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Late Pleistocene-Holocene paleoenvironments in the middle basin of the Salado river, province of Buenos Aires, Argentina

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A R T I C L E I N F O

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A B S T R A C T

The Salado river basin is the largest one in the Buenos Aires province, with an area near 170,000 km^2. This work aims to perform a stratigraphic analysis of the middle sector of this basin to provide information on the paleoenvironmental evolution during the end of the Quaternary. Results indicate that the evolution of this basin occurred largely in water deficit conditions. Different aeolian lithostratigraphic units are recognized and grouped into three units, as follows: La Postrera, Laguna Las Barrancas, and De la Riestra Formations. New lithological, paleontological, and chronological information is provided regarding the fluvial deposits, which allows for a deeper understanding of the paleoenvironmental conditions that prevailed during deposition. The integrated study of all these deposits with an adjusted chronological control suggests a paleoenvironmental model that is directly associated with the climatic conditions that prevailed at the end of the Quaternary.

1. Introduction

The climatic oscillations that occurred during the Quaternary, with its extremes between glaciations and interglacial periods, have left their footprints in virtually all environments, with greater influence where exogenous processes were the exclusive modelers of the landscape. However, not all sites respond synchronously or equally despite their global extension (Mayewski et al., 2004; Zárate, 2005). This last point highlights the complexity of the Holocene climate, further emphasizing the importance of having specific paleoclimatic data of the study site, to avoid the risk of extrapolating data series from other areas (Mayewski et al., 2004).

Even if the understanding of Late Cenozoic sedimentary dynamics has increased substantially in the last decades, it is still necessary to adjust the chronological frame and, especially, to reconstruct in detail the paleoenvironments through an interdisciplinary approach (Zárate, 2005). Fluvial, aeolian and fluvial-lacustrine deposits developed in the middle basin of the Salado river, are an excellent sedimentary succession to analyze different proxies, exploring the paleoclimatic conditions that prevailed in the area.

The main collector of this basin is the Salado river, which has its headwaters in the south of the province of Santa Fe, flowing with NW-SE direction along about 650 km to its mouth in the Samborombón Bay. During this path, it receives the contribution of numerous tributaries and artificial channels, mostly on its right bank. The drainage basin is 87,775 km^2 (Subsecretaría de Recursos Hídricos, 2002) or near 170,000 km^2 if the "Noroeste" (66,000 km^2) and "Lagunas Encadenadas del Oeste" (11,000 km^2) regions, which have been linked to the hydrographic basin by artificial channels, are included (PMI, 1999). Throughout the basin, there are periodically floods that affect villages and productive fields, as well as important droughts. In recent years, an extensive program of dredging and channel widening along the main course, its tributaries, and shallow lakes has been implemented to solve these problems. Those works left exposed significant outcrops, which increases at times of low water levels. Thus, it is easier to analyze them both lithologically and paleontologically, obtaining more profitable results in the search for a paleoenvironmental model.

From a regional point of view, this basin is located in the Pampean region, whose flat shape responds to aeolian processes, both erosive and related to mantiform accumulations of the aeolian sediments of the

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Pampeano Formation (González Bonorino, 1965). Subsequent exogenous processes have acted on these sediments in response to climatic cycles, resulting in morphologies of different ranges and diversity, which allow their separation into Pampa Arenosa (Sandy Pampa), Pampa Deprimida (Depressed Pampa), and Planicie Costera (Coastal Plain) (Fucks et al., 2012). The Salado river basin is mostly developed along the Pampa Deprimida, although it is characterized from its headwaters to near the locality of Alberti by dune-like shapes, whether linear or parabolic (Pampa Arenosa) located in the 'Central Pampean dunefields' (CPF) aeolian unit (Zárate and Tripaldi, 2011). The middle sector develops from Alberti and up to the vicinity of Pila, with deflation basins and *lunettes* as dominant geoforms, and corresponding to 'Loess and loess-like mantles and blowouts' (LMB) aeolian unit (Zárate and Tripaldi, 2011), although transverse and parabolic dunes are also present in the transition zone between both units.

The aim of this work is to recognize and define the existing stratigraphic units, which, associated with the geomorphological paleoenvironments, new datings and multi-proxy data, would allow inferring the evolutionary history of the region and its relationship with paleoclimatic changes.

We hypothesize that many geomorphological environments have developed throughout this basin, closely associated with climate changes during Late Pleistocene-Holocene, varying between glaciations and interglacial periods. Many minor events were developed within them, being sometimes clearly represented, either through geomorphological features or stratigraphic and paleontological records.

In order to continue and deepen our studies (Fucks et al., 2012, 2015; Mari et al., 2013; Pisano, 2015, 2016; Pommarés et al., 2018; Ramos et al., 2019), new surveys were carried out focused on the lithological and paleontological characterization of one of the most emblematic areas of the Quaternary stratigraphy in the Pampean plains. In addition, new chronological ages were obtained, which added to those previously acquired, are very significant since making extrapolations and correlations to other areas without precise chronological control generate uncertainties, especially when establishing paleoclimatic models.

2. Geological setting and background

Although the Salado river basin is the most important hydrographic network in the province of Buenos Aires, geological studies in the continental area have only been intensified in recent decades (Fucks et al., 2012, 2015; Mari et al., 2013). The pioneer works of Tricart (1973) and Fidalgo et al. (1973) have strong geomorphological and stratigraphic approaches, respectively. Both, in addition to establishing the foundations of the lithostratigraphic units, also stated the concepts of changes in the past climate.

The basis on which studied units are developed corresponds to the Pampeano Formation (González Bonorino, 1965), which have been subsequently reworked, forming new aeolian deposits referred to as La Postrera Formation (Fidalgo et al., 1973; Fidalgo, 1990). Zárate (2005), when studying the continental records of Late Cenozoic in Buenos Aires province, individualized four stratigraphic intervals based on a regional analysis of exposures, as well as the observed stratigraphic relationships, lithofacies characteristics and spatial distribution and deposits geomorphological expression. The fourth and last interval (Late Pleistocene-Holocene) registers the environmental conditions that prevailed previously and during the Last Glacial Maximum (LGM) as well as the climatic transition to the current Interglacial, which is also the time range of interest of this contribution.

Regarding fluvial units, they were grouped in the Luján Formation (Guerrero and Río Salado Members) and Aluvio (Fidalgo et al., 1973, Fidalgo, 1975). Subsequently, Dillon and Rabassa (1985) separated the basal part of the Guerrero Member into a new unit named La Chumbiada Member. This scheme was largely used, even in other basins of the Pampean region (Fig. 1). Since these initial schemes were not supported by absolute datings, in addition to recent changes in the Quaternary International Chronostratigraphic Chart (Cohen et al., 2013, updated), both limits and new subdivisions, correlations between previous and

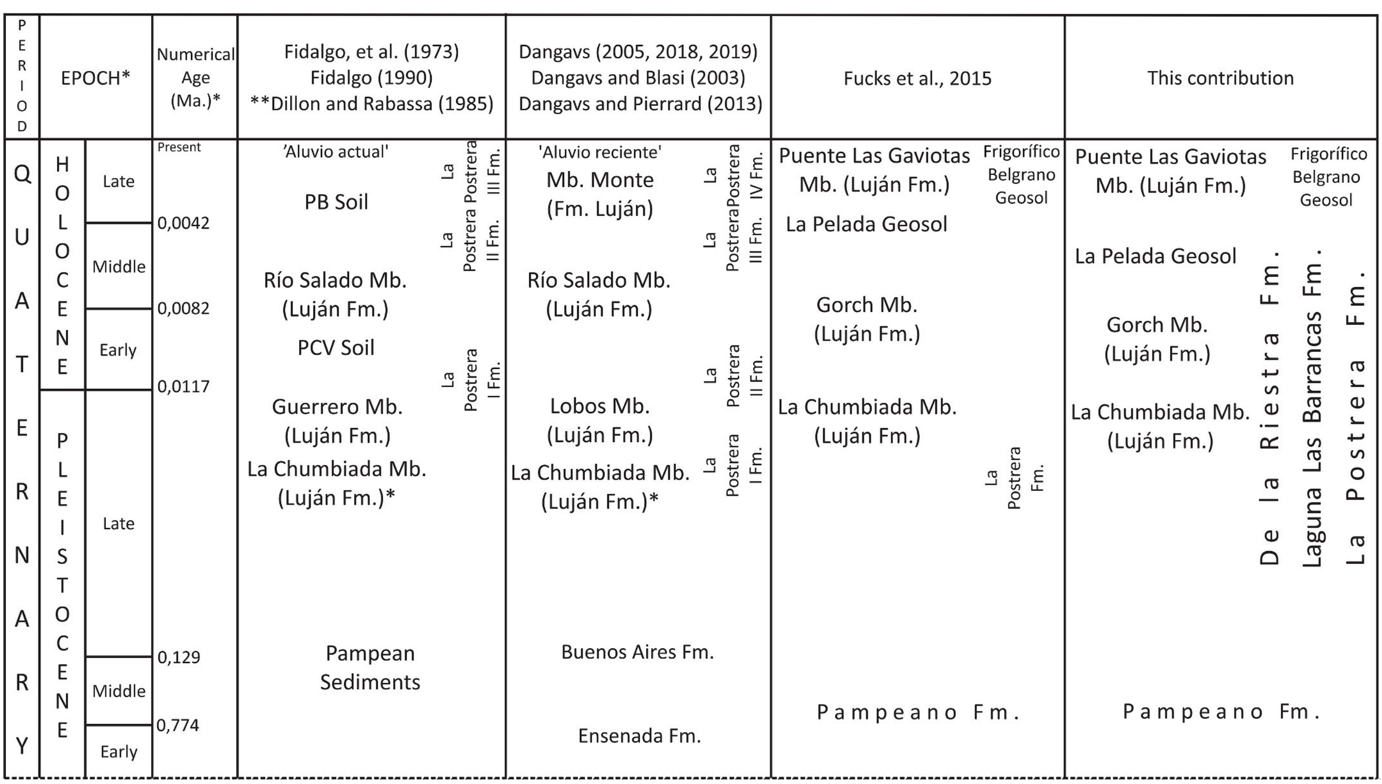

Fig. 1. Previous stratigraphic schemes for Pampean Region and the proposed in this contribution for Salado river basin. *According to ICS International Chronostratigraphic Chart (Cohen et al., 2013, updated). PB=Puesto Berrondo, PCV=Puesto Callejón Viejo.

current proposals are approximated. Research of recent years (Fucks et al., 2007, 2009, 2012, 2015; Mari et al., 2013; Pisano, 2015; Pisano and Fucks, 2016) was focused on radiocarbon dating, considering that abundant and reliable chronological data is necessary to build a paleo-evolutionary scheme. In this sense, these studies redefined and regrouped the fluvial sedimentary sequences of the Luján Formation into three members: La Chumbiada, Gorch, and Puente Las Gaviotas, with oldest numerical ages close to 16 ka, corresponding to the last stage of MIS 2 and all of MIS 1 (Fucks et al., 2015, Fig. 1).

3. Study area

The study area covers about 130 km along the Salado river and is located between the surroundings of the towns of Alberti and General Belgrano (Fig. 2). Upstream of Las Flores shallow lakes (Fig. 2), the river has low ravines (0.5–1 m) of irregular heights or they are absent, while downstream there are generally higher ravines of about 2–4 m, depending on this not only on the particular geomorphological environment (shallow lakes, paleo-shallow lakes, flood plains), but also on the water level, especially due to the important dredging works (Fig. 2).

3.1. Climate

The climate of the Pampa Deprimida is temperate-humid with a marked thermal seasonality. Mean annual temperature is between 14 °C and 17 °C, with minimum values lower than 5 °C in July and a maximum of 30 °C in January (Servicio Meteorológico Nacional, 2018) (Fig. 3).

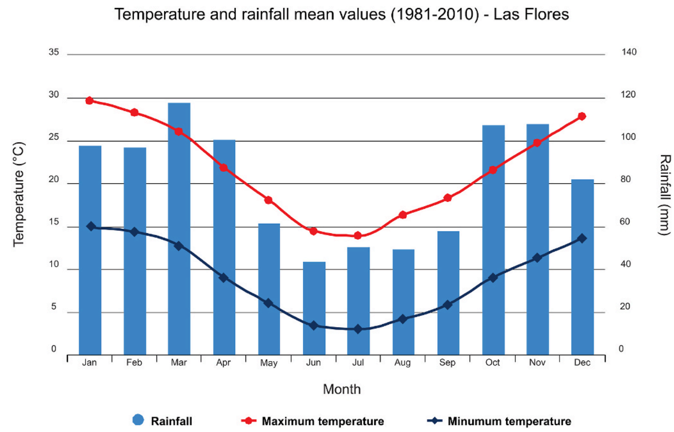

Fig. 3. Temperature and rainfall mean values (1981–2010) at Las Flores weather station (see location in Fig. 2). Data obtained from the Servicio Meteorológico Nacional (SMN, 2018).

The average relative humidity is 70%, with a dry (winter) and a wet (summer) season, with mild winds prevailing from the E and NE. The mean annual rainfall is 900 mm, with March being the rainiest month and June the least rainy (Fig. 3). Rainfall has shown a marked increase in recent decades, being 919 mm in the 1960s and more than 1000 in the 1990s (Dirección Provincial de Obra Hidráulica, 2016). This increase in annual rainfall has been very marked since the 1970s, rising to 20%.

