



Stratigraphy of the fluvial deposits of the Salado river basin, Buenos Aires Province: Lithology, chronology and paleoclimate



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ABSTRACT

The regional landscape of the Salado depression is related to weathering, eolian and fluvial processes generated under different climatic conditions. Although during most of the Holocene the climatic conditions were warm and humid, previously, a vast plain dominated by deflation processes and enhanced by weathering processes was developed in an arid environment. Fluvial deposits produced afterwards are continuous and lithologically homogeneous, which allows differentiation and characterization of the entire stratigraphic sequence. The stratigraphic units of this area, closely related to the paleoclimatic conditions, are recognized and characterized. Three lithostratigraphic units of fluvial origin (Members) and two paleosols have been differentiated. The first ones were grouped in the Luján Formation. Some of the units are related to other ones previously recognized in this area (La Chumbiada Member and La Pelada Geosol), but others have no similarity or relationship with previously known units (Gorch and Puente Las Gaviotas Members, and Frigorífico Belgrano Geosol). Radiocarbon ages suggest that the fluvial sequences were deposited after the glacial maximum, corresponding to MIS 1, except for the basal levels of the lower member which is late Late Pleistocene. Although the general paleoclimatic conditions were related to warm and humid climate, events related to water deficits were also recognized, which could be related to the Younger Dryas, the middle Holocene and the late Holocene.

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1. Introduction

The sedimentary record of the different basins of the Pampean region is composed of fluvial, lacustrine and eolian sequences that reflect the climatic changes of the Late Cenozoic. Because of the different geomorphological domains and the hierarchy of the water courses, the lithological components are variable, with alternation of aggradation, degradation and surface stabilization processes.

The Salado river basin is the most important hydrographic unit of the Buenos Aires Province that flows NW–SE into the

Samborombón Bay. Dunes, lowlands, lunettes, flood plains and the marginal coastal plain are the most outstanding features of this basin, which attest the eolian, fluvial and littoral processes as the most representatives of the area (Fucks et al., 2012).

The fluvial deposits generated by this water course are largely and continuously developed being among the main paleoenvironmental indicators. However, they have been the least studied if compared to similar deposits elsewhere in the Pampean region, either from the stratigraphic, paleontologic or chronologic standpoints.

For the Pampean region, one of the first contributions in which lithostratigraphic units were used, was focused on the lower sector of this basin (Fidalgo et al., 1973a,b). Later, these units were extrapolated and used for fluvial deposits in other parts of the region, keeping many similarities with the stratigraphic scheme proposed for the Luján river basin, northeast of the province of Buenos Aires (Ameghino, 1889).

The nomenclature of the units defined by Fidalgo et al. (1973a,b) replaced the designations employed so far such as “lujanense,

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platense, *querandinense* and *belgranense*” with chronostratigraphic connotations, which involved deposits of diverse origin and wide distributions.

From these works, it is in the coastal area where most contributions were developed concerning stratigraphic, geomorphological and paleontological aspects (i. e. Fidalgo, 1979; Parker et al., 1990; Codignotto and Aguirre, 1993; Schnack et al., 2005; Fucks et al., 2006), some of them reorganizing the stratigraphic scheme originally proposed (Fidalgo, 1979; Fucks et al., 2010).

In the strictly continental environment, some contributions made subdivisions of the original units (Dillon and Rabassa, 1985), and others replaced the original designations on the basis of the sedimentary content of the shallow lakes (Dangavs and Blasi, 1992, 2002). Other papers were focused on specific topics and followed the traditional scheme of Fidalgo et al. (1973a) yielding chronological, lithological, paleontological and geomorphological information (i.e. Dangavs, 1973, 2005, 2009; Dangavs and Reynaldi, 2008; Fucks et al., 2007, 2009, 2011, 2012; Mehl, 2011; Prado et al., 2013; Scanferla et al., 2013). However, there are few stratigraphic papers in which the sequences of the Salado river were re-studied, including radiometric ages to give support to the chronological ordering of the different stratigraphic units and their relationship with geomorphologic units of the study area.

In order to continue and deepen these studies, observations were conducted in the middle and lower sections of the Salado river basin, to define and correlate the lithostratigraphic units, considering that the study area is one of the most emblematic areas of the Quaternary stratigraphy in the Pampean region. Likewise, another goal was focused in determining the consistency of the large lithostratigraphic and edaphostratigraphic correlations of these environments.

2. Study area and methods

The study area involves 130 km along the Salado river in the province of Buenos Aires, from the “Las Flores Grande” lake (35°34'34"S/59°01'55"W) up to the vicinities of “Puente de Pascua” (35°55'39"S/57°43'14"W), near Samborombón Bay. In this sector, the river has winding and meandering designs, and cliffs irregular in heights, that depend on the geomorphological environment (such as permanent or transitory shallow lakes, paleolake or flood plains).

Most of the radiocarbon ages are obtained on freshwater molluscs (not very well specified in the text) and fewer on bulk organic matter. Both have concerns (e.g. hardwater and reservoir effect, contamination from young organic matter), which need at least mentioned; flood plains (Fig. 1). The analysis of 16 localities allowed recognizing, characterizing and correlating different lithologic units of fluvial origin, found in association with pedostratigraphic units.

The selection of sites, either on topographic maps or satellite images, was performed according to the different geomorphological environments, accessibility and background. On the outcrops, color, textures, structures, sedimentary facies and other features such as concretions, contact types and fossil content were analyzed. The textural descriptions were made in field and laboratory separating sand fractions of the mud with a sieve ASTM No. 230. Likewise remains of mollusks were also recovered for their identification and characterization.

Radiocarbon analyses were made in the Tritium and Radiocarbon Laboratory (LATYR – CIG). The treatment protocol for Organic Carbon in sediments and soils (COS) comprises separating roots, stone tools, etc. from the sample by a sieve ASTM N° 18. About one (1) kg of sediment was placed in a container with 1.5 L of MgCl₂ solution ($\delta = 1.1$ g/L) separating the by flotation. The solution

was washed and centrifuged repeatedly until pH = 7. The solid was dried in electric stove and ground coarsely for subsequent burning, purification of the obtained CO₂ and conversion to benzene (Huarte and Figini, 1988). The mollusk shells were separated from the sediment by washing with water on sieve ASTM N° 20 and then subjected to ultrasonic bath to remove traces of adhered material, then the specimens were treated with HCl solution to remove the 20% in wt of the surface carbonate, and the dried sample was transformed into benzene. The activity was measured by liquid scintillation spectrometry (LSC) with Packard and Packard Tricarb 3170TR/SL 1050TR/LL equipment. Ages are in radiocarbon years before present (1950 AD) – denominated conventional radiocarbon age-corrected by isotopic fractionation with $\delta^{13}\text{C}$ values estimated by table (Stuiver and Polach, 1977) and MO data express mean ages.

The datings were conducted on freshwater molluscs considered in equilibrium with the surface water and the environment, so if they exhibit a shift by reservoir effect, it is negligible for the purposes of the study for which they are employed.

The calibration for the terrestrial samples of the Southern Hemisphere is performed with the SHCal13.14c curve (Hogg et al., 2013), and for marine samples with the Marine13.14c curve (Reimer et al., 2013) and the CALIB 7.0.0 program used in conjunction with Stuiver and Reimer (1993). The subdivisions of the Holocene follow Walker et al. (2012).

