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A multi-proxy approach to paleoenvironmental changes in the southwestern Río de la Plata area (Argentina) during Late Pleistocene

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ABSTRACT

In the southwestern margin of the Río de la Plata (Argentina), mining works have uncovered deposits that correspond to the last glacio-eustatic cycle (< 120 Ky). Because deposits of this cycle are rare in the area, the studied succession provides an opportunity to study the paleoenvironmental and paleoclimatic evolution of the area during that time. Sedimentary analysis reveal an inner estuarine environment impacted by storm surges, followed by fluvial and eolian depositional environments. The paleontological record of the terrestrial deposits indicates open grasslands and semi-arid climatic conditions that can be biostratigraphically assigned to the Lujanian Stage (late Pleistocene). Nevertheless, the chronology of the succession is hereby modified based on OSL ages and geomorphological evidence suggesting that the lower levels of the studied succession are older than previously thought (i.e. MIS 5e instead of MIS 3). Relative changes of sea level are inferred: the estuarine deposits are related to a period of relative high sea-level (i.e. MIS 5e), and the subsequent fluvial system is associated to a global sea-level fall that reached its lowest point during MIS 2.

1. Introduction

The environmental and geomorphological evolution of the Río de la Plata and its area of influence in Argentina (Fig. 1A) is strongly related to the various sea-level fluctuations that occurred during the late Cenozoic, especially during the late Pleistocene and Holocene (Violante and Parker, 1999). The coastal dynamics and the climatic changes that took place during that period determined not only the evolution of the Río de la Plata, but also the variations in the faunal assemblages (Aguirre and Fucks, 2004; Cavallotto et al., 2005). Violante and Parker (1999) and Cavallotto and Violante (2005) have identified at least five pre-Holocene (Plio-Pleistocene) and one Holocene transgressive-regressive cycles for the north-eastern Pampean Region, that would correspond to glacial-interglacial cycles. These cycles are well preserved in several Pampean areas (e.g. Salado basin; Cavallotto and Violante, 2005), but in the Río de la Plata the record is incomplete due to the highly eroding coastal processes that took place during its evolution. Nevertheless, the mining labours in a quarry at Marcos Paz County (Buenos Aires, Argentina, Fig. 1B and C) have uncovered estuarine and continental deposits that correspond to the last glaci-eustatic cycle (< 120 Ky). Besides, these deposits contain abundant fossil remains from marine/transitional and continental vertebrates and invertebrates.

The main objective of this paper is to contribute to the knowledge of the paleoenvironmental conditions that prevailed during the late Pleistocene in the inner Río de la Plata area (Matanza-Riachuelo basin, Fig. 1B), and to correlate them to regional sea-level changes that took place during the last interglacial period. This objective requires a multi-proxy study that comprises high-resolution sedimentological analysis