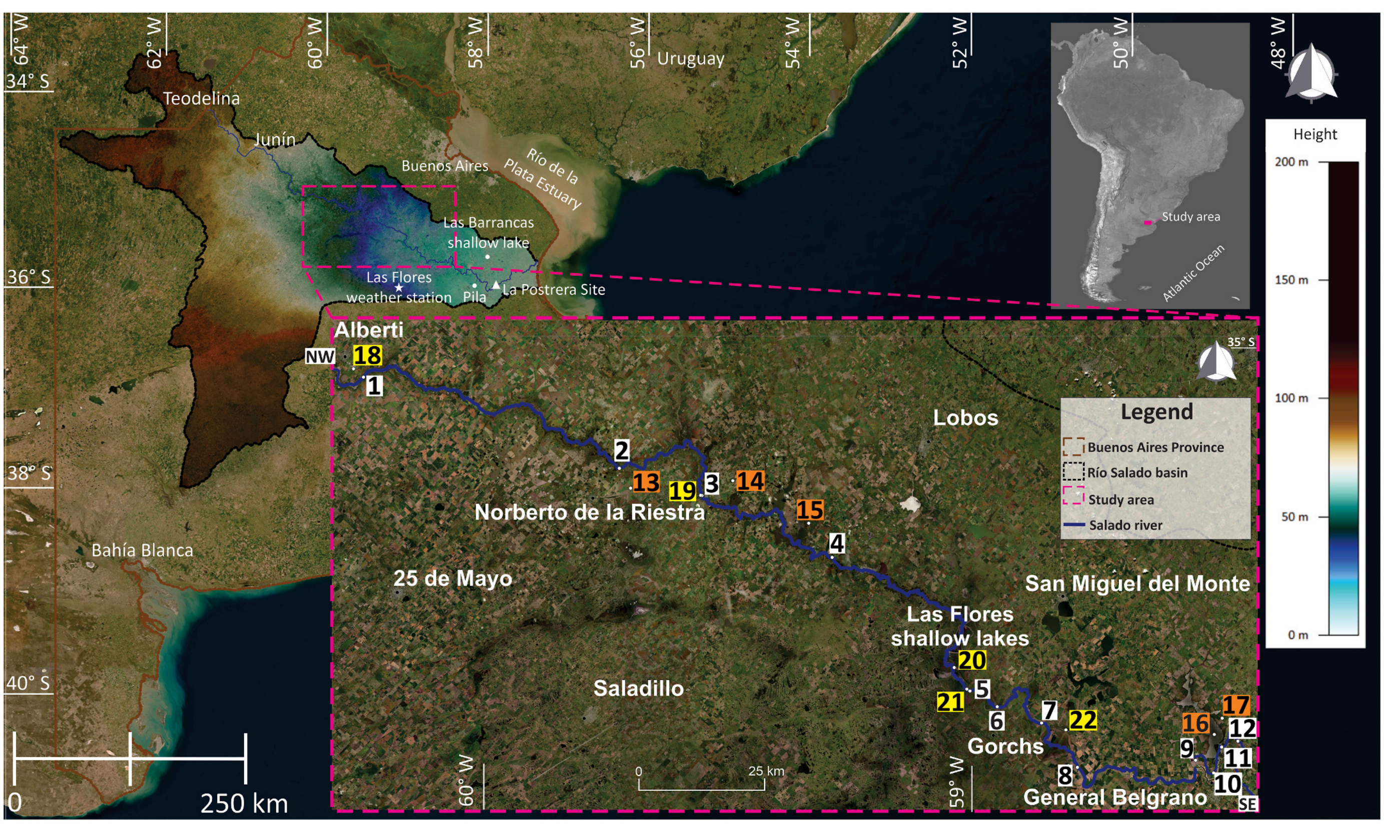

Fig. 2. Location map and sample sites. White labels correspond to fluvial outcrops and drillings: 1- Placita, 2- Route 30, 3- Ernestina, 4- Roque Pérez, 5- Puente Romero, 6- Gorchs, 7- Route 3, 8- Paraje La Chumbiada, 9- Route 41, 10- General Belgrano Camping, 11- Route 29, 12- Estación Río Salado. Orange labels correspond to aeolian outcrops: 13- Norberto de la Riestra, 14- Elvira, 15- Estancia La Concepción, 16- Estancia La Ginestra, 17- Estancia San Cayetano. Yellow labels correspond to datings: 18- Alberti (OSL), 19- Ernestina, 20- Las Flores shallow lakes (Radiocarbon – shells), 21- Puente Romero (Radiocarbon – calcrete), 22- Los Cerrillos (IRSL, Kruck et al., 2011). White star: Las Flores weather station. White triangle: La Postrera Site. Salado river basin contours (Subsecretaría de Recursos Hídricos, 2002) was acquired on the 2Mp website. The SRTM Worldwide Elevation Data (1-arc-second Resolution, SRTM Plus V3) is provided by NASA-USGS and was imported from Global Mapper (v18.0.0) Online Data. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Noteworthy, important floods have occurred, as well as droughts (Moncaut, 2003; Scarpati and Capriolo, 2013; Deschamps et al., 2013), which led to the construction of many hydraulic works throughout the basin.

4. Methods

Sampling sites were selected considering different geomorphological environments, best profiles development, equidistance, and remoteness of anthropized areas, accessibility, and background. On these sites, sampling was performed taking representative material from each stratigraphic unit, with the aim of performing laboratory and cabinet analysis. In sectors where direct observation of outcrops in natural ravines or artificial outcrops was not possible, manual drilling was performed on floodplains in order to get cores of the underlying sediments and thus be able to carry out a characterization of them. In each exposure and its samples, thickness, color, texture, structures, and other elements such as concretions, types of contacts and fossiliferous content, were analyzed. With these elements, each unit is assigned to or correlated with lithostratigraphic units defined for the region, as well as to new lithostratigraphic units. Textural descriptions were carried out in the field and in the laboratory, by sieving and pipetting, obtaining the percentage of sand, silt, and clay fractions. In addition, mineralogical studies were conducted on loose grain and thin sections under a magnifying glass and petrographic microscope.

Regarding paleosols, a morphological description of non-functional soil profiles was made (visible horizons and structures, thickness, etc.). To carry out the analysis of the mollusks, three locations were chosen for this study, from west to east: Placita (35° 4′9.60″S/60°14′32.70″W), Route 30 (35°13′20.80″S/59°43′4.00″W) and Ernestina (35°16′6.10″S/59°32′54.20″W) where a drill was used to extract undisturbed samples at regular 6-cm intervals, as there were no natural outcrops. At Placita, 32 samples were taken from a 184 cm thick profile; in Route 30, 31 samples of a 155 cm thick profile, and in Ernestina, 35 samples of a profile of almost 200 cm. In the laboratory, each sample was divided into two and each subsample was processed for the recovery of ostracods, which is still under study, and mollusks independently. Mollusks were recovered by sieving (0.5 mm), carefully washed and dried at room temperature, and samples were weighed before and after washing. 100 g per sediment were analyzed of each level. Mollusks were identified at the species level (whenever possible) and counted. Mollusks remains were analyzed to define its abundance and species diversity. Additionally, the type of sediment and the stratigraphic unit to which it belonged were recorded in each sample.

On the other hand, mollusks and a calcrete level were used for ^{14}C chronological studies. Moreover, sampling of aeolian sediments for OSL *(Optically Stimulated Luminescence)* dating method was obtained by sinking a 2″ PVC tube into the outcrops at about 25 cm, covering both ends with black tape, preventing sediments from receiving sunlight. Traditional radiocarbon analysis was carried out in the LATYR - CIG (CONICET, Argentina) while those of AMS in DirectAMS and those of OSL in Geoluminiscence Dating Research Laboratory, both in the USA. Radiocarbon dates were calibrated using the program Calib Rev. 7.0.2 (Stuiver and Reimer, 1993) against the Southern Hemisphere curve, SHCal13 (Hogg et al., 2013), using the range of values corresponding to 2 sigmas. Finally, previously published dates from the study area were also calibrated and added in order to complete and improve the temporal framing.

5. Results

5.1. Stratigraphy

In this work, lithological and paleontological information is updated and controlled by numerical ages. Most of the recognized stratigraphic units have been correlated with those previously identified in the area or its vicinity and have been integrated into the stratigraphic scheme set forth by Fucks et al. (2015). Fluvial units are grouped in the Luján Formation (Fidalgo et al., 1973), comprising La Chumbiada (Dillon and Rabassa, 1985), Gorch and Puente Las Gaviotas (Fucks et al., 2015) Members. On the other hand, aeolian deposits have been subdivided by their lithological aspects and geomorphological criteria were used to help on their recognition. They have been recognized at the top of the stratigraphic column throughout the area not influenced by the hydrographic network, as well as below the fluvial units, representing the most important elevations in the entire region. They have been gathered in the Pampeano Formation (González Bonorino, 1965), whose outcrops were only observed at the bottom of the river during times of droughts or low water levels, and La Postrera Formation (Fidalgo et al., 1973), which originally included deposits from various depositional events, including *lunettes* and mantiform deposits. As both deposits are very contrasting in lithological and geomorphological characteristics, genesis, and distribution, in this paper, were divided in Laguna Las Barrancas and La Postrera Formations. Another new stratigraphic unit was defined concerning aeolian sandy deposits which are located towards the west sector of the study area, called De la Riestra Formation.

5.1.1. Laguna Las Barrancas Formation

This unit was recognized in the crescent shape accumulations or *lunettes* to the E and NE of deflation basins, currently occupied by shallow lakes (Dangavs, 2005; Fucks et al., 2012, 2015) of the deflated material both during its formation and in the subsequent stages of erosive activity reactivation.

The type locality was defined at Las Barrancas shallow lake's *lunette* (Fig. 2), which is the greatest one throughout the basin, with maximum heights of 18–20 m (Fig. 4A and B), although the one developed in El Siasgo shallow lake (Fig. 4D and G) is the largest in the study area. The *lunette* is 7–8 m tall at the type location (35°52′31,19″S/58° 2′40,22″W; Fig. 4A and B) where four samples were taken on its stratotype at heights from the base of 0.5 (LB1); 1.5 (LB2); 4 (LB3) and 6.5 (LB4) meters, according to accessibility and observation of changes at megascopic scale. The first three samples correspond to sandy silts (Sand: 34–45%; Silt: 33–50%; Clay: 8–16%) while the texture of the topmost sample is silty-sandy (Sand: 56%; Silt: 33%; Clay: 11%), with colors ranging from very light brownish, yellowish and pinkish-reddish (10 YR 7/4; 5Y 6/1 and 7.5 YR 7/4). In binocular magnifying glass it was observed in all units an important amount of clay pellets, gypsum, calcrete nodules and a lesser proportion of quartz, plagioclases, feldspars, volcanic glass, micas, and magnetite. Dangavs (2005) emphasizes that the high content of pellets and gypsum increases the percentage of sand (sandy-silty or sandy pseudotexture). Dangavs (2005) also mentions the presence of aquatic organisms remains such as oogonies of charophytes, oysters, fish scales, foraminifera, *Heleobia parchappii*, *Lymnaea sp.*, *Ancylidae*, *Ampullaria sp.* and *Biomphalaria sp.*, among others. A sample was taken to perform an OSL analysis, but quartz and feldspar crystals were not the right size for this purpose.

In the study area, El Siasgo *lunettes* are the ones that have the largest dimensions, although this unit would be extrapolated to others developed in the Salado river basin. This unit overlies Pampeano Formation (González Bonorino, 1965) and may be covered by La Postrera Formation or have the current soil developed on it.

Texturally, Laguna Las Barrancas Formation consists of light brown to yellowish clay pellets, flocculated in particles of sand and coarse silt size, which give the sediment friable consistency and sandy silt pseudotexture (Fig. 5). They also have small radiciform calcretes, iron-manganese concretions, gypsum crystals and a few fossils remain, coming from deflated and redeposited lacustrine deposits (Dangavs, 2005). In some cases, these morphologies are more than 15 m high in relation to the bottom of the shallow lakes, among which El Siasgo (Fig. 4D and G), Las Barrancas (Fig. 4A and B), de Monte, La Tigra (Fig. 4C) and La Boca (Fig. 4F) are the most important ones.