3. Geological background

It has been 40 years since Fidalgo et al. (1973a,b) first studied the area, initiating the use of lithostratigraphic units in the Pampean region. Subsequent contributions dealing with fluvial sediments of this basin are scarce, instead those referred to lacustrine sediments have been more frequent (i.e. Dangavs and Blasi, 1992, 2002; Dangavs, 2005; Dangavs and Reynaldi, 2008). Fidalgo et al. (1973b) formally named the fluvial sequences as Luján Formation, with Guerrero and Río Salado Members, upper Pleistocene-Holocene in age, overlain by the modern Alluvium. Besides, they identified two paleosols: “La Pelada” and “Puesto Callejón Viejo”. Later Dillon and Rabassa (1985) established a new lithostratigraphic unit referred to the basal deposits of the Guerrero Member which they called La Chumbiada Member, upper Pleistocene in age. In this way, the Luján Formation was formed by the La Chumbiada, Guerrero and Río Salado Members.

Dangavs and Blasi (1992) defined the Lobos Formation, littoral in origin and Holocene in age, for the lacustrine environments associated with the Salado river. Later, Dangavs and Blasi (2002) placed this unit into de Luján Fm, and assigned it a fluvio-lacustrine origin and a Late Pleistocene age. Afterwards, Dangavs (2009) and Dangavs and Reynaldi (2008) proposed to change the hierarchy of the Lobos Formation into the Lobos Member being the Luján Fm formed by the members La Chumbiada, Lobos and Río Salado, covered by lacustrine sediments of the Subaluvial and Aluvial Formations (Fig. 2).

Recent stratigraphic and chronologic studies performed in some localities of this basin suggest ages very close to the Late Pleistocene–Holocene boundary, mainly Holocene, for most of the fluvial deposits (Fucks et al., 2007, 2009, 2011, 2012; Prado et al., 2013; Scanferla et al., 2013).

4. Geomorphologic environment

The Salado river basin occupies the central area of the Pampa deprimida (depressed Pampa) (Fidalgo, 1983) belonging to what Frenguelli (1950) named “área Pampásica deprimida o central” (depressed or central Pampean area). This basin has its source at the south of the province of Santa Fe, extending NW–SE over

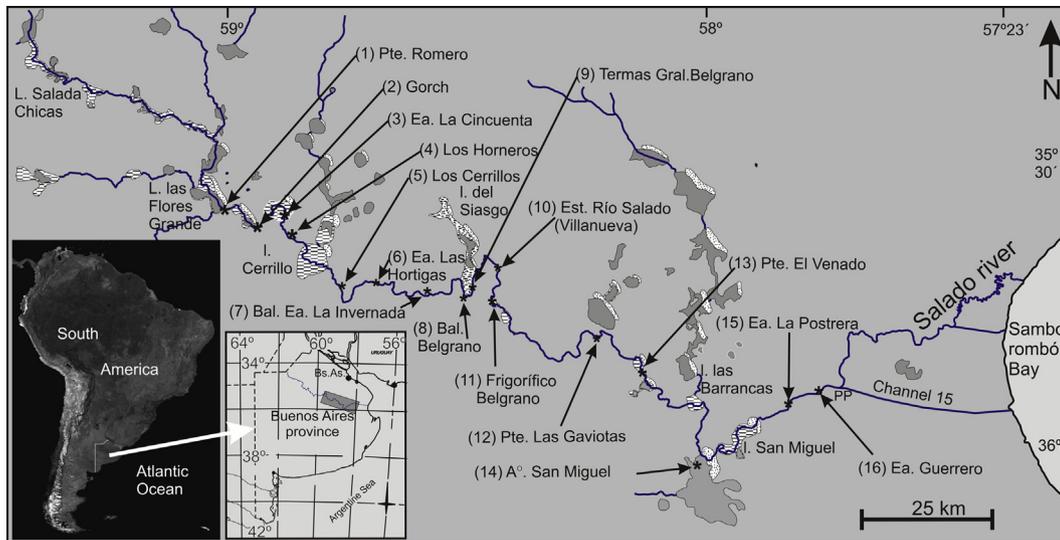


Fig. 1. Location map with sampling sites.

Age	Fidalgo et al., 1973a	Dillon y Rabassa, 1985 Fluvial environments	Dangavs y Blasi, 2002 A. El Siasgo	Dangavs, 2008 A. La Horqueta	Dangavs y Reynaldi, 2008 L. Los Cerrillos
Holocene	Modern Alluvium	Río Salado Mb.	Alluvium	Alluvium	Aluvial Fm.
	La Pelada Soil		Río Salado Mb.	Río Salado Mb.	Subaluvial Fm.
Late Pleistocene	Río Salado Mb.	Luján Fm.	Luján Fm.	Luján Fm.	Río Salado Mb.
	Puesto Callejón Viejo Soil		Lobos Fm.	Lobos Mb.	Lobos Mb.
	Luján Fm.		Guerrero Mb.	La Chumbiada Mb.	La Chumbiada Mb.
	Guerrero Mb.	La Chumbiada Mb.	Guerrero Mb.		

Fig. 2. Stratigraphic schemes of the study area.

about 650 km. Along its route this river crosses different geomorphologic environments that range from dune forms at its source (Pampa arenosa, sandy Pampa), shallow lakes, paleolake and flood plains in the middle and lower sector, to end in a littoral environment related to the Holocene transgression. It has a general winding and meandering design, the latter mainly when crossing paleolake and in the littoral area, with a low drainage density (Fucks et al., 2012).

From a regional point of view, the eolian processes, both erosive and of mantiform accumulation, of the Pampeano Formation (González Bonorino, 1965), or the more isolated ones of the La Postrera Formation (Fidalgo et al., 1973b) are the most important in the evolution of the Pampean region. Deflation basins, today occupied by shallow lakes, are among the most characteristic morphologies, and they are associated with arid-semiarid intervals established as a response mainly with the latter Andean glaciations (Rabassa, 2008), considered as major one in relation to the modern landscape (Fucks et al., 2012). Besides, the erosion produced by eolian processes forming the deflation basins (depression and lunette) must have been very strong along the whole depression, as evidenced by elevations and depressions of lesser magnitude but which attest the action of these processes. Another process related to the genesis of these depressions is the haloclasty, either disaggregating materials or pelletizing clay particles to form aggregates that are easily blown by the wind through rolling, saltation and suspension (Dangavs and Blasi, 2002; Gutiérrez Elorsa et al., 2005; Fucks et al., 2012).

5. Results and discussion

5.1. Recognized units

The different units recognized for this basin are well represented in outcrops of the banks of the Salado river, normally more than 2 m thick, although the exposure depends mainly on the water level. While in recent years drought has allowed direct observation of otherwise submerged levels, the dredging and the consequent construction of dams, produces an inverse and highly variable effect during the work progress.

Based on observations, radiometric ages, and trying to introduce the least possible changes to the current stratigraphic scheme, we propose the following organization of the sedimentary sequences (Fig 3), according to the CNE (Código de Nomenclatura Estratigráfico, 1992).