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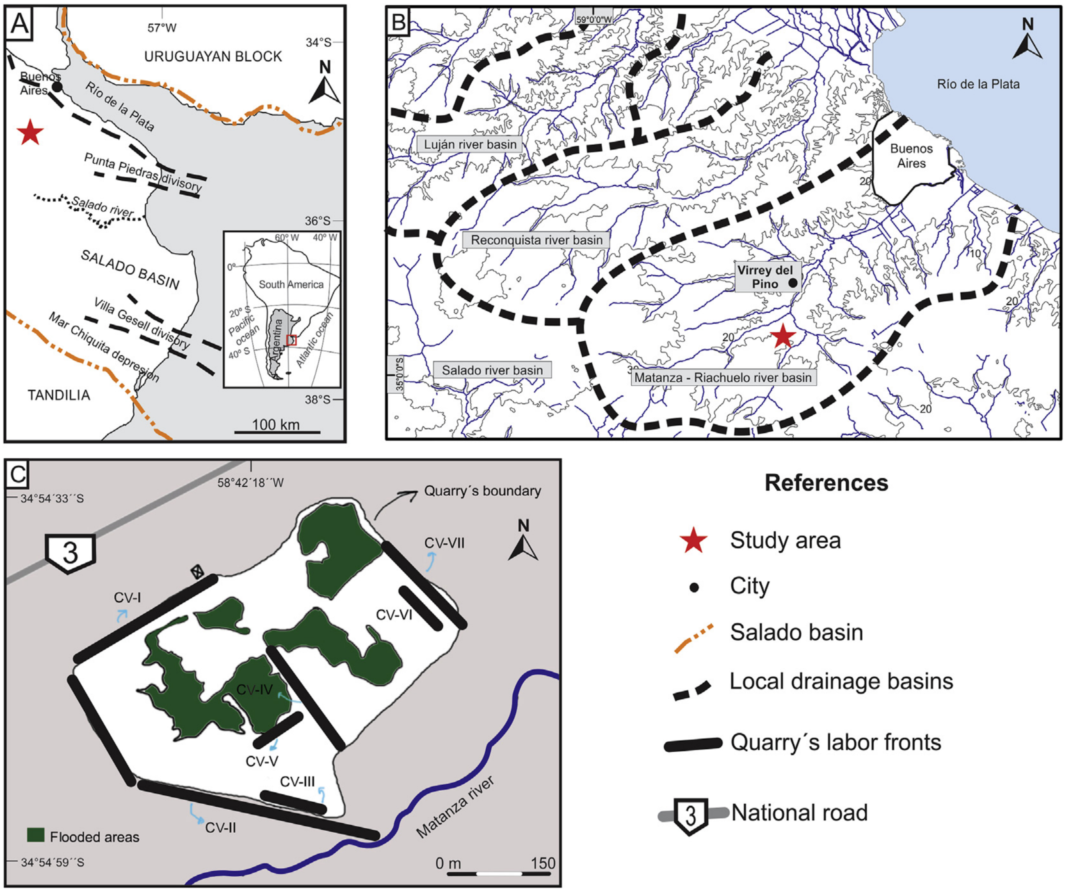

Fig. 1. Location maps. A- Morpho-structural scheme of coastal Buenos Aires province (modified from Violante and Parker, 1999). B– Location of the Matanza-Riachuelo river basin. C– Schematic map of the "Nicolás Vignogna III" quarry and the studied/open fronts.

(facies and architecture) and the characterization of the recovered vertebrates and invertebrates. These biological proxies are used to establish a biostratigraphic framework, and as an indicator of paleoenvironmental and paleoclimatic conditions.

2. Regional and geological setting

The study area is located in the Chacopampean Plain geological province (Ramos, 1999), which is divided into several sedimentary basins; the Río de la Plata occupies the northern boundary of the Salado basin (Cavallotto and Violante, 2005; Zárate and Rabassa, 2005) (Fig. 1A). The origin of the Salado basin is related to the opening of the Atlantic Ocean during the Jurassic-Cretaceous. It has a Precambrian-Paleozoic basement, volcanic and metamorphic rocks from the late Jurassic-early Cretaceous, and is filled by nearly 6000 m of marine and continental sedimentites of late Cretaceous-Cenozoic age (Violante, 1992; Cavallotto et al., 2005). The younger deposits correspond to Plio-Pleistocene and Holocene units (Cavallotto, 2002; Cavallotto and Violante, 2005). During the Plio-Pleistocene, the Salado basin was subject to successive transgressive-regressive cycles related to glacio-eustatic variations, all of which influenced the Río de la Plata since the conformation of its primitive valley, ~2.9 Ma ago (Parker, 1990; Parker et al., 1994). This process occurred because of the capture of the old drainage system of the Paraná river, which originally debouched into the Salado basin, by a pericratonic collector that flowed bordering the Uruguayan massif (Parker et al., 1994). Since that moment, the Río de la Plata evolved independently from the Salado basin (Cavallotto and Violante, 2005).

Several terms have been used to address to the late Cenozoic deposits in Buenos Aires province (Fig. 2). The lithostratigraphic schemes proposed by Ameghino (1884), Fidalgo et al. (1973a), Dillon and Rabassa (1985), Riggi et al. (1986) and Fidalgo et al. (1991) for the Pampean Region are the traditional ones and are still in use (Fig. 2), although some considerations have been made about their use (Blasi et al., 2009). The Pleistocene Pampeano Formation (Ameghino, 1884) is the most regionally extended unit. It is made up by clayey silts and silty sands with pedogenic calcareous accumulations and its deposition is related to fluvially reworked eolian sediments. In 1986, Riggi et al. divided the Pampeano Formation into the lower Ensenada and the upper Buenos Aires formations. Some *Diplodon* sp. shells found in the younger levels yielded ^{14}C minimum ages of 40 kyr (Fucks et al., 2005). Interbedded with these units, deposits of a Pleistocene transgression appear: the Pascua (Fidalgo et al., 1973b) or Pilar formations (Fucks et al., 2005) (Fig. 2). These units have been related to the "Belgranense" Stage (Isla et al., 2000).