Several erosive-sedimentary cycles were identified (Tricart, 1973;

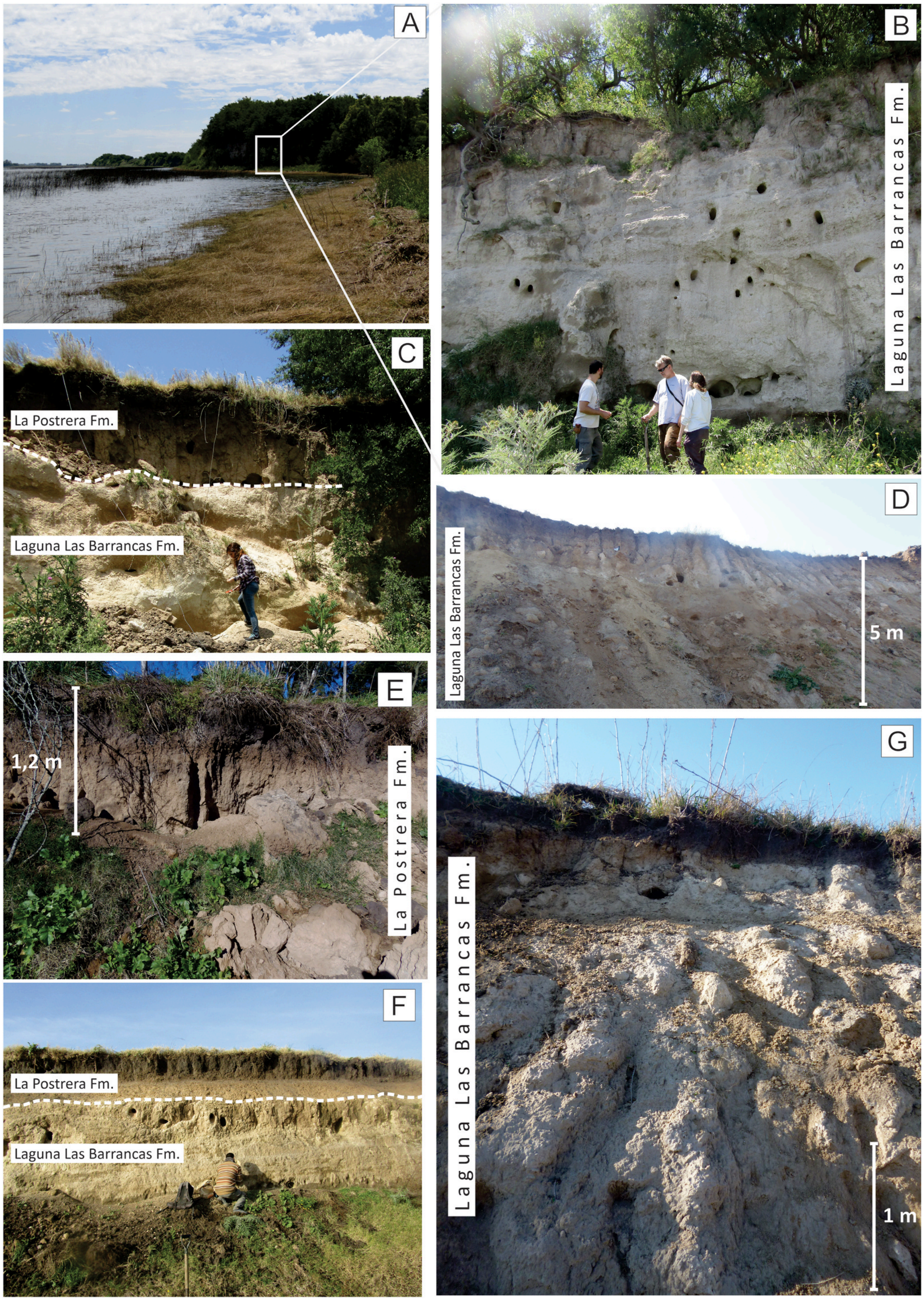

Fig. 4. Outcrops of Laguna Las Barrancas (A, B, C, D, F, G) and La Postrera (C, E, F) Formations located to the E and NE of different shallow lakes showing crescent shape (*lunettes*): A- Regional view of Las Barrancas shallow lake (looking northeast) and a detail (white rectangle) of Fig. 4B location, B- Las Barrancas shallow lake's *lunette's* outcrop where Laguna Las Barrancas Formation's stratotype was described in its type location, C- Outcrop at La Tigra shallow lake's *lunette*, where the lower 3 m correspond to Laguna Las Barrancas Formation, while the upper 2 m correspond to La Postrera Formation (with the current soil developed at the top), D and G- Near 8–10 m high outcrops of Laguna Las Barrancas Formation at El Siasgo shallow lake (Estancia La Ginestra), E– Outcrop of La Postrera Formation at Estancia Los Cerrillos site's *lunette*, and F- Outcrop of the upper 4 m of La Boca shallow lake's *lunette*, where the lower 2,5 m correspond to Laguna Las Barrancas Formation and the upper part (near 1,5 m) to La Postrera Formation, mostly pedogenized constituting the current soil.

Dangavs, 2005), which show the alternation of paleoclimatic conditions, the intensity of which depended on their duration and strength. It can be assumed that the main body of most *lunettes* would have formed in the Late Pleistocene, related to the arid episodes of MIS 2 which, in general, except for some cases, correspond to cold or warm but dry conditions, enhancing deflation (Table 1).

Comparing the shallow lakes from E to W, the first ones show the largest accumulations both in height and distribution, progressively decreasing westward until almost disappearing. In Estancia San Cayetano, located on the banks of El Siasgo shallow lake (35°39.64′S/58°28.91′W), with a maximum height of about 20 m above sea level, three volumetric samples were extracted from the upper 5 m corresponding, from base to top, to sandy to sandy-silty silts, yellowish brown (10 YR 5/3) dry, to pinkish gray (5 YR 6/2). Aggregates of gypsum with fine sand are observed in the sand fraction, while in the fine sand, very rounded lentils of mostly translucent gypsum appear together with other yellowish white, and a few aggregates of very fine sand and sparse glass. Finally, in the very fine sand, gypsum lentils decrease (there are also with fibrous habit) and oxides, gypsum, glass, quartz, plagioclase, feldspar, and zircon clasts predominate. Crotovins and bone remains of megamammals and rodents can be observed along the profile. The material is homogeneous, only interrupted by cemented structures.

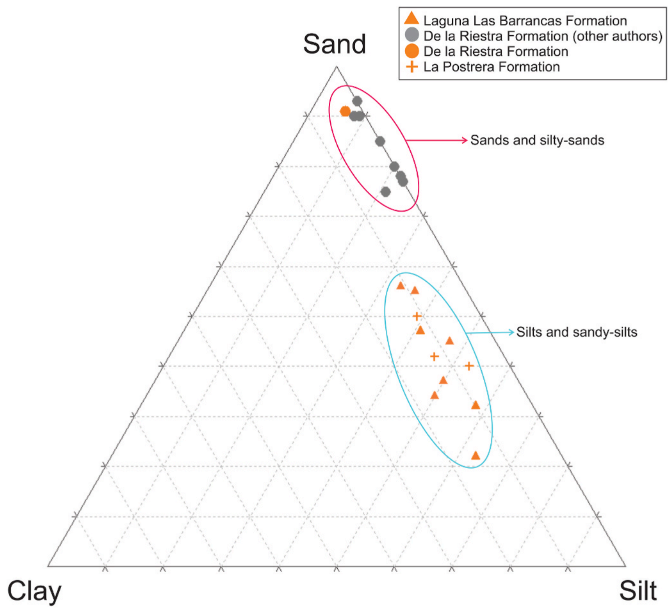

Fig. 5. Textural classification triangle for aeolian units (Folk, 1954, 1980). Note that textural data for Laguna Las Barrancas Formation corresponds to a pseudo-texture related to pelletizing processes. Additional textural data for De la Riestra Formation was obtained from Tripaldi et al. (2018) and Contreras et al. (2018).

5.1.2. La Postrera Formation

The aeolian mantiform deposits found throughout much of the study area belong to La Postrera Formation (Fidalgo et al., 1973), which in some cases forms soft rounded and also transverse hills barely visible in the field because of their low relative relief and the vegetation cover. However, due to its optimal spatial scale, they are easily recognizable by satellite images, especially during the wet season, when aeolian features are indirectly highlighted by detecting water bodies (interdune areas) and highlands (dune areas) (Fig. 6A) (Fucks et al., 2012; Martínez, 2001). They correspond to brownish silty sediments (Fig. 5), loose in wet to compact in dry, with the current soil developed on its top. In broad areas south of the Salado river, it is represented by symmetrical transverse silt hills with SE-NW strike, 150–200 m wide and 4 km long, which are separated by interdune areas (depressions) of equal dimensions, not exceeding relative heights of 0.50 m composed of sandy silt to silty sand, pinkish gray (5 YR 6/2) or brown (7.5 YR 4/2) to dark brown (7.5 YR 3/2) in dry, all darkening in wet.

La Postrera Formation was first defined by Fidalgo et al. (1973) for La Postrera Site (see location in Fig. 2) where it was described as a more or less continuous mantle of a few centimeters or up to 4 or 5 m that superficially constitute very low hills similar to degraded dunes. On the left bank of Salado river, in front of La Postrera Site, it comprises not stratified, yellowish brown sandy silts, while on the eastern side of Los Altos shallow lake the lower section of the exposure shows light gray sandy silts with scattered gypsum (Fidalgo et al., 1973). According to our proposal, these sediments present in Las Altos shallow lake would correspond to Laguna Las Barrancas Formation.

La Postrera Formation has subsequently been separated, indicating the presence of several aeolian episodes, into two (Fidalgo and Tonni, 1981) or three subunits (Fidalgo, 1990) at regional scale or four (La Postrera I to IV Fomations.) at local scale, exclusively associated with *lunettes* of different shallow lakes in the Salado river basin (Dangavs, 2005, 2009). In Los Cerrillos (Fig. 4E), a 2 m *lunette* can be seen in a quarry, whose sediments are composed of brownish silts with an incipient soil developed at the top. Kruck et al. (2011) obtained an age of 9.8 ka (OSL) for the top of this deposit (Fig. 4E). Other luminescence datings (OSL/IRSL) performed on this unit gave ages between 750 and 17,900 years BP (Figini et al., 1998; Kruck et al., 2011; Martínez, 2001,

Table 1
Ages and related data for aeolian units.

Coordinates and depth	Locality	Lithostratigraphic Unit	Geomorphologic Unit	Method	Age (ka BP)	References
35°50,15′S 58°24.12′W 1.5 m	Puente Las Gaviotas	Pampeano Fm.	Mantle	IRSL	57.8 ± 7.6	Kruck et al. (2011)
35°3,36′S 60°15.67′W 2 m	Alberti	La Postrera Fm.	Mantle	OSL	11.125 ± 0.8	This paper (Fig. 2–18) BG4690
35°50.15′S 58°24.12′W 1.2 m	Puente Las Gaviotas	La Postrera Fm.	Mantle	IRSL	17.9 ± 3.2	Kruck et al. (2011)
36°56.88′S 60°22.2′W 0.5 m	Arroyo Tapalqué	La Postrera Fm.	Mantle	^{14}C	4.08 ± 0.06	Figini et al. (1998)
37°40.24′S 57°40.63′W 0.20 m	Vivoratá	La Postrera Fm.	Mantle	OSL	0,75 ± 0.09	Martínez (2001)
36°5.71′S 58°9.85′W 1.35 m	Arroyo El Perdido	La Postrera Fm.	Mantle	IRSL	13.1 ± 1.8	Kruck et al. (2011)
36°3.34′S 58°0.18′W 1.2 m	Pila	La Postrera Fm.	Mantle	OSL	6.470 ± 0.425	This paper (Fig. 2) BG4691
36°17.33′S 61°11.09′W 1.4 m	Bolívar	De la Riestra Fm.	Paleodune	OSL	12.6; 6.3; 5.3; 4.1; 2.9; 2.6	Tripaldi et al. (2018).
35°35.87′S 59°44.71′W 1.4 m	Saladillo	De la Riestra Fm.	Paleodune	IRSL	14.2 ± 3.2	Kruck et al. (2011)
34°39.68′S 60°59.17′W 1.5 m	Junín	De la Riestra Fm.	Paleodune	IRSL	7.3 ± 1.4	Kruck et al. (2011)
35°39.67′S 58°48.11′W 1.4 m	Los Cerrillos	La Postrera Fm.	*Lunette*	IRSL	9.8 ± 1.2	Kruck et al. (2011) (Fig. 2–22)

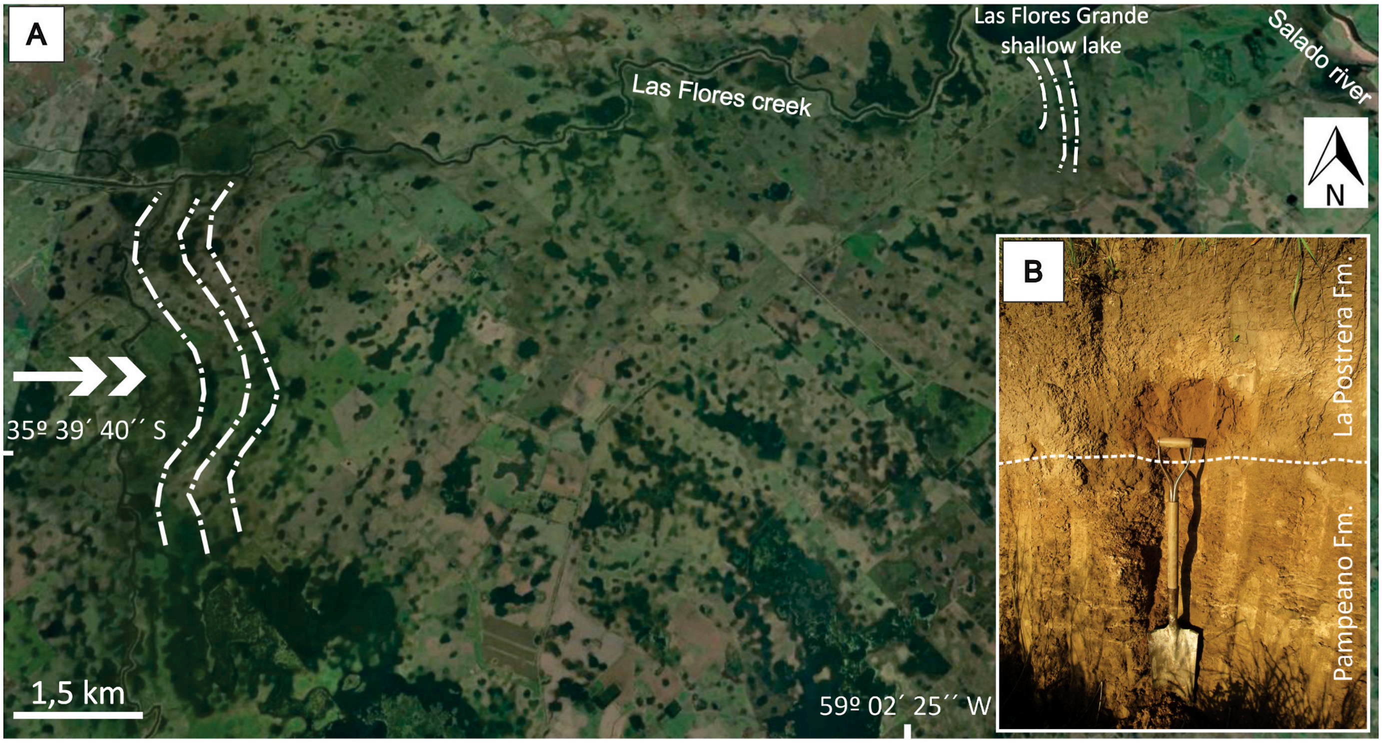

Fig. 6. A- Transversal paleodunes of La Postrera Formation, some of which were indicated with discontinuous white lines (Google Earth image during a wet season - 2002). White arrow in the left indicates inferred prevailing paleowinds direction (W-E). B- A 1.8 m outcrop of Pampeano and La Postrera Formations. near La Postrera Site.

