpreted as an erosion surface associated with an paleoenvironmental changes towards drier conditions than those occurring during accumulation of previous Unit III. Unit IV deposit correspond to loessoid deposits resulting from local remobilization of silt-loam materials deposited during this driest cycle. According to ^{14}C age obtained in II_4 the dry period is assigned to the Late Holocene (3500/3000 yr to 1400/1100 yr BP).

The development of the present soil on to Unit IV is supposed to start with the amelioration of climatic conditions, such as an increase in rainfall and temperature.

5. Discussion

Taking into account the presented information, the valleys of the summit planation surfaces of southern Sierras Pampeanas were filled due to loess accumulation, associated with current reworking, in the form of hyperconcentrated flows, of this silt, mixed with sand from weathered crystalline rocks. It seems there were at least four main sedimention events (Units I to IV) during the Holocene (since ca. 8.3 ka BP), that were periodically overprinted by soil formation.

According to Kröhling and Carignano (2014), the Holocene period in Córdoba Province is characterized by a significant decrease in loess sedimentation rate when compared with the late Pleistocene time. Eolian deposition is replaced by accumulation of fine sediments in marshy environment (with high organic matter content and diatom frustules in fluvial valleys), development of highly evolved soils in interfluvial settings, and a general expansion of water bodies (lakes, marshes). Similar deposits were described by Costa et al. (1999) in the high plains of the Sierra de San Luis (also part of the Sierras Pampeanas). These characteristics favored human settlement, as indicate by González (1960), Cantú et al. (1997), Tauber and Goya (2006) and Tauber et al. (2008).

The here studied loessoid deposits show similar features, but with some variations (like less thickness and areal extension, specific diatom species, among others) that are related to a higher relief position (summit planation surfaces) and place within a drainage system (headwater areas, low-order tributaries). These valley-fill successions represents local remobilization of available loessic deposits, possibly accumulated during the Last Glacial Maximum, like those described in interfluvial areas near the study area and dated in 23.0 ± 2.25 ka BP (Andreazzini et al., 2013). These loessoid deposits can be assigned to the La Invernada Formation (Cantú, 1992, 1998; Degiovanni et al., 2005) developed in the lowlands of Córdoba Province, and correlated with the unit “Limos de la parte central” of Kröhling and Carignano (2014).

The hyperconcentrated flows that reworked the primary loess are related to the evolution of valley slopes processes, characterized by thin sedimentary sequence overlying bedrock. They are interpreted as oversaturated flows, where the bedrock acts as a shear plane, and that could be associated with wet and warm periods as well as colder periods with frozen soils in the winter.

The important pedogenetic features registered in Section P1 is attributed to the Hypsithermal period, proposed for the Pampean region by Carignano and Ungaro (1988a,b), Cantú (1992), Iriondo and García (1993), Iriondo (1999), Carignano (1999) and Cantú et al. (2004), Carignano et al. (2012), Kröhling and Carignano (2014), among others. The wetter and warmer climatic conditions that characterized this warm period of Holocene (wet-cool conditions in winters, and wet-warm conditions in summers) are explained by Iriondo and García (1993) as linked to a change in the zonal circulation of westerly winds, and an intensified anticyclonic circulation around South Atlantic Anticyclon, which generated wet and warm air mass on the plains toward southwest. Iriondo et al. (2009) inferred an increase in atmospheric humidity, in the rainfalls (annual average *ca.* 2.200 mm/year), frequent intense storms and a highly positive water balance, linked to increased temperature.

Both in the lowlands and in mountain areas of Córdoba Province, several studies have described similar paleosoils in the Quaternary successions (Zamora, 1990; Iriondo and Kröhling, 1995, 2007; Manzur, 1995; Iriondo, 1999; Kröhling and Iriondo, 1999; Kemp et al., 2004a,b, 2006; Sanabria et al., 2006a,b; Sanabria and Argüello, 2011; Krapovickas and Tauber, 2012a,b; Andreazzini et al., 2013). Some authors assigned a formal name to this pedostratigraphic unit, among them Cantú (1992) who defines the Geosuelo Las Tapias for southern Córdoba Province. Carignano (1997) identifies the Geosuelo El Ranchito in Salinas Grandes basin (La Rioja province), and Cioccale (1999) describes the Río Pinto paleosoil on Sierras Chicas at the eastern slope of Sierras Pampeanas.

When the pedogenic features in the here defined Units II and III and in the Geosuelo Las Tapias (Cantú, 1992), described in the piedmont and surrounding plains are compared, it is possible to observe that the Geosuelo Las Tapias shows a lower development, without an argillic horizon, and only a cambic B horizon, then classified as a typical Hapludol (Cantú, 1992). These differences allow infering a higher water availability in the mountainous area than in the lowlands, as was also interpreted by Krapovickas and Tauber (2012b) according to the Pleistocene megafauna found in the loessoid deposits of Atum and Athos Pampa (Córdoba Province).