5.1.1. Luján Formation

This unit involves all the fluvial sediments partially or totally represented in the outcrops of the Salado river in the study area. The name “Lujanense” (Lujanian) is widely used since the end of the XIXth century in stratigraphic schemes of different authors despite its location more than 200 km away from the type locality. Its use would not be in accordance with the CNE (1992) but we decided to keep it given the tradition of this name for fluvial deposits of the region. These deposits vary between 2 and 6 m thick, being represented by three members.

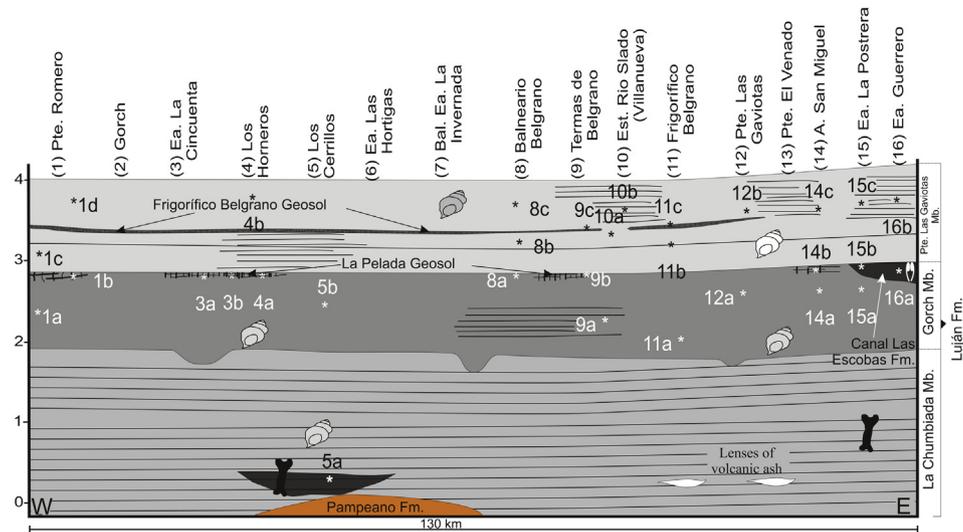


Fig. 3. Longitudinal profile of the Salado river between the "Laguna Las Flores" and "Estancia Buena Vista de Guerrero".

5.1.1.1. *La Chumbiada member* (Dillon and Rabassa, 1985). this unit is the lower section of the Luján Fm., unconformably lying on the Pampeano Fm. (González Bonorino, 1965). The contact is observed only in very restricted areas such as in the ranch Los Cerrillos. It is composed of gravel muds to sandy muds, dark brown in wet (10 YR 4/3), light brown to pinkish gray in dry (5Y 7/2), homogeneous to very stratified, compact but friable. Mineralogical composition includes vitroclasts, quartz, plagioclase, hornblende, microcline, volcanic lithoclasts, organic silica (phytoliths), and vegetal tissues. Presence of carbonatic cement in granulometry larger than 2 phi and anhydrite. Clay minerals have greater abundance of illite and to a lesser extent kaolinite and smectite. Normal thickness is about 2 m but maximum of 4 m and minimum of 0.5 can be observed depending on the geomorphological environment and water level.

This unit was defined on the homonymous place. Three kilometers downstream a muddy gray and black deposit 1.5 m thick is inserted in the La Chumbiada Mb and associated with a paleolake. This unit yielded remains of *Hippidion*, *Smilodon*, *Doedicurus* and *Megatherium* dated between 14 ky BP (Prado et al., 2013) and 12 ky BP (Scanferla et al., 2013) (Table 1).

At the base of "Puente Las Gaviotas" (Las Gaviotas bridge) there is a lens of volcanic ash (when dry: 2.5 YR 9/0, White), very pure, which suggests little or null re-deposition.

5.1.1.1.1. *Formation environment*. parallel laminar, trough and homogeneous sedimentary structures suggest sandy silt channel facies (Fig. 4), associated with flood plain and levees, deposited in restricted basin environments, as well as in more open depressed environments, which evolved into flood plains. The contact with the overlying unit is transitional.

Abundant gypsum content, spread and rosettes, several centimeters in size were found in certain sectors, which would be associated with local base levels or paleobasins precipitated during periods of aridity (Dangavs and Blassi, 2002; Fucks et al., 2012).

According to radiometric ages and the different geomorphologic environments, this unit began to be deposited after the glacial maximum, associated with the wide depression of the Salado where the deflation and eolian accumulation was significant during the cold and dry event (OIS 2), gathering and depositing the only sediments that formed the Pampeano plain. This is the reason for the great similarity with Pampeano loess.

5.1.1.1.2. *Age and correlation*. Late Pleistocene. Maximum age obtained was 14.040 ± 50 BP and minimum 12.100 ± 50 BP

(Table 1). It corresponds to the basal levels of the Guerrero Mb of the Luján Fm (Fidalgo et al., 1973b).

5.1.1.2. *Gorch member*. This unit represents the intermediate member of the Luján Fm. It is composed of sandy mud slightly gravely to slightly gravely sands, variable in color (basal section: 5 Y 5/1 gray in wet to 5 Y 6/1 gray in dry, and its upper section: 5 Y 6/1 gray in wet and 5 Y 8/1 white a 5Y 7/3 pale yellow in dry). This unit is very resistant when dry but soft when wet. Also, large amount of pulverulent calcium carbonate and gypsum, which can also appear as small rosettes are present.

It is composed of sub-rounded glass debris, some with canaliculus, plagioclase, quartz with inclusions, hornblende, chert, calcedonia, fresh sub-rounded microcline, traces of opaque minerals. Biosilica: phytoliths, scanty and fragmented diatoms and vegetal tissues. These components suggest higher humidity than in the underlying member. It is transitional with the lower unit and in net unconformity with the upper one, where some times there is a soil developed at the expense of the latter. Mainly the upper part is strongly disturbed, with large amount of root holes, with a dark color patina, which together with the volcanic ash gives it little specific weight.

This unit is observed along all the exposures, generally 1 m thick, although it may be thinner in the shallow lakes.

The deposits are homogeneous, but they can also bear parallel bedding, especially in those sectors little disturbed (Fig. 5). Some sectors, generally submerged, are greenish, showing variability in color depending on the humidity, although the normal color is gray and grayish yellow.

Commonly this member fills paleochannels in the underlying unit, with convolute structures or completely massive. This unit has large amount of spread carbonate which gives it high resistance in dry, but in the "Laguna Las Flores" its top is strongly cemented by calcrete (CO_3Ca) in its upper 15 cm as a table and also filling desiccation cracks. This important precipitation of calcium carbonate (exclusive of this locality in the study area) would be due to drainage of the streams Las Flores and Saladillo from the ranges and piedmont of the Tandilia system to an environment consolidated as base level, not only for these streams but also for the upper section of the Salado river.

5.1.1.2.1. *Formation environment*. Horizontal planar and homogeneous structures, development and filling of ravines cutting

Table 1

Radiocarbon ages in years BP and calibrated of the studied sites (Program CALIB 7.0.0, age range is 1σ). References: 1) Prado et al. (2013); 2) Scanferla et al. (2013); 3) Fucks et al. (2007); 4) Fucks et al. (2009); 5) Mehl (2011); 6) Figini et al. (2003).