Fig. 7. A- Parabolic paleodunes of De la Riestra Formation, some of which were indicated with discontinuous white lines (Landsat ETM + image, RGB: 742, obtained from https://zulu.ssc.nasa.gov/mrsid/, wet season). The white arrow in the lower left corner indicates inferred prevailing paleowinds direction (SW-NE) B- Top of a 4 m outcrop of De la Riestra Formation at its type location in the village of Norberto de la Riestra (35°15′20.6″S/59°41′41.53″W).

Table 1). An age of 11,125 years BP was obtained by OSL dating in a mantiform deposit of this unit near Alberti city (Point 18 in Fig. 2). This unit may overlie Pampeano Formation (Fig. 6B), Luján or Laguna Las Barrancas Formations (Fig. 4C and F) and has the current soil developed on it.

5.1.3. *De la Riestra Formation*

De la Riestra Formation corresponds to deposits of sands and silty sands (Fig. 5) located to the west of the study area, which stands out among the landscape as parabolic dunes (Fig. 7A). The village Norberto de la Riestra (35°15.34′S/59°41.69′W), which was selected as a type locality, is settled on a hill of about 8 km, with WSW-ENE strike and an approximate height of 45 m a.s.l. There, the outcrop where the stratotype of this unit was described (35°15′20.6″S/59°41′41.53″W), shows 4 m of sandy to silty-sandy sediments (Fig. 5, Fig. 7A and B), gray pink (5 YR 6/2) in dry, pedogenized towards the top. Within the medium sand fraction, highly rounded and isometric quartz grains with a Fe and Mn oxides patina (also crystals), clinopyroxenes and andesitic lithics, were observed. This unit overlies Pampeano Formation and has the current soil developed on it.

The longitudinal dunes of the Pampean Sand Sea become parabolic dunes eastward, generally with one arm more developed than the other (Fucks et al., 2012; Contreras et al., 2018, Fig. 7A). They are near 4 km wide, and their displacement was SW to NE (Fig. 7A). In most cases, these morphologies are associated with rounded and elongated deflation holes, currently occupied by shallow lakes, whose coalescence generates incipient runoff lines. Vegetation, periodic flooding and high groundwater levels may influence the formation of these features but, also a smaller contribution in sand input, can enhance the stabilization by increasing vegetation despite the decrease in moisture content, indicating that weather is not the only control over their activity (Hugenholtz, 2010). Near Bolivar these dunes have a textural composition about 85–90% sand and are lithologically characterized by volcanic rocks clasts, monocrystalline quartz clasts, alkaline feldspars, plagioclase, polycrystalline quartz, and glass shards (Tripaldi et al., 2018; Contreras et al., 2018).

This unit has been dated in several sites; ages range from 14.2 to 2.6 ka (Table 1), suggesting a continuous aeolian deposition up to the late

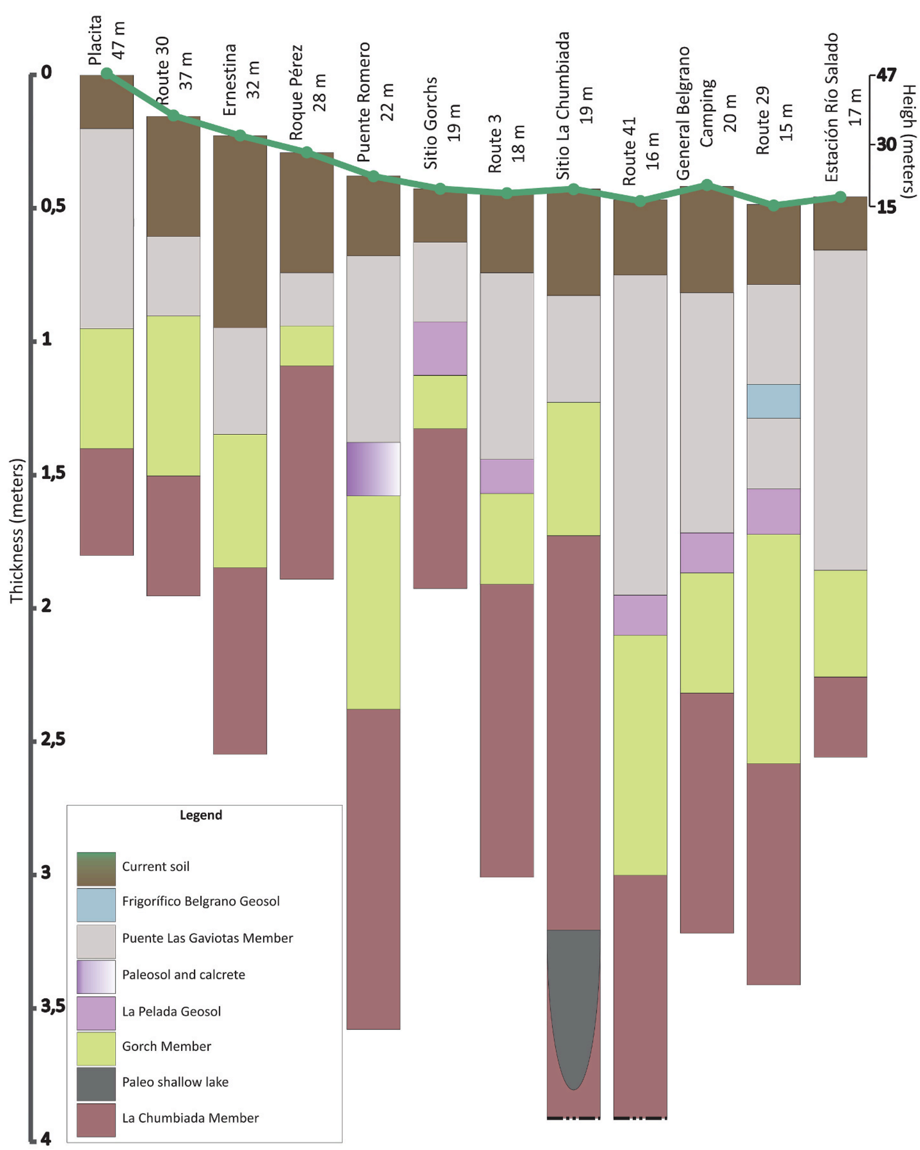

Fig. 8. Schematic stratigraphic profiles for most of the sample sites along Salado river.

Holocene (Kruck et al., 2011; Tripaldi et al., 2018).

Sediments generated by fluvial activity were studied in many sites along the study area, both in outcrops and drillings (Fig. 8). They are grouped in the Luján Formation (Fidalgo et al., 1973), currently subdivided into three members: La Chumbiada (Dillon and Rabassa, 1985), Gorch, and Puente Las Gaviotas (Fucks et al., 2015), which are variably developed, not only in thickness but also in distribution. The thickness of the outcrops in the ravines depends not only on the geomorphological feature but also on the water level at the time of observation (Fig. 8).

5.1.4. Luján Formation, La Chumbiada Member

This unit is composed of brownish sandy-silts to silty-sands (Fig. 9) and corresponds to the base of the fluvial deposits. It was defined by Dillon and Rabassa (1985) and corresponds to the base of the Guerrero Member of Fidalgo et al. (1973). In addition to the above-defined issues, field and laboratory observations yielded other features (Fig. 10). Sediments are brown, usually well stratified (Fig. 10A) and with a large amount of gypsum, also as large rosettes (Fig. 10G), and calcium carbonate precipitates. Small paleo shallow lakes deposits (Sitio La Chumbiada in Figs. 8 and 10F) with dark sediments bearing megamammal fauna are also observed (Scanferla et al., 2013). Evidence of paleochannels was also found within this unit (Fig. 10E). When a channel ceases to be part of an active river system, it stands buried and becomes a paleo-channel. These deposits show a typical 'Cut and fill' sedimentary structure (Fig. 10E), a concave-upwards erosion surface that cuts into the underlying bed and is then filled by younger sediments (Bates and Jackson, 1980).

Mineralogically, the thickest fractions are composed of carbonaceous concretions, and dark volcanic ashes together with glass and glassy shreds, which disaggregate under a small pressure. In the finest fractions vitreous shreds, amorphous silica, quartz, carbonaceous concretions, and gypsum crystals are observed. Molds of saline precipitates, associated with the absence of aquatic micro- and macrofossils, suggest water deficit conditions. Slump sedimentary structures (Fig. 10B and C) and parallel bedding (Fig. 10A and D) indicate very variable energy conditions, which correspond to concentrated flows at the exit of shallow lake's dams and wide floodplains deposits, respectively. An intercalated ash layer was found in some localities (Puente Las Gaviotas and Los Cerrillos).

The fauna associated with this unit consists of the vertebrates *Hippidion principale* (Perissodactyla), *Smilodon populator* (Carnivora), *Megatherium americanum* (Folivora) and the glyptodon *Doedicurus clavicaudatus* (Cingulata) (Scanferla et al., 2013, Fig. 10H), while invertebrates are represented by mollusks whose assemblages displayed very low diversity; only dispersed specimens of *Heleobia parchappii* and *Succinea meridionalis* were recorded occasionally (Fig. 11). According to numerical ages (Table 2), it was deposited at the end of the Pleistocene.

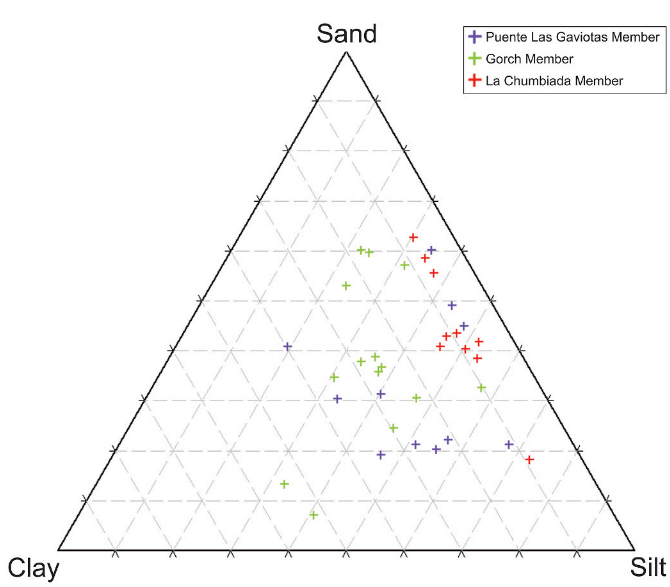

Fig. 9. Textural classification triangle for fluvial units (Folk, 1954, 1980).

5.1.5. Luján Formation, Gorch Member

This unit was defined by Fucks et al. (2015) and correlates with the top of Guerrero and Río Salado Members of the Luján Formation (Fidalgo et al., 1973). It is composed of yellow, green, and mainly gray silt or sandy loam sediments (Fig. 9), about 50–70 cm thick (Fig. 8).

In addition to the aspects defined above, mollusks specimens increase in relation to the lower member (Fig. 11), gypsum and carbonate precipitates show a higher proportion (Fig. 12C), sometimes filling paleochannels (Fig. 12E) or desiccation cracks (Fig. 12B), as well as the empty bioturbation holes, and those occupied by roots (Fig. 12D). Mineralogically it has carbonaceous concretions and gypsum, amorphous silica clasts, vitreous shreds, quartz, micas, and scarce mafic crystals. Its structure is massive and its limit with the lower unit is transitional. Otherwise, the upper limit of this unit is paraconformable, presenting carbonate precipitates (Fig. 12A, C, and 13C) that would indicate a stabilization surface of the floodplain. A carbonate layer observed near Puente Romero and located at the top of this unit was dated by radiocarbon and a 5,600-6,018 cal yr BP age was obtained (Table 3). Sometimes there is a paleosol developed at the top of this unit -La Pelada Geosol (Fidalgo et al., 1973), also indicating a stabilization surface. The latter was previously dated in 2,500-5,300 cal yr BP (Fucks et al., 2007, 2009, 2015; Mehl, 2011).

Gastropods assemblages recovered in this unit are characterized by a low to medium number of specimens, mainly of *S. meridionalis* and *H. parchappii*. Recently, specimens of *Miradiscops brasiliensis* and *Gastrocopta nodosaria* have been recorded in very low density (Fig. 11). These species, together with *S. meridionalis*, form a particular assemblage of terrestrial habits that live in the vegetation cover of humid areas or near water bodies. It is noteworthy that no mollusk shells were recovered from the samples where precipitates such as gypsum or calcium carbonate were recorded. Some radiocarbon dating was performed on samples of this unit, obtaining ages between 11,000-12,000 cal yr BP. According to these and previous numerical ages (Table 3), this unit was deposited at the end of the Pleistocene and beginning of the Holocene.