The late Pleistocene deposits were grouped in the Luján Formation, and their contact with the Buenos Aires Formation is erosive in nature. The Luján Formation is divided into three members: La Chumbiada (Dillon and Rabassa, 1985), Guerrero and Río Salado (Fidalgo et al., 1973a). The first two are well represented in the eastern Pampean Region and correspond to the late Pleistocene (MIS 4 to MIS 2) (Rabassa et al., 2005). The faunal assemblages of both members can be related to the Lujanian Stage and to the *Equus (Amerhipuus) neogaeus* Biozone (Cione and Tonni, 1999, 2005). The Río Salado Member has been assigned to the Holocene (MIS 1) (Fucks and Deschamps, 2008) and its faunal assemblage is correlated with the Platan Stage and with the *Lagostomus maximus* Biozone (Tonni et al., 1999). The La Chumbiada Member (Late Pleistocene, > 28.9 kyr) is made up by conglomeratic or silty brown sand of fluvial origin (Dillon and Rabassa, 1985). The Guerrero Member was defined by Fidalgo et al. (1973a,b) as a

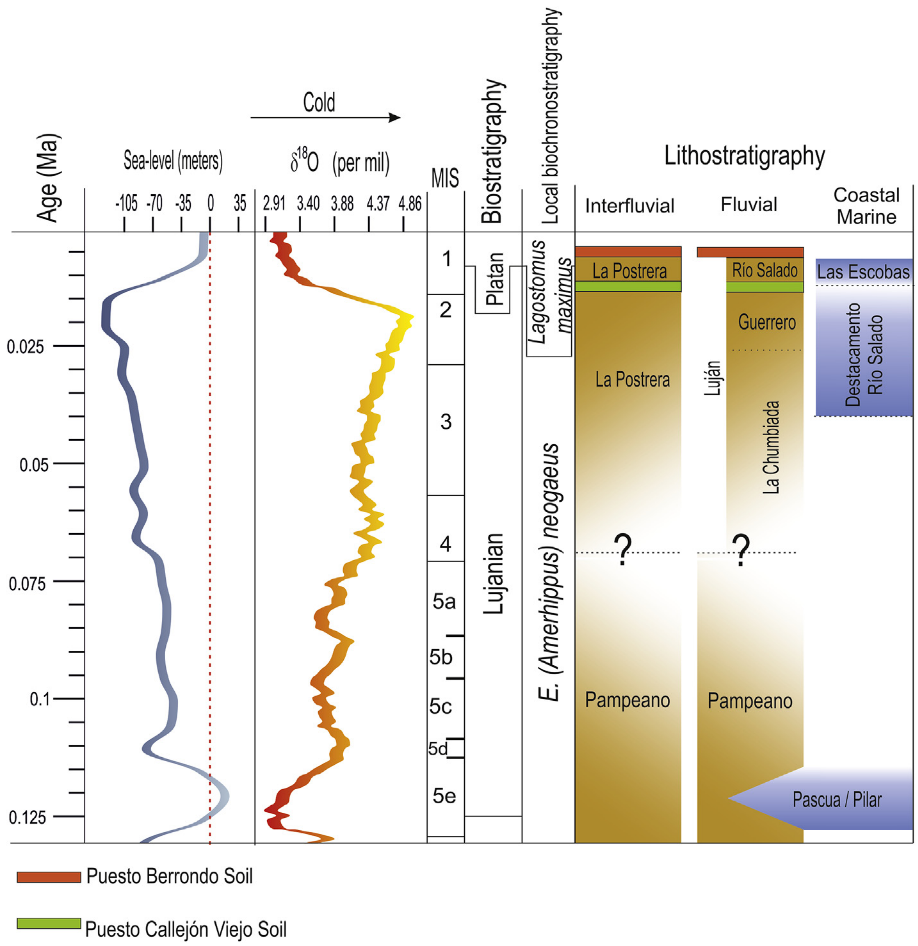

Fig. 2. Stratigraphic chart including geochronology (Gradstein et al., 2012) and local chronostratigraphic, biostratigraphic (Cione and Tonni, 2005), and lithostratigraphic units (Fidalgo et al., 1973, 1991; Dillon and Rabassa, 1985), and their correlation with the mean sea level (Haq and Schutter, 2008) and with the Plio-Pleistocene $\delta^{18}O$ composite curve (Lisiecki and Raymo, 2005). Marine isotopic stages are also shown.