Unit	Locality	Coordinates	Code. lab	Age ^{14}C BP	Age cal BP	Material	Profile and ref.
Canal Las Escobas Fm	Estancia El Callejón	35°55'16.01"S/57°43'48.94"W	LP-1209	5640 ± 70	5946–6125	<i>Zidona</i> sp.	(6)
			LP-1211	5870 ± 50	6234–6346	<i>T. plebeius</i>	
LA Pelada Geo-Sol	Estancia Guerrero	35°56'9.15"S/57°47'9.51"W	LP-2597	6730 ± 100	7160–7363	<i>T. plebeius</i>	14 b
			LP-2509	5920 ± 90	6556–6788	<i>T. plebeius</i>	13 b
	A° San Miguel	36°2'58.81"S/58°0'30.55"W	LP-2119	2580 ± 50	2880–2831	M.O	12 b (4)
					2821–2631		
	Termas de Belgrano Balneario Belgrano	35°43'39.28"S/58°29'36.23"W	LP-2514	5100 ± 100	3954–3760	M.O.	7b
			LP-1773	4220 ± 90	2880–2831	M.O.	8a
	Los Horneros	35°38'59.27"S/58°51'8.44"W	LP-2703	3960 ± 90	2821–2631		(3)
			AA89917	2989 ± 43	4226–4438	M.O.	4a
	La Cincuenta (San Genaro 1)	35°36'48.28"S/58°53'2.29"W			2950–3252	M.O	3b (5)
La Cincuenta (San Genaro 2)	35°36'26.1"S/58°52'50.7"W	AA89718	4530 ± 56	4884–4931	M.O.	3a	
				4958–5305		(5)	
Puente Romero	35°35'38.52"S/58°59'19.55"W	LP-2697	2900 ± 60	2870–3038	M.O	(1b)	
Pte. Las Gaviotas Mb.	Estancia. Guerrero	35°56'9.15"S/57°47'9.51"W	LP-2586	1070 ± 80	899–986	<i>H.parchappi</i>	16 b
			LP- 2817	960 ± 50	772–844	<i>P.canaliculata</i>	10 b
	Est. Río Salado (Villanueva)	35°41'57.01"S/58°26'52.62"W			856–905		
			LP- 2825	1710 ± 60	804–985	<i>H.parchappi</i>	10 a
					1024–1050		
	Ea. La Postrera	35°56'9.15"S/57°47'9.51"W	LP-2577	1840 ± 80	133–269	<i>H.parchappi</i>	15 c
			LP-2120	820 ± 60	663–741	<i>P.canaliculata</i>	14 c
	A° San Miguel	36°2'58.81"S/58°0'30.55"W					(4)
	Pte. Las Gaviotas	35°49'44.19"S/58°22'37.09"W	LP-2483	1550 ± 80	1306–1418	<i>P.canaliculata</i>	12 a
LP-2179			1.240 ± 60	772–899	<i>P.canaliculata</i>	11 c	
Frig. Belgrano	35°46'15.35"S/58°26'55.81"W	LP-2278	3.040 ± 70	3068–3265	<i>H.parchappi</i>	11 b	
		LP-2519	1.770 ± 40	1563–1692	<i>H.parchappi</i>	9c	
Termas de Belgrano	35°43'39.28"S/58°29'36.23"W	LP-1445	1340 ± 50	1186–1204	<i>P.canaliculata</i>	8c (3)	
				1240–1304			
		LP-1769	2440 ± 70	2346–2612	<i>H.parchappi</i>	8b (3)	
				2637–2686			
Los Horneros	35°38'59.27"S/58°51'8.44"W	LP-2693	710 ± 40	1288–1318	<i>P.canaliculata</i>	4b	
		AA89720	3002 ± 40	2962–3253	Shells	3a (5)	
La Cincuenta (San Genaro 2)	35°36'26.1"S/58°52'50.7"W						
Pte. Romero	35°45'04.5"S/58°30'44.5"W	LP-2153	680 ± 60	560–653	<i>P.canaliculata</i>	1d	
		LP-2228	1650 ± 80	358–365	<i>H.parchappi</i>	1c	
				381–571			
Gorch Mb.	Ea. La Postrera	35°58'20.16"S/57°53'56.11"W	LP-2561	9.510 ± 110	8859–8607	<i>H.parchappi</i>	15 a
			LP-2127	5.610 ± 110	6222–6230	<i>H.parchappi</i>	14 a
	Pte. Las Gaviotas	35°49'44.19"S/58°22'37.09"W	LP-2515	9.280 ± 150	6276–6487		
			LP-2253	11.690 ± 110	10234–10579	<i>H.parchappi</i>	12 a
Frig. Belgrano	35°46'5.26"S/58°27'15.80"W	LP-1770	8.640 ± 90	13347–13575	<i>H. parchappii</i>	11 a	
				9473–9704	<i>H. parchappii</i>	9a (3)	
				9723–9799			
Ea. Los Cerrillos	35°44'40.65"S/58°45'48.50"W	LP-2299	9.570 ± 150	10608–10614	<i>H. parchappii</i>	5 b	
				10658–11101			
La Chumbiada Mb.	Pte. Romero	35°35'32.80"S/59°0'31.66"W	LP-2699	8.720 ± 100	9530–9777	<i>H. parchappii</i>	1 a
			LP-2184	12.100 ± 100	13777–14024	M.O.	5 a
	Estancia Los Cerrillos	35°44'49.19"S/58°45'52.17"W	LP-2259	12.860 ± 120	15111–15512	<i>Doedicurus</i> sp	(2)
			LP-2184	13.400 ± 200	15761–16339	<i>Smilodon</i> sp	(1)
	LP-2568	12.380 ± 190	14054–14786	Bone			
	Beta-311032	14.040 ± 50	16886–17116	Bone			

underlying sediments, associated with abundance of phytoliths and diatoms suggest a fluvial environment with processes of sub-aquatic decantation. The large amount of calcium carbonate and gypsum, the high degree of organic activity, and the development of soils in depressed sectors would be related to large periods of aerial exposition with high levels of evaporation.

5.1.1.2.2. Age and correlation. Holocene Early and Middle (Walker et al., 2012). Radiometric ages vary between 11.690 ± 110 and 5.610 ± 110 BP. (Table 1). It is difficult to correlate this unit with some stratigraphic schemes, but it would correspond to the Lobos Fm or Lobos Mb, not Pleistocene but Holocene in the schemes of Dangavs and Blasi (1992 and subsequent). With respect to the scheme of Fidalgo et al. (1973b), because it involves yellowish and gray sediments, and those restricted greenish yellow sediments, Holocene in age, it would correspond to the Río Salado Mb, and probably the greenish portion of the Guerrero Mb, being the latter

very scarce in the study area. In this sense, shells from a green sediment of General Belgrano locality were dated in an intermediate age of the mentioned interval in Table 1 (8 ky BP, Fucks et al., 2007). In addition, regarding what Fidalgo et al. (1973b) stated about the presence of a paleosol near the ranch "La Pelada", that would separate this member from the Aluvio, and because we have recognized in this locality an inter-alluvial soil, it is likely that Fidalgo et al. (1973b) included in the Río Salado Mb the basal sediments of the Aluvio, in which large concentrations of *Heleobia parchappii* and *Biomphalaria peregrina* are found, mollusc species repeatedly mentioned by the authors. They also stated the difficulties to separate this member from the overlying alluvium when the La Pelada paleosol is not represented.