5.1.6. Luján Formation, Puente Las Gaviotas Member

This unit was defined by Fucks et al. (2015) and corresponds to the upper part of the fluvial sediments, which is variable in thickness, with a mean value of 1 m (Figs. 8 and 13). It is composed of sandy mud fractions, slightly gravel to sand slightly gravel (Fig. 9), light grayish (10 YR 7/1), or light brown gray (10 YR 6/2) in dry but may show brownish colors depending on the humidity content. They are resistant in dry to weak in wet, massive (Fig. 13C, 13D and 13E) or with parallel lamination (Fig. 13A, 13B and 13D). The mineralogical composition includes quartz, sub-rounded zoned plagioclase and glass debris, epidote, hornblende, and much-altered opaques and lithics, as well as abundant crysophytes and diatoms fragments. A paleosol -Frigorífico Belgrano Geosol (Fucks et al., 2015)- is sometimes developed in the middle part of this unit (Figs. 8 and 13.A, 13.B and 13.E) which was dated by Ramos et al. (2019) near Pila city in 1,589-1,752 cal yr BP (Table 4). This paleosol, when present, divides this unit into a lower section, grayish from light to dark gray with large concentrations of *H. parchappii* and an upper section, which is brownish with abundant remains of *P. canaliculata* at the base (Fig. 13A and 13.D). An intercalated ash layer was also found in some localities such as Bajo Los Cerrillos.

The mollusk assemblages with the highest number of specimens and species of all sequences were recorded in this unit. *H. parchappii* was observed in all the studied samples. It was associated mainly with *Biomphalaria peregrina* added to other species such as *Uncancylus concentricus*, *P. canaliculata* and *S. meridionalis,* and only occasionally *Antillorbis*

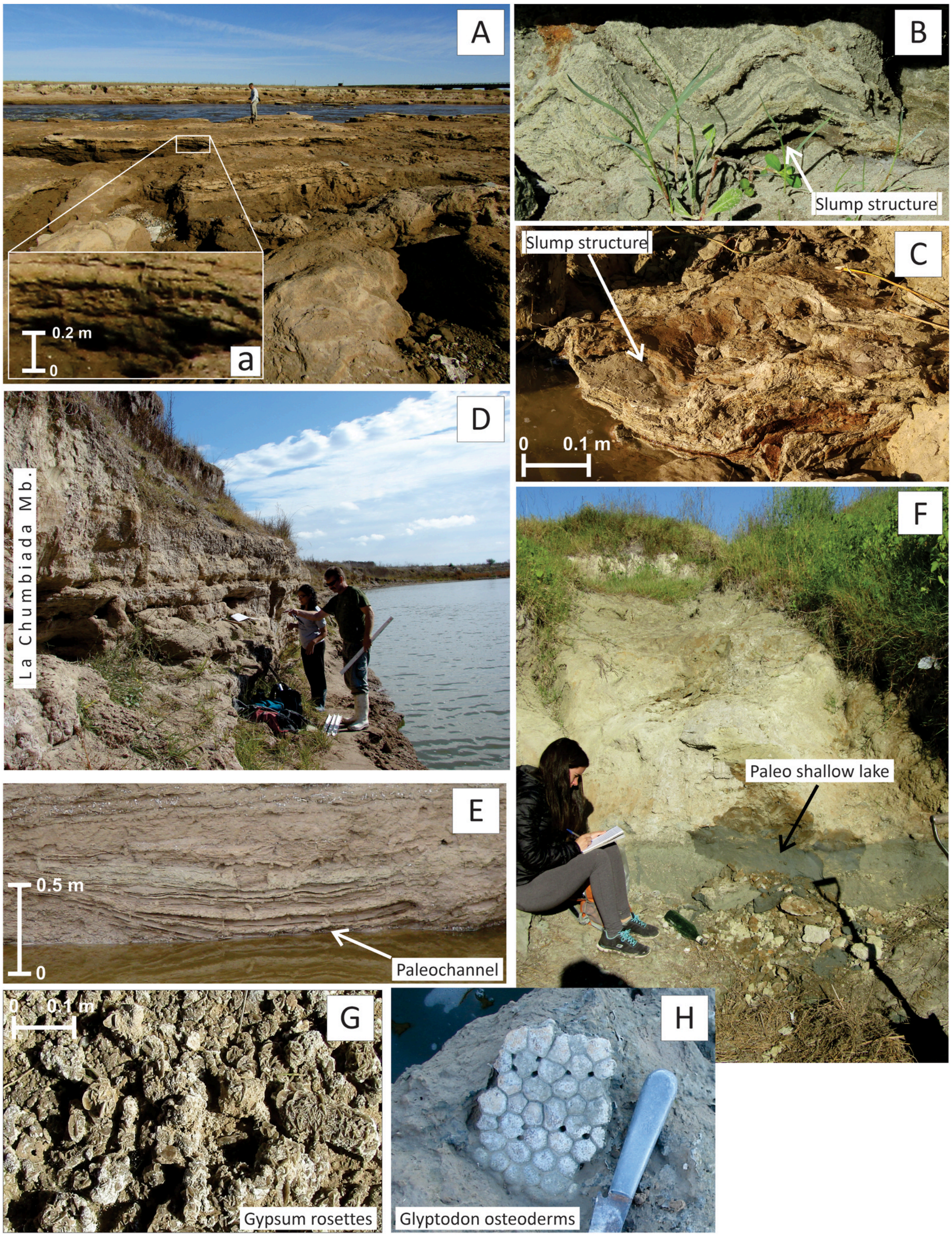

Fig. 10. Photographs of La Chumbiada Member outcrops: A- Parallel bedding under Route 3 bridge. (a = inset); B- and C- Slump structures; D- Luján Formation outcrop at Sitio Puente Las Gaviotas, the lower section corresponds to La Chumbiada Member, with parallel bedding highlighted by gypsum precipitates; E– Paleochannel deposits showing its typical 'Cut and fill' sedimentary structure at Sitio Gorchs; F- Paleo shallow lakes deposits; G- Several and oversized gypsum rosettes from La Chumbiada Member at the homonym site, H- Glyptodon osteoderms, which are usually found in this unit.

nordestensis and *Drepanotrema heloicum* were recorded (Fig. 11). Except for *S. meridionalis*, the rest of the mentioned species are associated with low-energy water bodies, with associated vegetation.

This deposit represents the levees of the main course and their affluents where it presents the greatest thickness and coarsest textures, while in the flood plains and shallow lakes thicknesses are smaller and textures are finer (Fucks et al., 2015). According to numerical ages (Table 4) this unit was deposited in the Late Holocene.

6. Discussion

Even though Salado river's sedimentary basin has an ancient structural origin, which is associated with the separation of Pangea and the formation of the Atlantic Ocean (Yrigoyen, 1975; Introcaso and Ramos, 1984), its most recent sediments have exclusively dependence with exogenous processes.

The climatic oscillations that occurred during Quaternary, with its extremes between glaciations and interglacial periods, have left their footprints in virtually all environments, with greater influence in those where exogenous processes were the exclusive modelers of the landscape. However, not all sites respond synchronously or equally despite their global extension (Mayewski et al., 2004; Zárate, 2005). These climatic variations are attributed to changes and intensifications of the Pacific and Atlantic anticyclones that affected the circulation of the zonal wind (Iriondo and García, 1993). These changes had an undoubtedly important influence on the various accumulation-erosion environments in the Pampean region, as a variety of geoforms were developed, establishing a polygenetic landscape.

The general appearance of the Pampean plain is related to sedimentary accumulations of aeolian origin and the reworking of these

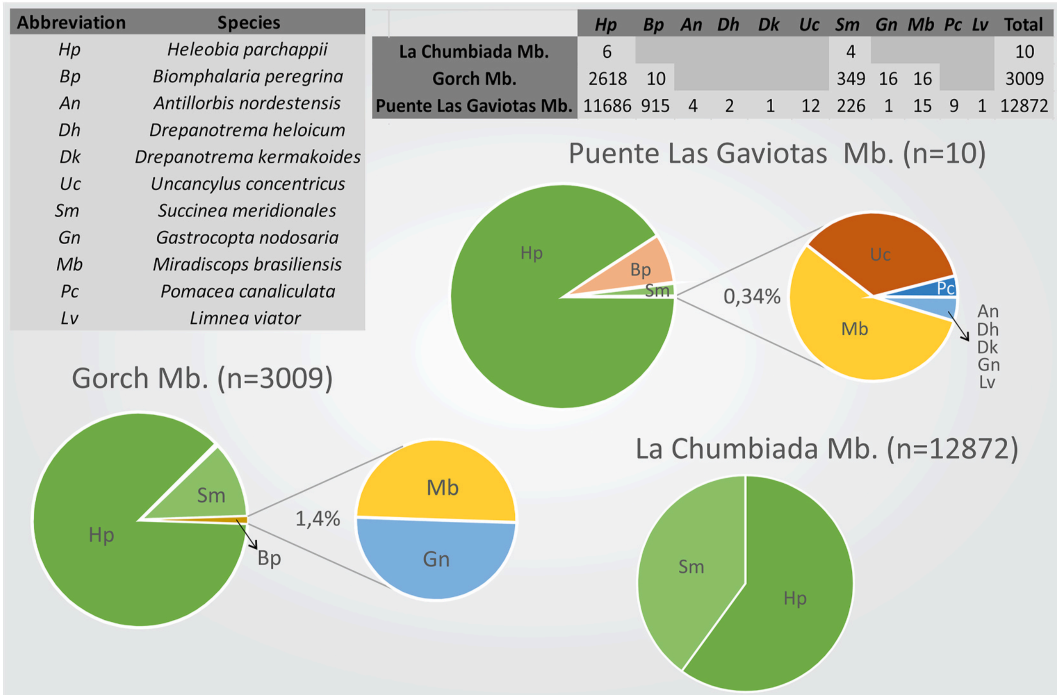

Fig. 11. Mollusk assemblages' analysis. Total and percentage abundances of the species of mollusks found in the different fluvial members that make up the Lujan Formation.

Table 2
Ages and related data for La Chumbiada Member.

Coordinates	Locality	Environment	Age (^{14}C yr BP)	Age (cal yr BP)	Material	References
35°44.82′S 58°45.87′W	La Chumbiada (Estancia Los Cerrillos)	Paleo shallow lakes	12,100 ± 100 12,860 ± 120 13,400 ± 200 12,380 ± 190 14,040 ± 50	13,705-14,182 14,860-15,735 15,403-16,658 13,809-15,105 16,722-17,224	Organic matter Megamammal bones	Fucks et al. (2015) Scanferla et al. (2013)

deposits by, mainly, wind and water activity, as well as to weathering processes, either at a regional or local scale. The inferred climatic conditions for the most part of the Holocene in the Pampean plain show some discrepancies. These discrepancies have been associated with an increase in the regionalization of the climate during the Holocene (Barrientos and Pérez, 2005; Mancini et al., 2005), although they are also likely to be due to differences in the spatial and temporal resolution of the records and/or to the different sensitivity of the analyzed indicators (Stutz et al., 2014).

The most accepted paleoclimatic scenario for the southeast and south of the Pampean plain is that of relatively arid conditions toward 5,000–4,000 cal yr BP (e.g., Zárate, 2005; Vilanova et al., 2010; Laprida et al., 2014). These conditions would have affected those more sensitive geomorphological environments involving shallow lakes desiccation, deflation basins re-excavation and renewed pulses of the aeolian sedimentation processes related to deflated material, among others (Zárate, 2005). Other works indicate earlier dry conditions, from ca. 7,000 to 2,000 cal yr BP, when a gradual shift toward more humid conditions began and achieved ca. 700-500 cal yr BP (Stutz et al., 2014); also an increasing runoff is observed since 1,600 cal yr BP (Laprida et al., 2014). This last point highlights the complexity of the Holocene climate, further emphasizing the importance of having specific paleoclimatic data of the study site, to avoid the risk of extrapolating data series from other areas (Mayewski et al., 2004).

Some of this information is based on the water deficit that occurred in eastern South America during the middle Holocene due to the low insolation of the southern summer. This caused a reduced land-sea temperature contrast and, therefore, weakened the circulation of the South American monsoon system, producing a decrease in precipitation over the area of the South Atlantic Convergence Zone (Prado et al., 2013). In the middle latitudes of Chile, the climate was drier between 6,000 and 5,000 cal yr BP, becoming wetter during 3,500–2,500 cal yr BP (van Geel et al., 2000). In southern Brazil, the vegetation record indicates a relatively dry and cold environment during glacial times, and warm and dry during postglacial times, with wetter conditions from 5,170 cal yr BP, and especially after 1,550 cal yr BP (Behling et al., 2005). In this sense, the Brazilian Amazon forest reached its maximum expression between 9,000 and 8,000 yr BP. This was followed by regression between 7,500 and 3,000 yr BP, from where it recovered again (Villagrán and Ortlieb, 1992), coinciding with a maximum dryness of the coastal sector about 8,000 years (Servant et al., 1989).