succession of fluvial silty brown sand that developed in its top the Puesto Callejón Viejo Soil. Tonni et al. (1999) and Tonni et al. (2003) stated that this unit encompasses a period between ~21 and ~10 kyr (MIS 2 and part of MIS 1). Finally, the Río Salado Member is characterized by gray silt of lacustrine and paludal origin, assigned to the Holocene (~10 kyr–3.5 kyr) by Prieto et al. (2004) and to the MIS 1 by Fucks and Deschamps (2008). The top of this unit shows the development of the Puesto Berrondo Soil (Fidalgo et al., 1973b), dated by Prieto et al. (2000) in 3.5 and 2.9 kyr. Contemporaneously with the accumulation of part of the Río Salado Member, a Holocene (~6500–2600 years) marine transgression deposited the coastal Las Escobas Formation (Fidalgo, 1979; Fidalgo et al., 1973a) (Fig. 2). This unit is characterized by the black to greenish-bluish color of its deposits and by the presence of estuarine fossil invertebrates (Fucks et al., 2005).

The Matanza-Riachuelo river basin is emplaced in the coastal riverine area of the Buenos Aires province (Fig. 1B), and drains its waters towards the northeast, to debouch in the Río de la Plata, constituting the southern limit of the Buenos Aires City. Near the head of this system, in the northern margin of the Matanza river and at approximately 40 km from the Río de la Plata coastline, some late Pleistocene–Holocene deposits were uncovered by the mining labours of the "Nicolás Vignogna III" quarry. This excavation has an approximate area of 250,000 m^2; the topographic surface is at 14 m above sea level and it was excavated to ~0 m above sea level. Seven sections were studied within the quarry: CV-I, CV-II, CV-III, CV-IV, CV-V, CV-VI and CV-VII (Figs. 1C and 3). The age of the deposits was determined during previous works in the study area, when six radiocarbon age determinations were made on gastropod and bivalve shells (*Biomphalaria* sp., *Diplodon* sp., *Heleobia parchappii* and *Ostrea* sp.) (Gasparini et al., 2014, 2016; Soibelzon et al., 2012).

3. Materials and methods

The field methodology consisted on making detailed sedimentological logs (1:20) (Fig. 3A and B) of those accessible exposures within the quarry. The described and logged information included texture, composition, sedimentary structures, thickness and geometry of the strata, nature of the bounding surfaces, color (Munsell Color Chart) and post-depositional features (i.e. paleopedological features), all in accordance to Miall's schemes (Miall, 1978, 2006) for facies. Facies associations were determined with the aid of facies vertical arrangement, paleocurrents, geometry, and dimensions of the lithosomes. The interpreted facies are shown in Table 1. In addition, several samples of fine- and coarse-grained sediments were taken to analyze their compositional and mineralogical aspects. Petrographic and X-ray diffractometric (XRD) studies were carried out at the Centro de Investigaciones Geológicas (La Plata, Argentina). Samples were classified following Pettijohn (1975). For XRD methodology see Raigemborn et al. (2014). Geochemical analysis for C and O isotopic values on *Heleobia parchappii* shells were conducted at the INGEIS laboratories (Buenos Aires, Argentina).