5.1.1.3. Puente Las Gaviotas member. The deposits of this unit are gray both in wet (5Y 5/1) and dry (5Y 6/1) although they may

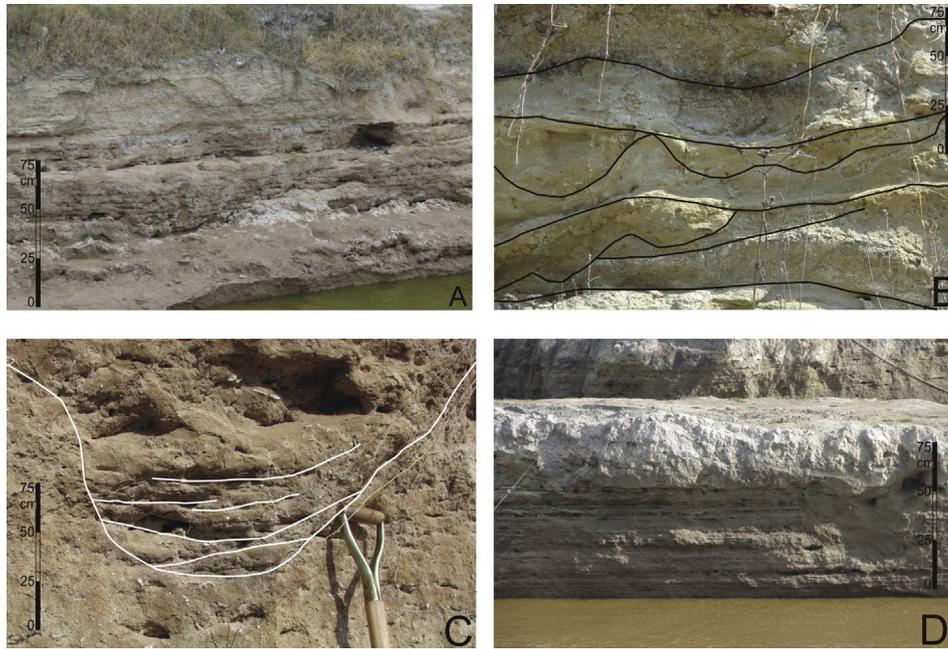


Fig. 4. Different exposures of the La Chumbiada Mb.: A and D, parallel bedding; B trough, and C: cut and fill. Localidades: A: Frigorífico Belgrano; B: La Chumbiada; C: Los Cerrillos; D: Pte. Las Gaviotas.

show brownish colors, and resistant depending on the humidity content. It is composed of sandy mud fractions; slightly gravel to sand slightly gravel, finely stratified, although commonly with important sectors completely homogeneous. Mineralogical composition includes quartz; sub-rounded zoned plagioclase almost unaltered, altered and sub-rounded glass debris and others very fresh, sub-angular to sub-rounded, epidote, not altered hornblende, and much altered opaques and lithics. Biosilica: abundance of crysophytes and fragments of diatoms. Mean thickness is about 1 m, although it depends on the environment and the geomorphological feature involved. This unit lies

unconformably on the Gorch Mb and has a soil on its top; it is little developed on the banks of the river but increases in thickness toward the flood plain.

Levels formed mainly by freshwater gastropods of *H. parchappii* are common, and also remains of *Pomacea canaliculata* are present, being the latter exclusive of this unit.

It can be separated into two units because of the presence of the “Frigorífico Belgrano” Geosol in the middle. Generally the lower section is grayish from light to dark gray depending on the humidity content and the large concentrations of *H. parchappii*. The upper section is brownish with abundant remains of *P. canaliculata*

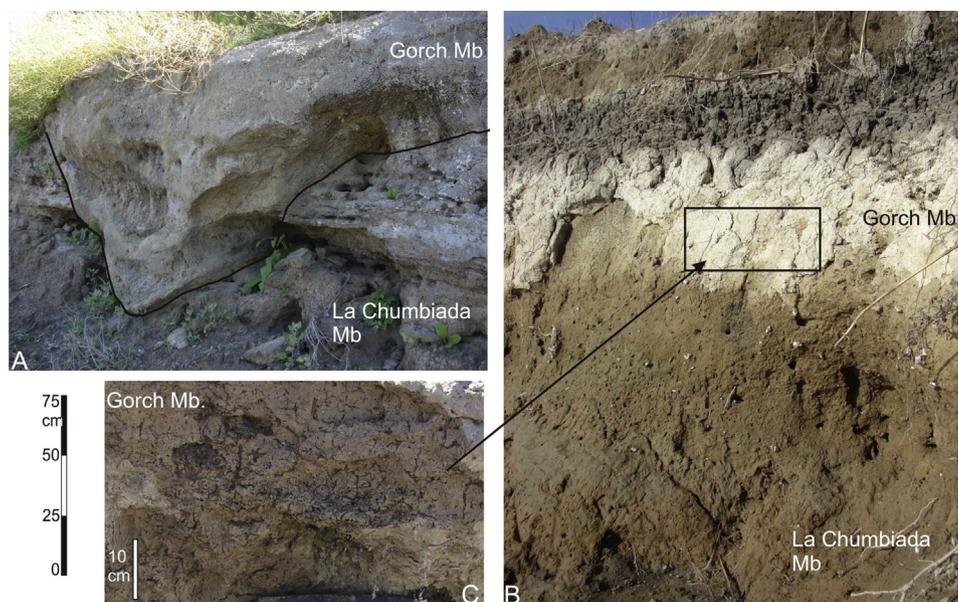


Fig. 5. The Gorch Mb. A: Cut and fill in deposits of the La Chumbiada Mb. B and C: transitional disposition over La Chumbiada Mb with the characteristic yellow color and bio-turbation structures. Localidades: A: Estancia Los Cerrillos; B: Gorch City; C: General appearance of the unit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

at the base, in contact with the soil, being a single unit when the soil is missing.

5.1.1.3.1. Formation environment. it represents the levees of the main course and affluents, where it reaches the largest development and the coarsest textures. In the flood plains and bottom of shallow lakes thicknesses are smaller, textures are finer and colors are more greenish and dark, although generally these landforms are always interconnected.

5.1.1.3.2. Ages and correlation. it corresponds to the Late Holocene. Radiometric ages vary between 3040 ± 70 and 680 ± 60 years BP being the chronologic limit between both sectors around 1.5 ky BP on the basis of the almost constant level of *P. canaliculata* directly lying on the Frigorífico Belgrano Geosol that divides this unit when present (Table 1 and Fig. 6).

These numerical chronologies suggest an older age than traditionally assigned to this unit, although it is variable depending on the geomorphological environment in which it is developed.

This unit corresponds to the Aluvio, Aluvio Actual, Aluvial Fm and Subaluvial Fm (Fidalgo et al., 1973b; Dangavs and Blasi, 2002; Dangavs, 2009; Dangavs and Reynaldi, 2008).

5.1.2. La Pelada Geosol

This geosol is 50 cm thick, composed of sandy mud slightly gravel, black, structured in columns 5–7 cm long with cutans on its sides. It is discontinuously present along the exposures depending on the geomorphologic environment, associated with deflation basins (Los Cerrillos, El Siasgo, Las Flores and San Lorenzo). It was formed at the expense of the fluvial sediments of the Gorch Mb, although it cannot be discarded that during its formation it has incorporated sedimentary supply from the Puente Las Gaviotas Mb.