6.1. Paleoenvironmental reconstruction

The studied region is located on the eastern edge of the Pampean Sand Sea, from where the Llanura Costera (Coastal Plain), Pampa

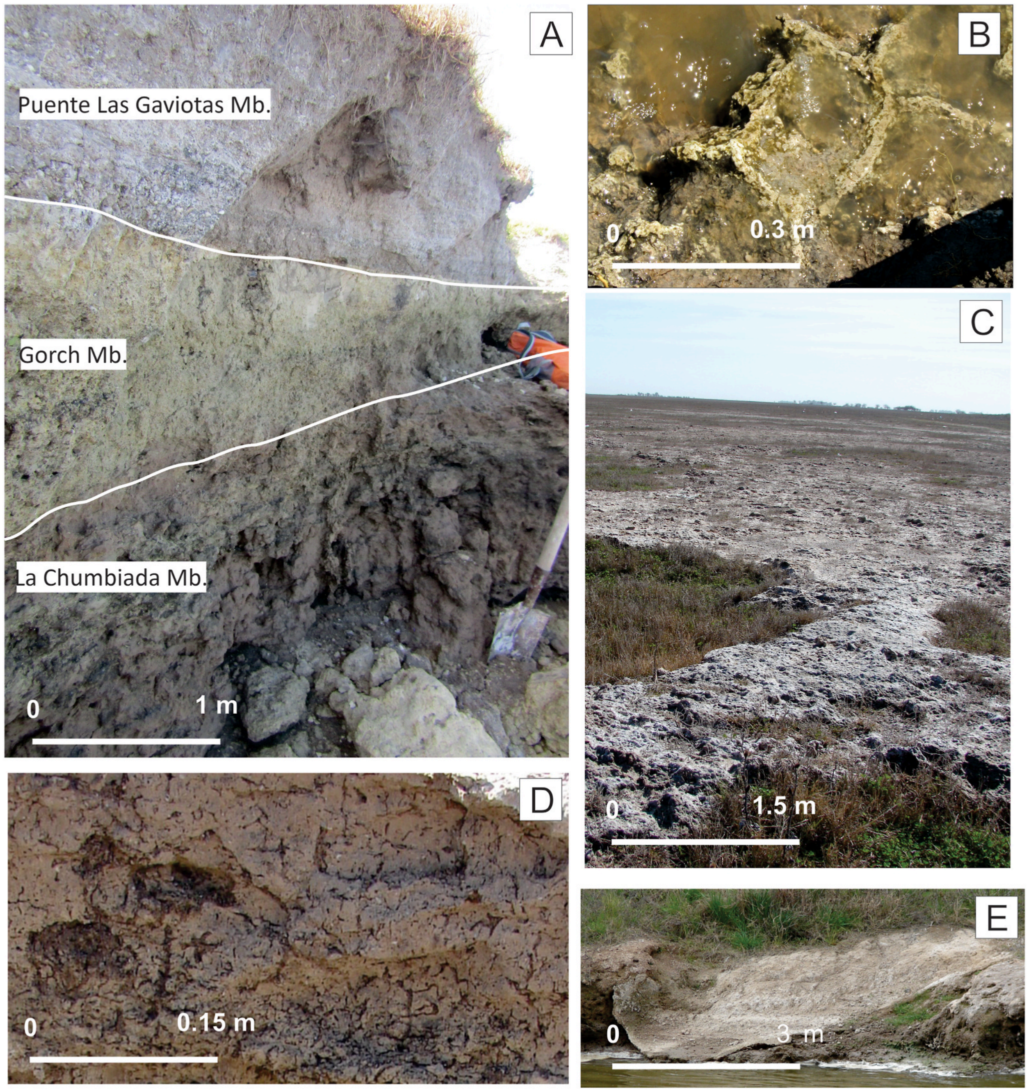

Fig. 12. Photographs of Gorch Member outcrops. A- Exposure of the Luján Formation at Puente Romero; B- Desiccation cracks; C- Calcrete dated in ca. 5 ka at the top of the Gorch Member in Las Flores shallow lake; D- Bioturbation structures; E– Asymmetrical-shaped paleochannel cutting La Chumbiada Member (Salado river tributary channel) with a thin calcium carbonate layer similar to that of Gorch Member.

Deprimida (Depressed Pampa) and Pampa Arenosa (Sandy Pampa) are developed with very contrasting features due to the prevailing climatic conditions, not only during extremes (glacial-interglacial) but essentially in their transitions.

In order to establish a paleoenvironmental reconstruction, a multidisciplinary study was performed, including stratigraphical, geomorphological, topographic, and paleontological approaches, both through field and laboratory analysis. Regarding the composition of the gastropod assemblages, the species found in this work are similar to those found in Quaternary sediments of the Salado River basin (Pisano and Fucks, 2016) and of other sectors of the Pampean region (Tietze and De Francesco, 2010; De Francesco et al., 2013; Steffan et al., 2014). According to their preferential environments the species can be grouped into two groups. *H. parchappii, B. peregrina, U. concentricus, L. viator and Pomacea canaliculata* inhabit fresh waterbodies, lotic and mainly lentic with high vegetation. Whereas *S. meridionalis, M. brasiliensis and G. nodosaria* have terrestrial or amphibian habits and live in humid areas near water bodies (Castellanos and Fernández, 1976; Castellanos and Landoni, 1981; Rumi, 1991; Tietze and De Francesco, 2010, 2012).

Based on the results obtained, a series of block diagrams were built, which represent the proposed paleoenvironmental reconstruction for the late Pleistocene-Holocene of the Salado river middle basin (Fig. 14A–F).

6.1.1. Paleoenvironmental scenario for MIS 4? to MIS 2 lapse

During MIS 2 and probably previously (MIS4?) when whether conditions where extremely dry, there was significant sand remobilization of the Pampean Sand Sea (PSS), and a wide strip of loess or Peripheric Loess Belt (PLB) with NW-SE orientation was also deposited 700 km closer to the core of the PSS than in MIS 4 (Iriondo and Kröhling, 1995). According to the loess deposits of Chaco-Pampean region of Argentina, aeolian deposits were dominant during the last glacial period, with predominant west and southwest winds (Zárate, 2007). These winds and the extremely dry conditions, with greater intensity during Last Glacial Maximum (LGM), led to the formation of deflation basins which were dug in the Pampeano Formation sediments (PLB) or those remobilized of La Postrera Formation throughout the entire basin. Along some sectors, especially to the east, the presence of salts and saline sediments led to the development of haloclasty, with the consequent physical weathering of those sediments and their break into sand to silt size particles called pellets (pelletizing). This process promotes the availability of sediments that can be deflated by wind. Most of this material was deposited close to where it was deflated, mainly due to its grain size. As prevailing winds were from SW, they were deposited to the NE of deflation basins, with a

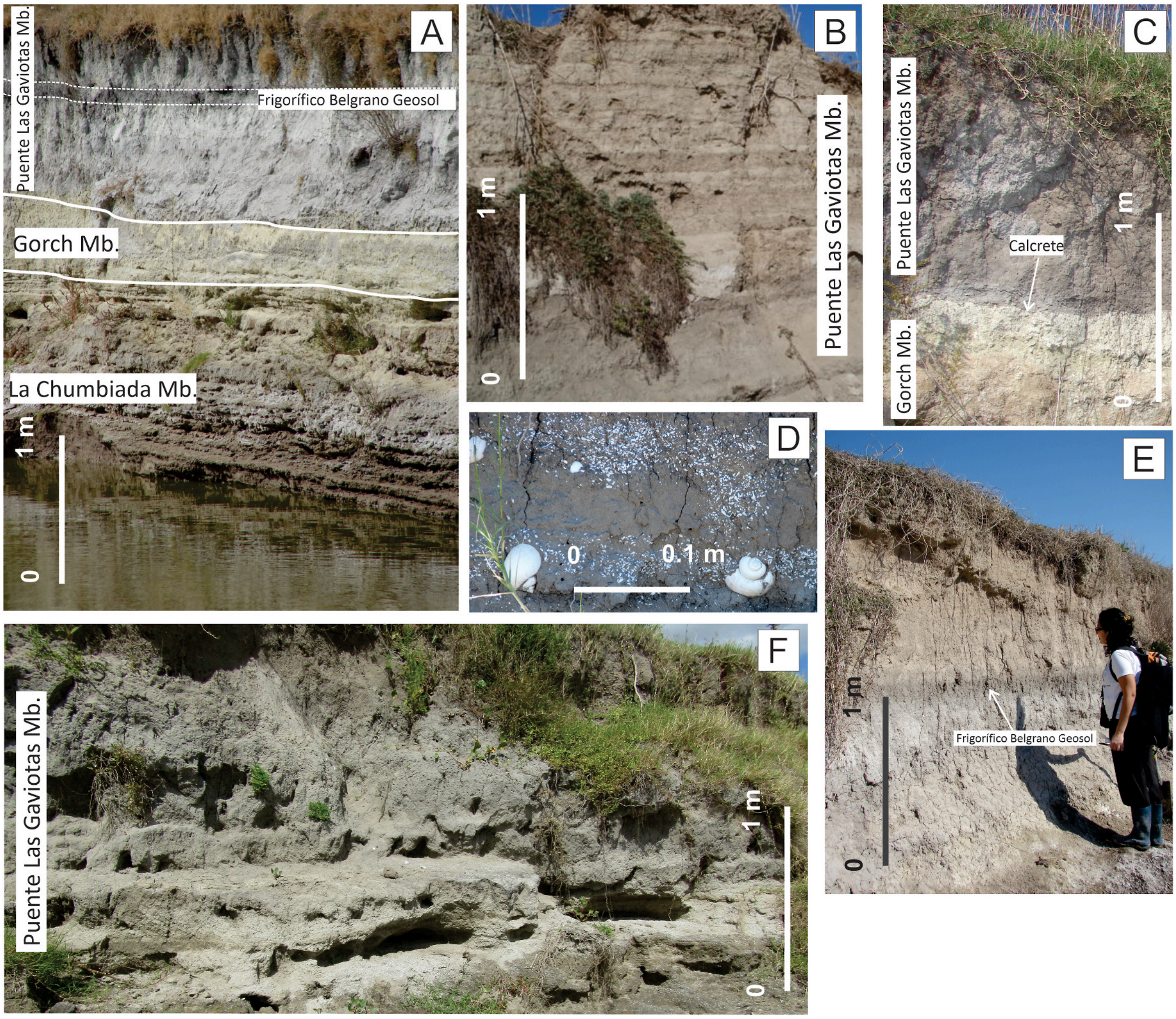

Fig. 13. Photographs of Puente Las Gaviotas Member outcrops. A) Exposure of Luján Formation near General Belgrano; B) Parallel bedding at Estancia Guerrero; C) Discordance and calcrete of the Gorch Member underlying Puente Las Gaviotas Member; D) Levels with high concentrations of fossil mollusks, mainly *P. canaliculata* and *H. parchappii*; E) Paleosol developed in Puente Las Gaviotas Member; and F) Parallel bedding.

Table 3
Ages and related data for Gorch Member.

Coordinates	Locality	Environment	Age (^{14}C yr BP)	Age (cal yr BP)	Material	References
35°44.82′S 58°45.87′W	La Chumbiada	*Levee*	9,570 ± 150	10,477-11,226	*H. parchappii*	Fucks et al. (2015)
35°46.09′S 58°27.26′W	Frigorífico Belgrano	*Levee*	11,690 ± 110	13,275-13,731	*H. parchappii*	Fucks et al. (2015)
35°43.57′S 58°29.52′W	Termas de Belgrano	*Levee*	8,640 ± 90	9,439-9,832	*H. parchappii*	Fucks et al. (2015)
35°35.55′S 59°0.53′W	Puente Romero	*Levee*	8,720 ± 100	9,485-9,948	*H. parchappii*	Fucks et al. (2015)
35°16.08′S 59°33.03′W	Ernestina	*Levee*	10,539 ± 36	12,398-12,560	*H. parchappii*	This paper (Figs. 2–19) D-AMS 025862
35°33.43′S 59° 1.9′W	Laguna Las Flores	*Levee*	9,889 ± 39	11,191-11,342	*H. parchappii*	This paper (Fig. 2–20) D-AMS 033454
35°35.57′S 59°0.32′W	Puente Romero	Upper calcrete	5,130 ± 100	5,600-6,018	$CaCO_3$	This paper (Fig. 2–21) LP- 3679

characteristic crescent shape, which gives them the name of *lunettes* and included within the Laguna Las Barrancas Formation (Figs. 14A and 15). The shallow lakes located to the W have little development of *lunettes*, while those located to the E have the greatest expressions of its morphology, both in height and areal development, the most important being between 15 and 20 m above the level of the shallow lakes. This fact could be related to the presence of salts to the E and other solutes such as carbonates, which inhibit pelletizing, to the W. The presence of salts is a central factor, which could be promoting their greater development, as transgressive littoral waters of MIS 1 occupied many of the shallow lakes located in the eastern part of the area. *Lunettes* develop when evaporation is considerably greater than the sum of precipitation and groundwater discharge. In addition, evaporation and drying of clays should occur early in the dry season to allow the effective formation of

Table 4
Ages and related data for Puente Las Gaviotas Member.

Coordinates	Locality	Environment	Age (^{14}C yr BP)	Age (cal yr BP)	Material	References
35°35.66′S 59° 0.12′W	Puente Romero	Levee	1,650 ± 80 680 ± 60	1,348-1,634 536–676	H. parchappii P. canaliculata	Fucks et al. (2015)
35°41.81′S 58°26.92′W	Estación Río Salado	Levee	960 ± 50 1,710 ± 60	736–924 1,420-1,708	P. canaliculata H. parchappii	Fucks et al. (2015)
35°45.96′S 58°27.28′W	Frigorífico General Belgrano	Levee	1,240 ± 60 3,040 ± 70	969–1190 2,969-3,362	P. canaliculata H. parchappii	Fucks et al. (2015)
35°44.94′S 58°30.75′W	Balneario General Belgrano	Levee	1,340 ± 50 2,440 ± 70	1,090-1,300 2,327-2,717	P. canaliculata H. parchappii	Fucks et al. (2015)
35°43.65′S 58°29.60′W	Termas de General Belgrano	Levee	1,770 ± 40	1,543-1,721	H. parchappii	Fucks et al. (2015)
35°38.95′S 58°51.05′W	Los Horneros	Levee	710 ± 40 3,002 ± 40	559–618 2,967-3,243	P. canaliculata Shells	Fucks et al. (2015)

aggregates. All these conditions must coincide with a season of strong and preferably unidirectional winds, and the presence of vegetation that promotes entrapment (Bowler, 1973).

Otherwise, to the west, silty sand to sand size sediments from PSS where also remobilized by these winds, leading to the formation of longitudinal and parabolic dunes, the last's sediments corresponding to De la Riestra Formation (Fig. 15).

6.1.2. Paleoenvironmental scenario for 20–16 ka (post-LGM) lapse

After the Last Glacial Maximum, a wet stage begins to develop, with shallow lakes incipient formation, as deflation basins previously formed were occupied by water (Fig. 14B).