During fieldwork, special attention was paid to identify the fossil bearing strata. The recovered fossils were processed and stored in the

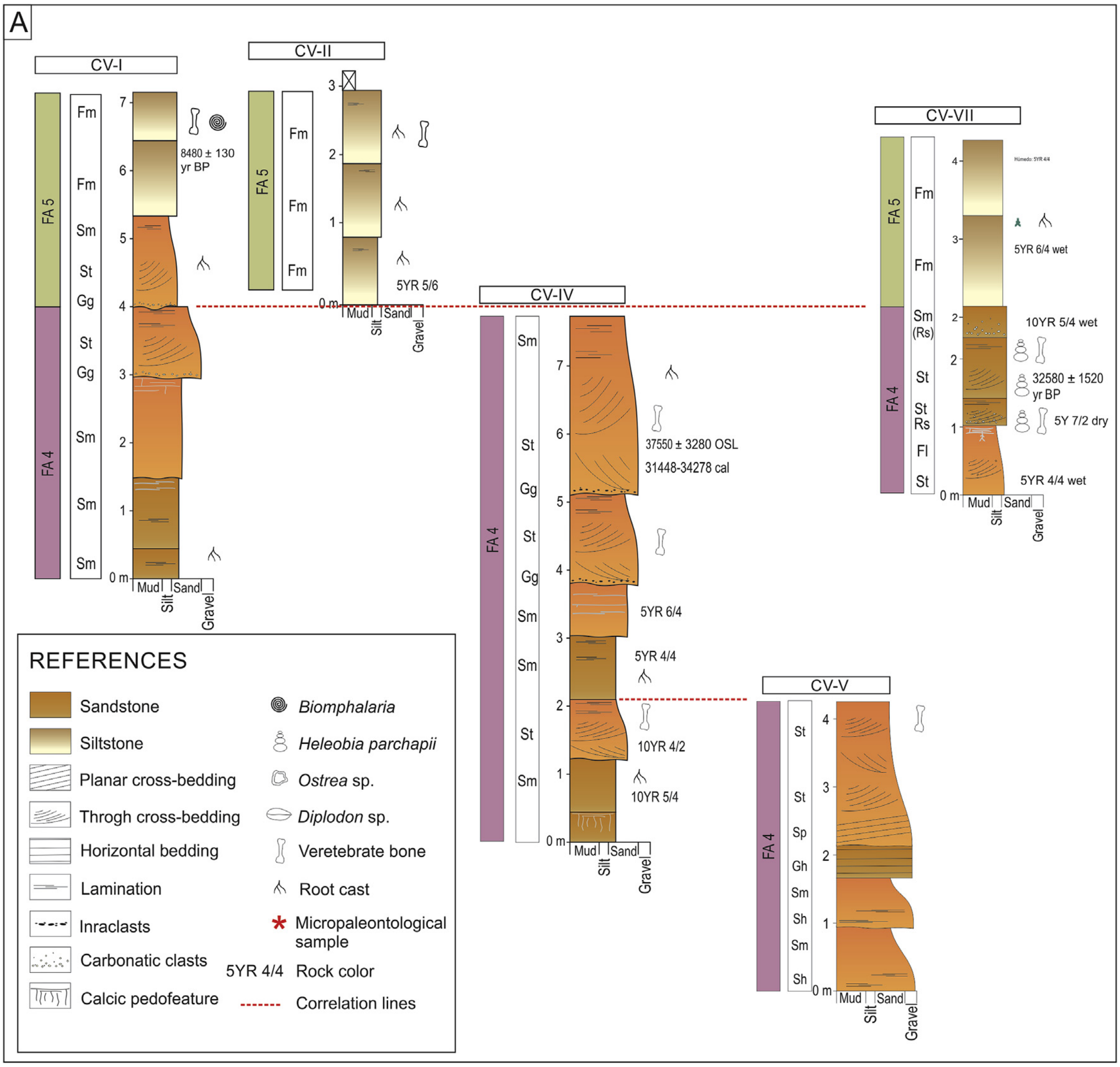

Fig. 3. A: Sedimentological logs including facies, sampling sites for ^{14}C and OSL dating and paleontological data.
B: Sedimentological logs including facies, sampling sites for ^{14}C and OSL dating and paleontological data. For references, see Fig. 3A.

paleontological collections of the Museo Histórico "Brigadier General Don Juan Manuel de Rosas" (Virrey del Pino, Argentina) and of the Museo de Ciencias Naturales "Lucas Kraglievich" (Marcos Paz, Argentina). Some of the fossils are in temporal custody at the Vertebrate Paleontology Department, Museo de La Plata, Argentina.