In the ranch La Cincuenta, this geosol is very dark gray in wet (5 Y3/1) and brown grayish in dry (10 YR4/3). It is composed of sub-angulose quartz and some have Bohm laminae, altered glass and also fresh glass, sub-rounded zoned plagioclase, rounded or sub-

rounded opaques, volcanic lithics, and hornblende. Biosilica: diatoms, gramineae cells, phytoliths and spicules.

5.1.2.1. Formation environment. It has been observed in modern shallow lakes or paleolake, for which it may be related to depressed environments that in absence of major river accumulations, evolved as a swamp soil.

5.1.2.2. Age and correlation. it was developed in the Middle–Late Holocene, with ages between 5100 ± 100 and 2580 ± 50 BP (Table 1). It would correspond to the La Pelada paleosol (Fidalgo et al., 1973b) described for the continental area, which was later almost replaced by the Puesto Berrondo paleosol defined for the littoral area and used in large part of the Pampean plain. It was developed at the expense of the Gorch Mb and is covered by the Puente Las Gaviotas Mb (Fig. 7).

5.1.3. Frigorífico Belgrano Geosol

This geosol is thin (20–25 cm) but it stands out in the outcrops by the contrast with the overlying and underlying sediments. It is composed of very dark black mud, granular structure and cutans in the faces of the aggregates which disappear downward, whereas its upper contact is clear (Fig. 6). In many sites it is only seen because of the darker colors, bioturbation and light structure.

5.1.3.1. Formation environment. It is identified scarcely developed in levee sediments, covered by deposits of the same origin. It would be related to a brief episode of no fluvial deposition.

5.1.3.2. Age and correlation. This unit has been developed in the Late Holocene. Based on radiometric ages of the upper limit, it was buried approximately since 1.5 ky BP. This unit has no direct correlation with any other unit defined in the area, although farther NE in the province, similar ages have been obtained from an intra-alluvial level (Fucks et al., 2007, 2009).

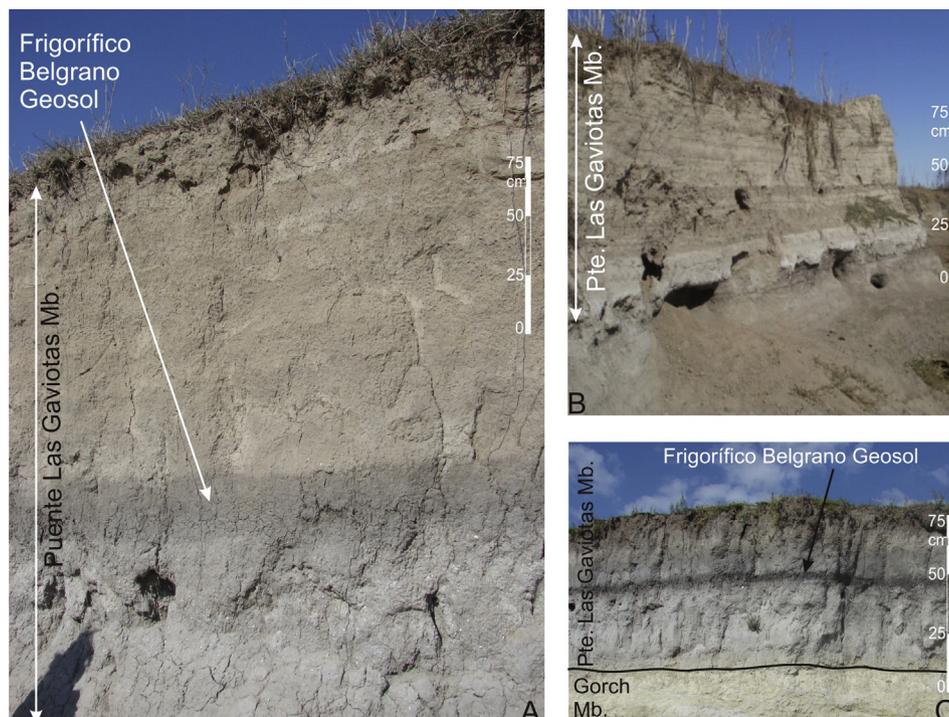


Fig. 6. Puente Las Gaviotas Mb. A: net contrast between gray and brownish sediments separated by the Frigorífico Belgrano Geosol. B: Deposit with parallel bedding. C: Very similar deposits above and below the Frigorífico Belgrano Geosol. Localities: A: Estancia La Cincuenta; B: Estación General Belgrano. C: Frigorífico General Belgrano.

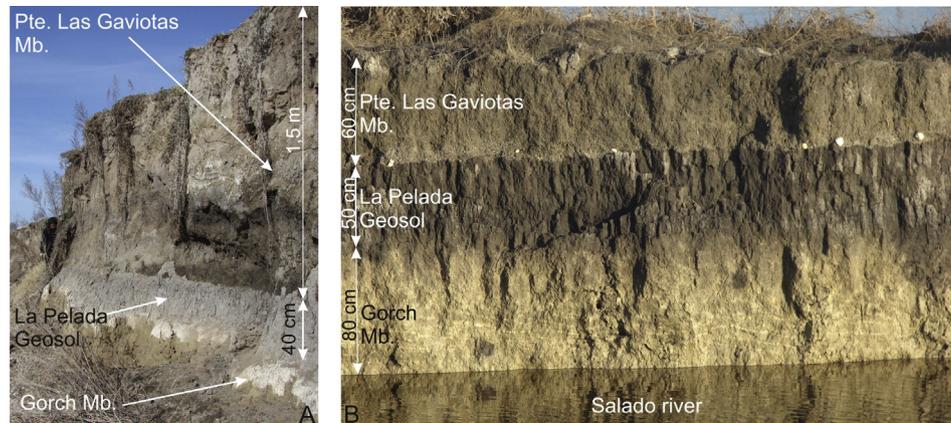


Fig. 7. Characteristics and stratigraphic position of the La Pelada Geosol. Localities: A: Los Horneros; B: Termas de Belgrano.

5.1.4. Canal Las Escobas Formation (Fidalgo et al., 1973a; Fucks et al., 2010)

Eastwards, a wedge of marine sediments of the MIS1 is interposed in the fluvial sediments (Fig. 7A). The lower sector is a black mud finely laminated with a large amount of marine shells, *Tagelus plebeius* with articulated valves and vertical position (Fig. 8B), being the bioerosion structures observed in the Gorch Mb. (Fig. 8C). A grayish brown sandier facies is developed above this level. The whole set is about 50 cm, unconformably overlying the fluvial sediments of the Puente Las Gaviotas Fm. (Fig. 8).

5.1.4.1. Formation environment. The marine transgression entered the study area exclusively through the Salado river, advancing toward the continent while the topography enabled it, and overflow into the paleolake such as in the ranches “Guerrero” or “La Postrera”.

5.1.4.2. Age and correlation. it belongs to the maximum transgression of the MIS1, Middle Holocene (Table 1). Las Escobas Fm

(Fidalgo et al., 1973a), Querandinense and Platense (Frenguelli, 1950).