6.1.3. Paleoenvironmental scenario for 16–10 ka lapse

As water levels continue to rise, an interconnection between shallow lakes by incipient water courses promotes Salado river consolidation by this persistent joining. The depths reached by deflation along the basin are variable, noting that many of the deflation basins (currently shallow lakes) are at lower topographic heights compared to that of the main course (Monte and Chascomús Chained shallow lakes, Esquivel and del Siasgo shallow lakes, among others). In addition, in sectors where paleodunes dominates over deflation basins, mainly to the W and SW, these features acted as a geomorphological control. Where they are not present, the river basin has typically dendritic pattern, while where there are longitudinal paleodunes, a sub dendritic pattern (*sensu* Howard, 1967) can be observed. Likewise, a sub-parallel pattern (*sensu* Howard, 1967) is developed where there are parabolic paleodunes, also due to a geomorphological control caused by aeolian deposits.

Basal fluvial sediments, which correspond to La Chumbiada Member, started to be deposited mainly associated with channels and floodplains (Fig. 15), showing continuity both in shallow lakes and the main course (Fig. 8). They show lack or absence of invertebrate fossils (Fig. 11), indicating that the watercourse is in an initial stage of stabilization. Structures associated with precipitation of salts, oversized gypsum rosettes (Fig. 10G) and, in some sectors, slump structures (Fig. 10B and C) with conglomerates (Dillon and Rabassa, 1985; Fucks et al., 2015) and parallel lamination (Fig. 10A and D) indicate a variety of sub-environments and energy levels throughout its path (Fig. 14C).

6.1.4. Paleoenvironmental scenario for 10–8 ka lapse

During this lapse, wet conditions persist, and fluvial sediments continue to be conformably deposited, associated with low energy facies. Unlike the underlying, this unit, Gorch Member, contains a large number of mollusks of terrestrial habits that lived in the vegetation cover of humid areas or near water bodies. (Figs. 11, 14D and 15).

6.1.5. Paleoenvironmental scenario for 8–3 ka lapse

This was a water deficit period when the courses experienced a significant reduction in its flow. Because of intense evaporation, either due to a decrease in precipitation or high temperatures, gypsum and calcium carbonates precipitated above Gorch Member (Fig. 12B, C and 12E), causing a yellowish or greenish white color change on those sediments (Fig. 12A). These dry conditions are also attested by a reactivation of aeolian processes with aeolian and fluvial remobilization by wind (transverse dunes and *lunettes* formation), but chiefly by the absence of chronological data in fluvial fossils of that age. Intense bioturbation (Fig. 12D) and the presence of a paleosol (La Pelada Geosol) towards the top of Gorch Member in the floodplains and a calcrete level (Fig. 12C), indicate a prolonged subaerial exposure and stabilization during ca. 5 ka. Paleowinds prevailing directions must have been from W and SW, evidenced by dunes and *lunettes* orientation (Figs. 14E and 15).

6.1.6. Paleoenvironmental scenario from 3 ka to present time

From 3 ka. there was a gradual return towards wet conditions. The discordant deposits of Puente Las Gaviotas Member began to be deposited ca. 3 ka, after an important hiatus of about 5 ka (Fig. 13C). Both the abundance of mollusk remains and the diversity of species indicate a great proliferation of aquatic mollusks (Fig. 11). In some sectors and "interfluvial" soil, Frigorífico General Belgrano Geosol develops towards 1.8 ka (Fig. 13A and E), indicating a period of stability with little alluvial contribution (Figs. 14F and 15).

7. Conclusions

- An interdisciplinary study on the Late Quaternary of Salado river middle basin, including stratigraphical, geomorphological, and paleontological approaches, was carried out.
- Two new aeolian lithostratigraphic units, Laguna Las Barrancas and De la Riestra Formations, were defined and La Postrera Formation (Fidalgo et al., 1973) was redefined.
- The reconstruction of a paleoenvironmental model, considering fluvial units development, their ages and topographic heights of the affluent shallow lakes, suggest that the main collector formed gradually as wet conditions increased, through the union of deflation basins by incipient water courses. It achieved its definitive formation at the end of the Pleistocene, with the deposition of its basal unit, La Chumbiada Member.
- Although it is possible to temporarily delimit fluvial units according to several datings, this is not the case of aeolian units, whose datings are less and temporarily desultory. However, it is highly likely that their deposition has begun at least from the Last Glacial Maximum (LGM, ca. 20 ka.) with subsequent reactivations of such activity in successive dry or less wet stages (8-3 ka. and 1.8 ka.). Thus, aeolian deposits are chronologically distributed throughout much of the Holocene, although they are not necessarily continuous.
- Two moments of non-deposition and/or stabilization of the floodplain have been recorded, indicating water deficit conditions. The first, a hiatus from 8 to 3 ka (5 ka) is represented not only by the almost absence of fluvial sequences (conformity between Gorch and Puente Las Gaviotas members), but also by different aeolian deposits,

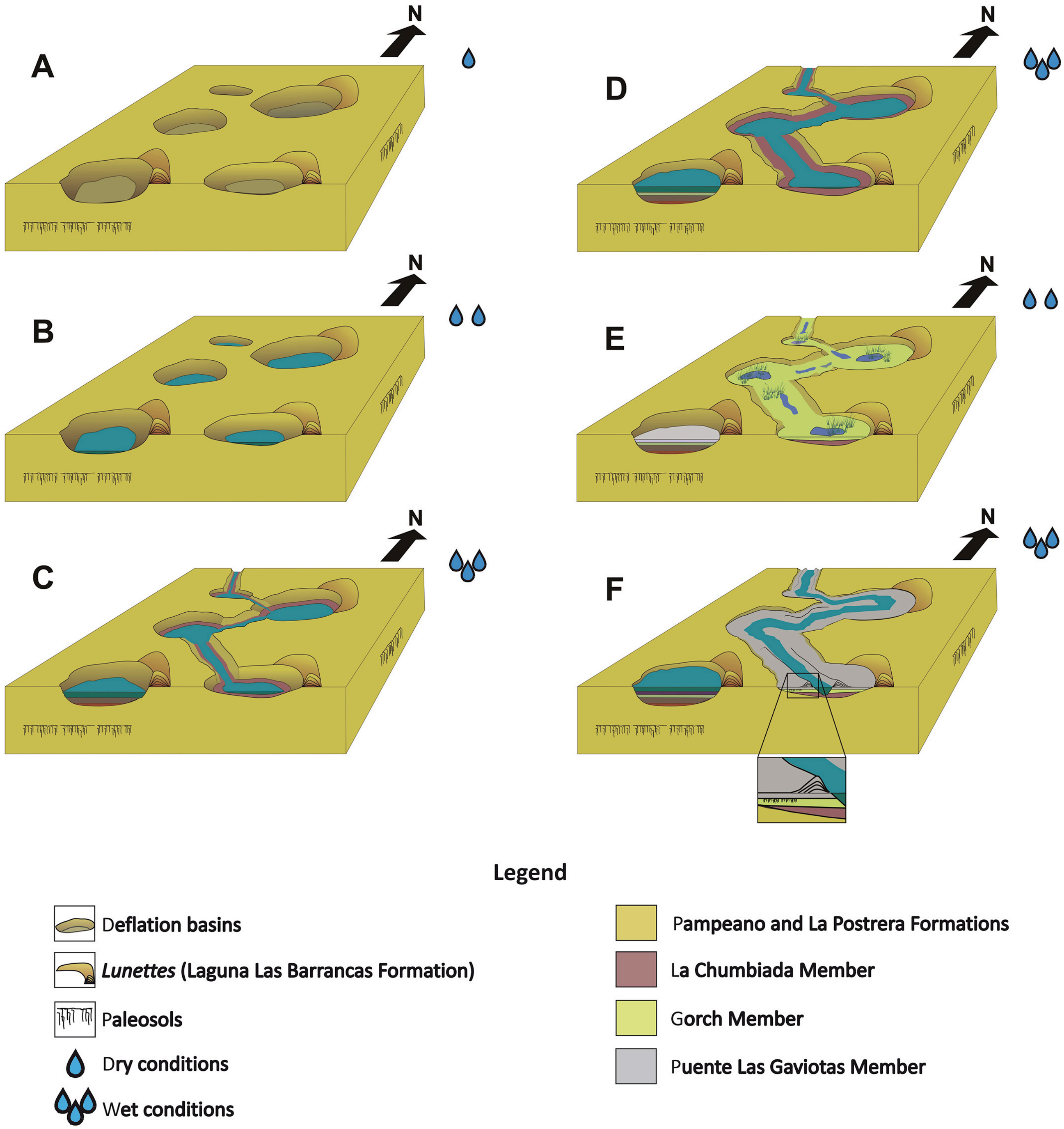

Fig. 14. Paleoenvironmental reconstruction for: A- MIS 4? to MIS 2 lapse, B- 20 – 16 ka (post-LGM) lapse, C- 16 – 10 ka lapse, D- 10 – 8 ka lapse, E– 8 – 3 ka lapse, and F- 3 ka to present time. Blue drops indicate prevailing climatic conditions (1 = Dry, 2 = Intermediate, 3 = Wet). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

a calcrete layer and a swamp paleosol (La Pelada Geosol) dated in ca. 5 ka. The second moment took place near 1.8 ka and is inferred through a thin paleosol (Frigorífico Belgrano Geosol) that would represent a short depositional hiatus.

- The integrated study of all these deposits with an adjusted chronological control suggests a paleoenvironmental model for Salado river middle basin which is directly associated with the climatic conditions that prevailed at the end of the Quaternary.

Credit author statement

Nicole N. Pommarés: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration. **Enrique E. Fucks:** Conceptualization, Methodology, Investigation, Resources, Writing - Original Draft, Supervision, Project administration, Funding acquisition. **Maria Florencia Pisano:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Visualization,

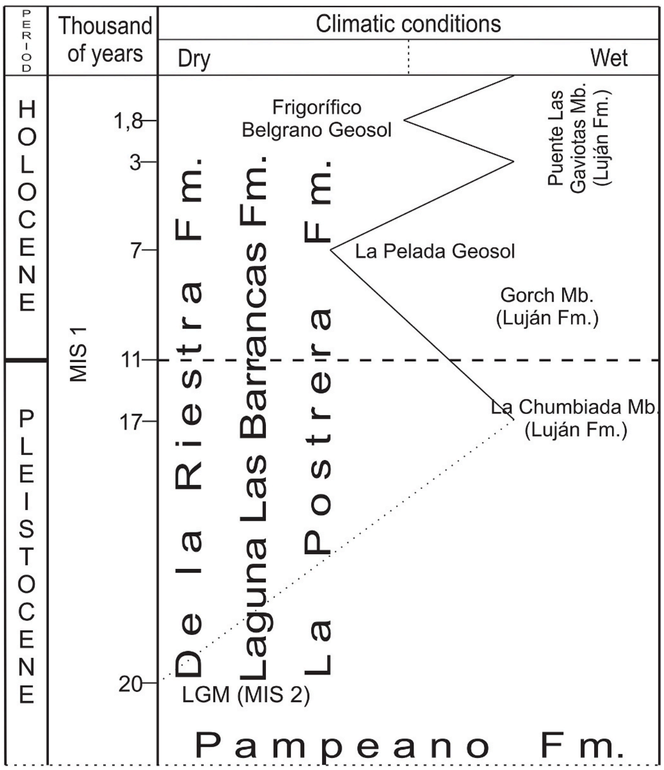

Fig. 15. Stratigraphic chart with aeolian and fluvial stratigraphic units defined in this work in relation to prevailing paleoclimatic conditions.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Barrientos, G., Pérez, S.I., 2005. Was there a population replacement during the Late mid-Holocene in the southeastern Pampas of Argentina? Archaeological evidence and paleoecological basis. Quat. Int. 132 (1), 95–105.

Bates, R.L., Jackson, J.A., 1980. Glossary of Geology. Falls Church. American Geological Institute.

Behling, H., Pillar, V.D., Bauermann, S.G., 2005. Late Quaternary grassland (Campos), gallery forest, fire, and climate dynamics, studied by pollen, charcoal and multivariate analysis of the São Francisco de Assis core in western Rio Grande do Sul (southern Brazil). Rev. Palaeobot. Palynol. 133 (3–4), 235–248.

Bowler, J.M., 1973. Clay dunes: their occurrence, formation and environmental significance. Earth Sci. Rev. 9 (4), 315–338.

Castellanos, Z.A., Fernández, D., 1976. Mollusca, Gasteropoda, Ampullariidae. In: Ringuelet, R.A. (Ed.), Fauna de Agua Dulce de la República Argentina. Fundación para la Educación, la Ciencia y la Cultura, Buenos Aires, vol. 15, pp. 5–33, 1.

Castellanos, Z.A., Landoni, N., 1981. La Familia Lymnaeidae en la República Argentina. In: Ringuelet, R. (Ed.), Fauna de agua dulce de la República Argentina. Buenos Aires, vol. 15, pp. 55–82, 5.

Cohen, K.M., Finney, S.C., Gibbard, P.L., Fan, J.-X., 2013. The ICS international chronostratigraphic chart (updated). Episodes 36, 199–204.

Contreras, F.I., Mavo Manstretta, G., Perillo, G., Piccolo, M., 2018. Caracterización de médanos parabólicos de la región pampeana oriental, centro oeste de la provincia de Buenos Aires (Argentina). Lat. Am. J. Sedimentol. Basin Anal. 25 (1), 1–15.

Dangavs, N., 2005. La Formación La Postrera I, II, III y IV de la laguna Las Barrancas de Chascomús, provincia de Buenos Aires. In: XVI Congreso Geológico Argentino, vol. 4, pp. 115–122 (La Plata).

Dangavs, N., 2009. Paleolimnología de las lagunas periódicas (secas) Esquivel, del Medio y El Espartillar, Chascomús, Buenos Aires. In: IV Congreso Argentino de Cuaternario y Geomorfología. Resúmenes, vol. 265, pp. 290–299 (La Plata).