Moreover, the high content of organic matter and diatom species identified in section P1 also indicate that temperature in mountainous area would have been lower than in the surrounding plains, especially during the winter. Diatom deposits assigned to this period have been extensively identified in the Quaternary Pampean plains (Frenguelli and Cordini, 1937; Frenguelli, 1945; Kröhling, 1999; among others), but barely in mountain areas (Cappannini, 1955; Costa et al., 1999). In this study, diatom accumulations are thin and discontinuous, and the communities have small number of individuals adapted to more restricted environmental conditions. At present, with a temperate-wet climate in the region, a similar phenomenon is observed, especially in the winter period, where snow accumulation and low evapotranspiration are frequent, resulting in a large volume of water that is incorporated into the soil. It is considered that the current vegetation of the high pampas, characterized by a dense grass cover, can be thought as an analogue to the climatic conditions during the more wet cycles in the past.

During the driest period of the Middle-Late Holocene erosive processes associated with torrential currents, mass movement and subordinately localized deflation, would have dominated. These processes removed partially the soil generated during the Hypsithermal period. Subordinately, alluvial processes and hyperconcentrated flows occurred. Similar climatic conditions were described for Pampean region by Iriondo (1990), Iriondo and García (1993) and Iriondo (1999), and for Córdoba Province by Cantú (1992) and Carignano (1999), among others.

This arid cycle ends with deposition of very fine sandy/loessic sequences, represented in central Argentina by the Laguna Oscura (Cantú, 1992), San Guillermo (Iriondo and Kröhling, 1995), Guanaco Muerto (Carignano, 1997) and Estancia El Carmen (Cioccale, 1999) Formations. The deposits described as Unit IV in the study area, which show a reduced thickness similar to others in nearby high pampas, are attributed to this period. We consider that the source of these sediments comes from the southwest, supported by mineralogical and geomorphological studies of Laguna Oscura Formation in surrounding plain area (Blarasin, 1984; Degiovanni et al., 2005; Matteoda, 2012).

Approximately at 1000–1500 yr BP, an improvement in climatic conditions would have favored the pedogenesis of these deposits and the reactivation of the drainage network. In the surrounding plain area, the rising water table and expansion of lakes and water bodies have been described in several works (Cantú, 1992; Iriondo, 1999; Carignano, 1999; Carignano et al., 2014).

The reinstallation of fluvial systems 1000–1500 yr BP, caused the incision and partial erosion of these sequences in the high pampas. These restricted water circulation environments were reduced to headers or lower order channel reaches, where the lower slopes, presence of loessoid sediments and bedrock proximity favor the installation of saturated environments (swamps). Although there is no evidence of Little Ice Age (ca. 700–150 yr BP) in the analyzed section, in the surrounding landscape features linked to colder conditions, high snow precipitation (polygonal soils) are observed. Currently all sequence acts as a polygenic soil.

6. Conclusions

1 The drainage network, integrated at least since Middle Pleistocene, was still not adjustment. During the Holocene period, the valleys in the summit planation surfaces were dominated by aggradation processes. The hydrological connectivity with major order stream (out the high pampas) would be temporal, associated with significant rainfalls.
2 The valley-fill deposits are composed exclusively of loessic/loessoid materials from surrounding areas. Only the basal lithological sequence contains a minimum percentage of sand/gravel from the basement rocks. Thus, it is interpreted that remobilization processes involve only the Cenozoic cover without affecting the erosional paleosurfaces.
3 The dominant transport mechanisms were laminar and/or hyperconcentrated flows, mainly associated with slope evolution processes such as sheet flow/shallow concentrated flow, mass movement with high water content (intense rainfalls, freeze-thaw cycles) and the bedrock at shallow depths.
4 A low energy and restricted water movement conditions dominated in the valleys, which favored the occurrence of isolated swamps environments, with important biological activity. These environments demonstrate alternating pedogenic cycles.
5 Even if several pedogenesis cycles (pedocomplexes) were recorded, the most important was the Middle-Late Holocene, indicating a landscape stabilization tendency in this period. The soil corresponds to a well developed Argiudoll.
6 The stratigraphic and pedological characteristics, diatom levels presence, geomorphological features and altitude conditions of the study area allow us to infer: a) temperate-wet climatic conditions and high seasonality for Medium-Early Holocene, corresponding to the Hypsithermal period; b) More arid conditions during Late Holocene; and c) return to temperate-wet climatic conditions from 1500 to 1000 yr BP to the present, that include the cold period of Little Ice Age.
7 According to all the available data we infer important differences in the climatic condition between the mountain sector and the surrounding plains. In the mountains, both in wet and dry periods, rainfalls were highest, temperature was lowest, especially in winters, reaching periglacial conditions during more arid periods.

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