5.2. General discussion

Based on the observations reported in this contribution, important differences arise in the stratigraphic scheme proposed by Fidalgo et al. (1973b) for the lower section of the Salado river, mainly on lithological aspects. One of the most controversial issues with respect to this paper is the almost constant reference of “green” sediments that were not much seen in the area, restricted to reduced areas saturated with water.

The reasons for this difference may be due to purely visual aspects and also the influence of previous works. This latter issue is related to the name “lujanense verde” (green Lujanian) that prevailed in those times (Ameghino, 1884, 1889 and subsequent authors). In view of its stratigraphic position these sediments correspond to those yellow to gray sediments associated with high concentration of gypsum and carbonate precipitates. Dominant

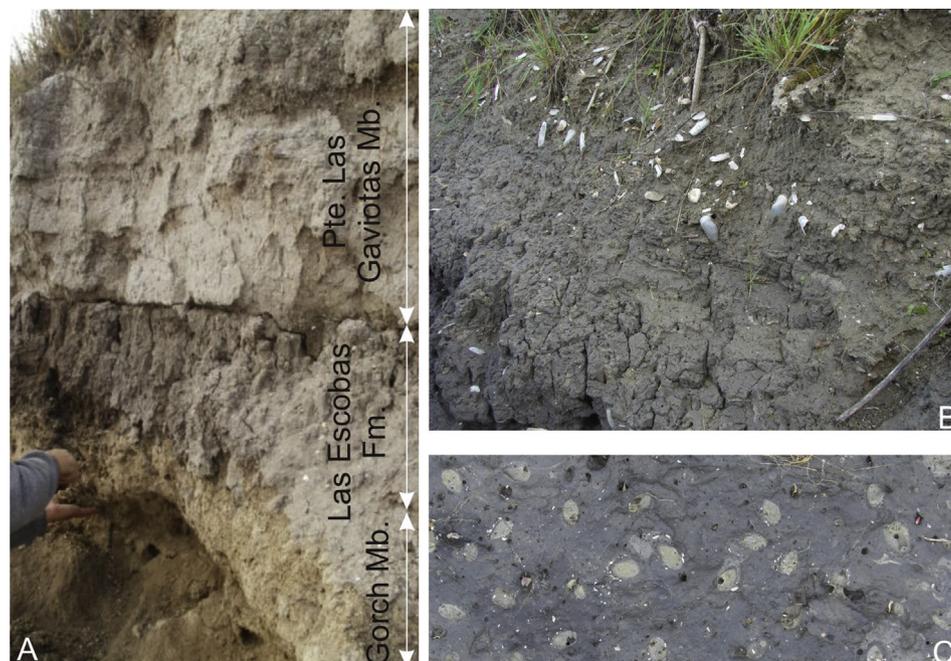


Fig. 8. A: Exposure of the MIS1 deposits, interposed in the Puente Las Gaviotas Fm in La Postrera site. B and C: *T. plebeius* in life position and bioturbation produced in the Gorch Mb.

colors of the Gorch Mb are light gray, yellowish gray and gray, being the “yellow olive” secondary, and always having priority yellow to green (5Y 7/3.5 and 6/4).

It is noteworthy that this scheme involves all the recognized fluvial units, including the most modern fluvial sediments that are known through different names (Aluvio, Aluvio Actual, Aluvio Reciente, Aluvio Fm, Subaluvial Fm), without respecting in most cases the rules of the stratigraphic code (CNE, 1992).

Another controversial issue is the presence or absence of paleosols defined in this basin (Fidalgo et al., 1973a,b). According to our analysis, the presence in this area of the oldest paleosol (Puesto Callejón Viejo) has to be reconsidered. As this paleosol was defined mainly for littoral environments and fluvial sectors of the Salado river influenced by the Holocene marine transgression, and it was based in observations in holes made manually, this unit might be mistaken with the Destacamento Río Salado Mb of the Canal Las Escobas Fm (Fidalgo et al., 1973b; Fucks et al., 2010). It must be taken into account that from an evolutionary standpoint this unit represented the hiatus between the second marine ingression (Destacamento Río Salado Fm) and the last one (Las Escobas Fm), in a scheme in which both were independent transgressions. In the study area, the Puesto Callejón Viejo paleosol was not recognized; instead, in most cases it is observed a transitional passage between La Chumbiada and Gorch members.

La Pelada Geosol, or Puesto Berrondo Geosol as it is most commonly known, is rarely observed in the study area. It is stratigraphically between the Gorch and Puente Las Gaviotas members, mainly associated with depressed sectors (paleolakes). Besides, within the Puente Las Gaviotas Mb there is the Frigorífico Belgrano Paleosol, more constantly observed in the area. Fidalgo et al. (1973a) stated the difficulty to separate the Alluvium from the Río Salado Mb when La Pelada Geosol was not present. This suggests that the Frigorífico Belgrano Geosol defined in this paper may correspond to the Suelo La Pelada in the scheme of Fidalgo et al. (1973a).

The formation of the most modern geosol is generally related to “benign climatic conditions” that would correspond to humid cycles, in opposition to drier cycles. This analysis contrasts with the present situation reflected by the levees where, despite the quite constant warm humid climate, enough to generate a soil, it is not formed. This would be related to the permanent accumulation of fluvial sediments which prevent the formation of soil profiles by weathering. Thus, it can be estimated that the formation of the interalluvial Frigorífico Belgrano Geosol corresponds to a moment of lesser precipitations, producing the temporary stabilization of the surface. Instead, in the modern bottoms of the shallow lakes and flood plains, there are muddy deposits with high organic matter content, which in periods of lesser precipitation would be favorable for developing weathering profiles, represented by the La Pelada Geosol.

These comments are not meant to interpret the presence or absence of paleosols and their relationship with climatic cycles in the opposite way. We try to establish a different relationship according to the paleoenvironment in which they occur. Consequently, the presence of a paleosol would not always be related to more benign climatic conditions, but to those in which in light of favorable geomorphological situations (e.g. an interruption of fluvial accumulation because of less precipitations) could give the necessary time for surface weathering.

6. Paleoenvironmental and paleoclimatic analysis

There are solid arguments on climate variations in the Pampean region, reflected in geomorphological, stratigraphical and paleontological papers (Tonni and Fidalgo, 1978; Iriondo, 1999; Prieto,

1996, 2000). Likewise, the isotopic curve obtained in Antarctica by Mulvaney et al. (2012) reflects the climatic changes for the southern hemisphere, which can be tentatively correlated, although the small scale climatic variations of the Salado Basin cannot be appreciated because of the lack of so accurate chronological control (Fig. 9).

First, the arid to semiarid conditions of the last glacial period (end of EI3 and EI2) left the most clear geomorphological expressions in the region, as demonstrated in the deposits of the La Postrera Fm of 18 ky (Kruck et al., 2011). The deflation basins and lunettes, as well as the wide depression where the Salado river drains today were generated mainly in this period. The eolian action and weathering, mostly chemical (haloclastism and hydroclastism), had major incidence in the area, more pronounced in certain places of the deflation basins, which could be related to playa lakes (Gutiérrez Elorza et al., 2005). Quite probably, the poor fluvio-lacustrine accumulations generated before or during this period were always deflated, explaining the presence of fresh water fossils and gypsum in the lunettes (Dangavs, 2009).