De Francesco, C.G., Tietze, E., Cristini, A.P., 2013. Mollusk successions of Holocene shallow-lake deposits from the southeastern Pampa plain, Argentina. Palaios 28, 851–862.

Deschamps, J.R., Otero, O., Tonni, E.P., 2013. Cambio climático en la pampa bonaerense: las precipitaciones desde los siglos XVIII al XX. Documento de Trabajo N°, vol. 109. Universidad de Belgrano, pp. 1–18.

Dillon, C., Rabassa, J., 1985. Miembro La Chumbiada, Formación Luján (Pleistoceno, provincia de Buenos Aires): Una nueva unidad estratigráfica del valle del Río Salado. I Jornadas Geológicas Bonaerenses. Resúmenes 27 (Tandil).

Dirección Provincial de Obra Hidráulica, 2016. "Evaluación de Impacto Ambiental y Social. Ampliación de la Capacidad Río Salado Superior-Tramo IV, Etapa 1B". Apoyo a la Gestión Integral de la Cuenca del Río Salado y Ejecución de Obras Contempladas en el Tramo IV, Etapa 1B del Plan de Manejo Integral de la Cuenca del Río Salado.

Fidalgo, F., De Francesco, F., Colado, U.R., 1973. Geología superficial en las hojas Castelli, J. M. Cobos y Monasterio (Pcia. de Buenos Aires). In: V Congreso Geológico Argentino, Actas, vol. 4, pp. 27–39 (Carlos Paz).

Fidalgo, F., 1975. Geología superficial de la llanura bonaerense. In: Geología de la Provincia de Buenos Aires, VI Congreso Geológico Argentino. Bahía Blanca, Relatorio, pp. 103–138.

Fidalgo, F., 1990. La Formación La Postrera. Simposio Internacional sobre Loess, INQUA, vols. 78–83. Resúmenes Expandidos, Mar del Plata.

Fidalgo, F., Tonni, E.P., 1981. Sedimentos eólicos del Pleistoceno tardío y reciente en el área interserrana bonaerense. In: Actas VIII Congreso Geológico Argentino, 3. Asociación Geológica Argentina, pp. 33–39.

Figini, A., Huarte, R., Carbonari, J., Tonni, E.P., 1998. Edades C-14 en un perfil del Arroyo Tapalqué, Provincia de Buenos Aires, Argentina. Contribución a la cronología de acontecimientos faunístico-ambientales, vol. I. Actas X Congreso Latinoamericano de Geología y VI Congreso Nacional de Geología Económica, Buenos Aires, pp. 27–31.

Folk, R.L., 1954. The distinction between grain size and mineral composition in sedimentary – rock nomenclature. J. Geol. 62, 344–359.

Folk, R.L., 1980. Petrology of Sedimentary Rocks. Hempill Publishing Company, Austin, TX, p. 182.

Fucks, E., Huarte, R., Carbonari, J., Figini, A., 2007. Geocronología, paleoambientes y paleosuelos holocenos en la Región Pampeana. Rev. Asoc. Geol. Argent. 62 (3), 425–433.

Fucks, E., Huarte, R., Carbonari, J., Pisano, F., 2009. Cronología de los depósitos fluviales del Pleistoceno Tardío-Holoceno en la Cuenca Inferior y media del Río Salado, provincia de Buenos Aires. In: IV Congreso Argentino de Cuaternario y Geomorfología, XII Congresso da Associação Brasileira de Estudos do Quaternário, II Reunión sobre el Cuaternario de América del Sur. La Plata, p. 361.

Fucks, E., Pisano, F., Carbonari, J., Huarte, R., 2012. Aspectos geomorfológicos del sector medio e inferior de la Pampa Deprimida, provincia de Buenos Aires. Rev. Soc. Geol. Espana 25, 107–118.

Fucks, E., Pisano, M.F., Huarte, R., Di Lello, C., Mari, F., Carbonari, J., 2015. Stratigraphy of the fluvial deposits of the Salado River basin, Buenos Aires province: lithology, chronology and paleoclimate; Pergamon-Elsevier Science Ltd. J. S. Am. Earth Sci. 60, 129–139.

González Bonorino, F., 1965. Mineralogía de las fracciones arcilla y limo del pampeano en el área de la Ciudad de Buenos Aires y su significado estratigráfico y sedimentológico. Rev. Asoc. Geol. Argent. 20 (1), 67–148.

Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M., Zimmerman, S.R.H., 2013. SHCal13 Southern Hemisphere calibration, 0–50,000 years cal BP. Radiocarbon 55, 1889–1903.

Hugenholtz, C.H., 2010. Topographic changes of a supply-limited inland parabolic sand dune during the incipient phase of stabilization. Earth Surf. Process. Landforms 35 (14), 1674–1681.

Introcaso, A., Ramos, V., 1984. La cuenca del Salado. Un modelo de evolución aulacogénica. In: Noveno Congreso Geológico Argentino, 3, pp. 27–46 (Bariloche).

Iriondo, M.H., García, N.O., 1993. Climatic variations in the Argentine plains during the last 18,000 years. Palaeogeogr. Palaeoclimatol. Palaeoecol. 101 (3–4), 209–220.

Iriondo, M., Kröhling, D., 1995. El Sistema Eólico Pampeano, vol. 5. Comunicaciones Museo Provincial de Ciencias Naturales, Santa Fe, pp. 1–68.

Kruck, W., Helms, F., Geyh, M.A., Suriano, J.M., Marengo, H.G., Pereyra, F., 2011. Late pleistocene-holocene history of Chaco-Pampa sediments in Argentina and Paraguay. Quat. Sci. J. 60 (1), 188–202.

Laprida, C., Plastani, M.S., Iruzún, A., Gogorza, C., Navas, A.M., Valero-Garcés, B., Sinito, A.M., 2014. Mid-late Holocene lake levels and trophic states of a shallow lake from the southern Pampa plain, Argentina. J. Limnol. 73 (2), 325–339.

Mancini, M.V., Paez, M.M., Prieto, A.R., Stutz, S., Tonello, M., Vilanova, I., 2005. Mid-Holocene climatic variability reconstruction from pollen records (32–52 S, Argentina). Quat. Int. 132 (1), 47–59.
Mari, F., Fucks, E., Pisano, F., Carbonari, J., 2013. Cronología radiocarbónica en paleoambientes del Pleistoceno tardío y Holoceno de la Pampa Deprimida, provincia de Buenos Aires. Revista del Museo de La Plata 13, 51–58.
Martínez, G.A., 2001. Geomorfología y geología del Cenozoico Superior de las cuencas de los arroyos Los Cueros y Seco, vertiente nororiental de las Sierras Septentrionales, provincia de Buenos Aires. Universidad Nacional del Sur. Ph.D. thesis.
Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., Lee-Thorp, J., 2004. Holocene climate variability. Quat. Res. 62 (3), 243–255.
Mehl, A.E., 2011. Sucesiones aluviales del Pleistoceno tardío-Holoceno, Valle de Uco (provincia de Mendoza): inferencias paleoambientales y paleoclimáticas. Ph.D. thesis. Universidad Nacional de La Plata.
Moncaut, C.A., 2003. Inundaciones y sequías tienen raíces añejas en la pampa bonaerense (1576-2001). In: Inundaciones en la región pampeana, Honorable Cámara de Diputados de la provincia de Buenos Aires. Universidad Nacional de La Plata, Editorial de la Universidad Nacional de La Plata, Buenos Aires. Argentina.
Pisano, M.F., 2015. Moluscos y paleoambientes del Pleistoceno tardío-Holoceno en la cuenca media e inferior del Río Salado, provincia de Buenos Aires. Ph.D. thesis. Universidad Nacional de La Plata.
Pisano, M.F., Fucks, E.E., 2016. Quaternary mollusc assemblages from the lower basin of Salado River, Buenos Aires Province: their use as paleoenvironmental indicators. Quat. Int. 391, 100–111.
PMI, 1999. Informe Plan Maestro Integral Cuenca del Río del Salado. Informe de tirada reducida. Ministerio de Economía de la Provincia de Buenos Aires-Halcrow-Banco Mundial, 1999, La Plata, Buenos Aires, Argentina, 1300.
Pommarés, N., Fucks, E., Pisano, M.F., 2018. Inundaciones en la Cuenca del Salado: aspectos generadores y potenciadores. Libro de resúmenes, Séptimo Congreso Argentino de Cuaternario y Geomorfología, Puerto Madryn, pp. 164–165.
Prado, L., Wainer, I., Chiessi, C., Ledru, M.P., Turcq, B., 2013. A mid-Holocene climate reconstruction for eastern South America. Clim. Past, Eur. Geosci. Union (EGU) 9 (5), 2117–2133.
Ramos, N.A., Carignano, A.P., Cusminsky, G.C., Fucks, E., 2019. Calcareous microfossils (Ostracoda and foraminifera) from the holocene (MIS 1) at the Salado basin (Arroyo san Miguel site, Pila, Buenos Aires province, Argentina). In: Advances in South American Micropaleontology. Springer, Cham, pp. 159–174.
Rumi, A., 1991. La familia Planorbidae Rafinisque, 1815, en la República Argentina. In: Ringuelet, R. (Ed.), Fauna de agua dulce de la República Argentina, vol. 15, pp. 5–51, 8.
Scanferla, C.A., Bonini, R., Pomi, L., Fucks, E., Molinari, A., 2013. New Late Pleistocene megafaunal assemblage with well-supported chronology from the Pampas of southern South America. Quat. Int. 305, 97–103.
Scarpati, O.E., Capriolo, A.D., 2013. Sequías e inundaciones en la provincia de Buenos Aires (Argentina) y su distribución espacio-temporal. Investigaciones Geográficas. Bol. Institut. Geogr. (82), 38–51.
Servant, M., Soubiès, F., Suguio, K., Turcq, B., Fournier, M., 1989. Alluvial fans in Southeastern Brazil as an evidence for early Holocene dry climate period. In: International Symposium on Global Changes in South America during the Quaternary: Past, Present, Future. Special Publication N° 1: Program, Abstracts and General Information. ABEQUA; INQUA, São Paulo, pp. 75–77.
Servicio Meteorológico Nacional, 2018. Ministerio de Defensa. Secretaría de Planeamiento. Datos estadísticos de temperaturas máximas y mínimas. www.smn.gob.ar.
Steffan, P.G., Aguirre, M.L., Miquel, S.E., 2014. Malacofauna continental holocena (región pampeana, Argentina). Rev. Bras. Palaontol. 17 (2), 225–248.
Stuiver, M., Reimer, P.J., 1993. Extended 14C data base and revised CALIB 3.0 14C age calibration program. Radiocarbon 35 (1), 215–230.
Stutz, S., Tonello, M.S., Sagrario, M.Á.G., Navarro, D., Fontana, S.L., 2014. Historia ambiental de los lagos someros de la llanura Pampeana (Argentina) desde el Holoceno medio: inferencias paleoclimáticas. Lat. Am. J. Sedimentol. Basin Anal. 21 (2), 119–138.
Subsecretaría de Recursos Hídricos, 2002. Atlas Digital de los Recursos Hídricos Superficiales de la República Argentina CD-ROM (Buenos Aires).
Tietze, E., De Francesco, C.G., 2010. Environmental significance of freshwater mollusks in the Southern Pampas, Argentina: to what detail can local environments be inferred from mollusk composition? Hydrobiologia 641 (1), 133–143.
Tietze, E., De Francesco, C.G., 2012. Compositional fidelity of subfossil Mollusk assemblages in streams and lakes of the southeastern Pampas, Argentina. Palaios 27 (6), 401–413.
Tricart, J., 1973. Geomorfología de la pampa deprimida. INTA, Colección Científica 12, 202.
Tripaldi, A., Alonso, M.S., Messineo, P.G., Salvo Bernardez, S., 2018. Composición petrográfica y proveniencia de arenas eólicas de las dunas de La Pampa central, Argentina. In: VII Congreso Argentino de Cuaternario y Geomorfología, vol. 10. Libro de resúmenes, pp. 342–343 (Puerto Madryn).
van Geel, B., Heusser, C.J., Renssen, H., Schuurmans, C.J., 2000. Climatic change in Chile at around 2700 BP and global evidence for solar forcing: a hypothesis. Holocene 10 (5), 659–664.
Vilanova, I., Prieto, A.R., Stutz, S., Bettis III, E.A., 2010. Holocene vegetation changes along the southeastern coast of the Argentinean Pampa grasslands in relation to sea-level fluctuations and climatic variability: palynological analysis of alluvial sequences from Arroyo Claromecó. Palaeogeogr. Palaeoclimatol. Palaeoecol. 298 (3–4), 210–223.
Villagrán, M., Ortlieb, L., 1992. Una interpretación climática del registro palinológico del último ciclo glacial-postglacial en Sudamérica. In: Bulletin de l'Institut français d'études andines, vol. 22. Perú. Institut Français d'Études Andines, pp. 243–258, 1.
Yrigoyen, M.R., 1975. Geología del subsuelo y plataforma continental. In: Relatorio 6° Congreso Geológico Argentino. Bahía Blanca, pp. 139–168.
Zárate, M.A., 2005. El Cenozoico tardío continental de la provincia de Buenos Aires. In: Geología y Recursos Minerales de la provincia de Buenos Aires, Relatorio del XVI Congreso Geológico Argentino, pp. 139–155 (La Plata).
Zárate, M.A., 2007. South America loess. In: Elias, S.A. (Ed.), Encyclopedia of Quaternary Science. Elsevier, Amsterdam, pp. 1466–1479.
Zárate, M.A., Tripaldi, A., 2011. The aeolian system of central Argentina. Aeolian Res. 3 (4), 401–417.