During the last glaciation, most of the continent would have had arid climatic conditions, and the subtropical grasslands extended toward the savanna areas in the austral Neotropical sectors (Behling and Hooghiemstra, 2001). The loess deposits of the Chaco-Pampean region suggest that the eolian deposition was dominant during the last glacial period, with main transport direction from the W and SW of the continent, in coincidence with the paleowind models (Zárate, 2007).

From these new climatic conditions generated by deglaciation (EI1), fluvial sequences associated with La Chumbiada Mb were deposited, with radiometric ages consistent with the end of the Pleistocene (Table 1). Channel and flood plain sedimentary structures (planar, trough and massive) with textures and colors similar to the Pampean loess, paleolakes, large amount of gypsum in rosettes and discontinuous laminae, associated with local base levels, and notable scantiness of fresh water fauna, suggest channeled runoff transporting the surrounding loess, explaining the great similarity, except for stratification, with loess sediments. This climatic stage could represent the first warming—interstadial—of the tardiglacial (Allerød: 14.1–12.9 ky BP), characterized by sub-humid and warmer conditions than the previous ones, representing a climatic improvement between the Oldest and Younger Dryas.

In the adjacent shallow lakes, over the La Chumbiada Mb the development of eolian deposits (Dangavs and Blasi, 2003) and lunettes (Kruck et al., 2011) may represent arid conditions assignable to the Younger Dryas, which may also be responsible for the gypsum precipitation in this member.

Associated with the valley, and transitionally, the sediments of the Gorch Mb are deposited. The greatest differences between these sediments with the underlying ones is the yellowish color and the high content of fresh water mollusks, with mechanical sedimentary structures almost absent probably because of bioturbation. Radiometric ages are between 11 and 5 ky, belonging to the Hypsithermal period, and it is generally associated with precipitation and temperatures higher than the previous ones. They are also characterized by important climatic fluctuations from arid to humid, which were also recorded in other sectors of the region (Prieto, 1996, 2000; Behling et al., 2005; Iriarte, 2006; Tonello and Prieto, 2010).

These climatic conditions associated with high sea level and less developed levees, made possible that large surfaces of the Salado depression could be subject to periodic flooding and drought, allowing the slow but continuous sedimentary accumulation with the presence of freshwater fossils and precipitation of carbonates and gypsum in the entire unit. Intense bioturbation is observed in all its thickness, although it is more pronounced in the upper part.

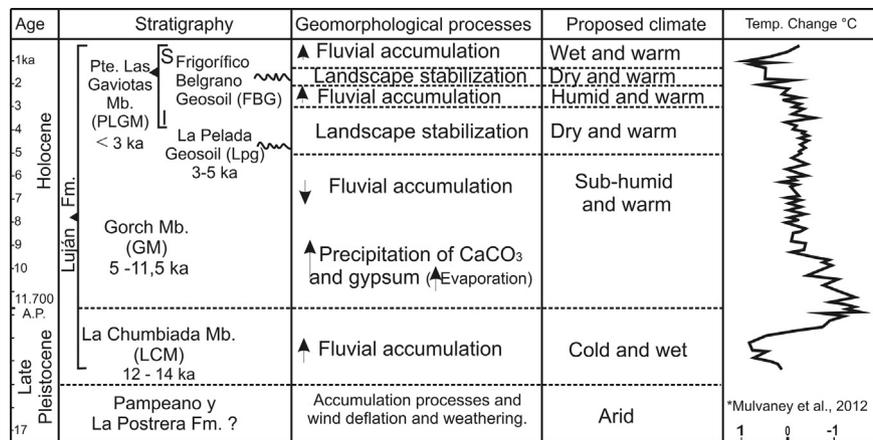


Fig. 9. Stratigraphic, geomorphologic and paleoclimatic scheme proposed for the study area.

Sedimentation was slow, allowing the action of the mentioned processes. Evapotranspiration was very strong, and sea level was about 3–4 m above the present one (Fucks et al., 2010). Humid conditions have been observed in different areas of the Pampean region (Tonello and Prieto, 2010) although in southern Brazil the changes were toward warmer and also dryer climate (Behling et al., 2005).

Deposition of this unit ends because of the change toward more arid conditions. Because of the new environmental conditions, the development of the La Pelada Geosol began in the depressed sectors between 5 and 4 ky BP. This shift from warm humid conditions toward sub-humid and arid has been observed in different areas of the region (Prieto, 1996; Iriarte, 2006; Zárate and Páez, 2002), even with glacial advances in the Andes (Espizua, 1998; Gil et al., 2005). In the Luján river basin, Prieto et al. (2004) recognized a dry period in the Middle Holocene, with abundant carbonate precipitation in alkaline swamp environments. In the “Laguna Mar Chiquita” a new dry phase is recorded ca. 4220 ± 95 years BP (Piovano et al., 2009). In the Sauce Grande River, the pollen record and eolian deposits suggest a dryer climate (sub-humid) around 4–5 ky BP (Zárate and Flegenheimer, 1991).

The sediments of the Puente Las Gaviotas Mb are thick, with a rich freshwater fauna and precipitates as cement that give a great resistance when dry. It represents the last 3 ky BP, associated with similar climatic conditions to the present ones, with some interruptions. The development of a soil in the intermediate sector suggests a transitory stabilization of the levee during its formation, around 1.5 ky BP which would correspond to an event o lesser humidity. In the Arroyo Chasicó, south of the province of Buenos Aires, a record between 3.1 and 1.5 ky BP, suggests a dominance of fluvial accumulation within environments of relative instability, changing toward more stable conditions during the last 1500 years (Zech et al., 2009).

According to this, it can be seen that within the Holocene major alternations occurred in climate conditions, which, although not as extreme as in glacial episodes, they produced reactivation and/or stabilization of the landscape, clearly recognized in the sedimentary sequences.

7. Conclusions

- A new stratigraphic scheme is proposed for the lower and middle basin of the Salado river, in view of the differences observed in the deposits with previous schemes. Fluvial sediments are united in the Luján Formation, composed by three members: La Chumbiada, Gorch and Puente Las Gaviotas.

- Two paleosols are recognized, La Pelada and Frigorífico Belgrano, associated with fluvial deposits, which would represent depositional hiatus around 5–4 ky and 1.5 ky BP respectively.
- The modern landscape of the Pampean plain is the result of the interaction of geomorphological processes generated under much variable climatic conditions. From arid to humid extremes to warm and cold ones, these fluctuations took part in the evolution of the landscape resulting in particular forms representative of their action.
- The development of the deflation-lunettes basins and loess sheet deposits are representatives of the different arid episodes, in which the eolian processes and weathering are dominant. Likewise, the Frigorífico Belgrano Geosol would also be related to a period of less precipitation, allowing the development of a soil profile on the levees because of the absence of fluvial accumulations.
- According to the radiometric ages, fluvial sediments were developed after the Last Glacial Maximum, with ages younger than those obtained for other areas of the Pampean plain.
- The sediments of the Holocene marine transgression (MIS 1), farther into the continent, are wedged between the fluvial sediments of the Gorch and Puente Las Gaviotas members of the Luján Fm with ages of 6.7–6 ky BP.

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