For micropaleontological (ostracods and forams) studies, sampling was performed at regular intervals of 10 cm, from the base level up to the top. Microfaunal collection and analyses were conducted following the standard protocols of Boltovskoy (1965) and Armstrong and Brasier (2005). Dry sediment was processed and disaggregated using tap water. Samples were then washed through a sieve of 63 mm mesh and dried at room temperature. From the residue, 1 g of material was extracted; the available entire tests were picked and studied under binocular microscope. Taxonomic determinations for Foraminifera were based mainly on Buzas-Stephens et al. (2002), Calvo-Marcilese (2011), Loeblich and Tappan (1987), and Boltovskoy et al. (1980), while for Ostracoda were based mainly on Bertels and Martínez (1990), Ferrero (2009), and Moore et al. (1960).

Two Optically Stimulated Luminescence ages (OSL) were obtained in order to test and complement the previously established ^{14}C age model (Soibelzon et al., 2012; Gasparini et al., 2014, 2016). For luminescence studies, sampling was carried out on cleaned and logged profiles. Samples for equivalent dose (De) determination were obtained by using metal tubes and black opaque plastic bags, while extra sediment was collected from the immediate surrounding for dose rates and water content analysis using watertight pots. The OSL dating was performed at Dataçao Labs (São Paulo, Brazil), employing the SAR protocol (Table 2). Conventional radiocarbon dates were calculated at the LATYR (Laboratorio de Radiocarbono del Centro de Investigaciones Geológicas, CONICET-Universidad Nacional de La Plata, La Plata, Argentina). The calibration of the dates was done using the CALIB Rev 7.0.4 program (http://calib.qub.ac.uk/calib/) and the calibration curve for the Southern Hemisphere named as Shcal13.14C (Hogg et al., 2013) (Table 3).

4. Results

The studied deposits were grouped into five facies associations according to their sedimentological (facial and architectural) characteristics.

4.1. Facies association 1 (FA1): salt marsh deposits

This facies association includes the lower strata of the studied succession (0.8 m) and crops out at the CV-III section (Fig. 3B). Clayey siltstones and fine silty sandstones that occur as tabular bodies, massive

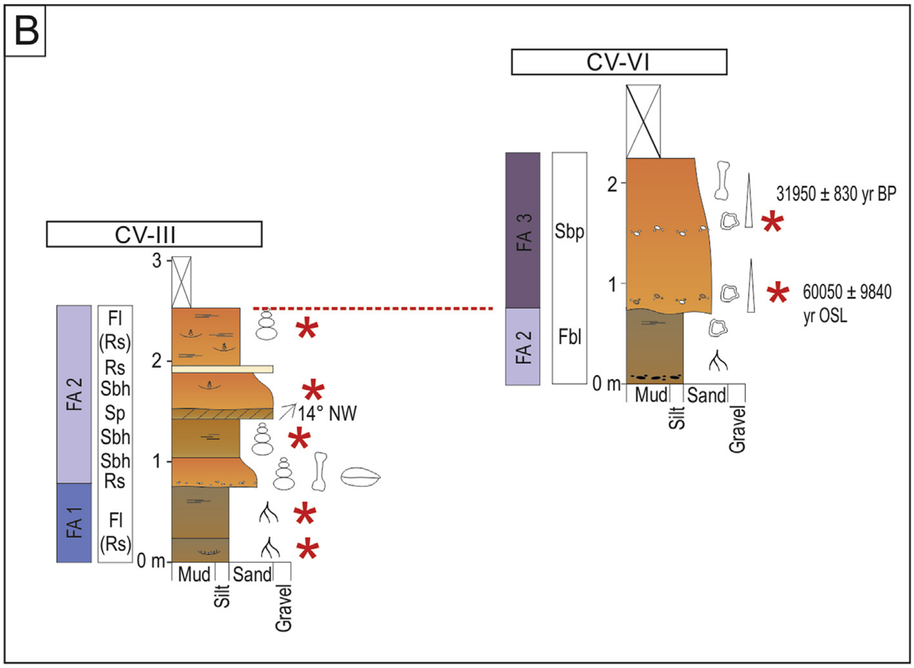

Fig. 3. (*continued*)

or with faint lamination, with minimal bioturbation and abundant root casts (Fl facies) represent this association (Fig. 4A). Clay minerals of Fl facies are mainly illite, illite/smectite mixed-layers and smectite with subordinate amounts of chlorite. These deposits have a light olive gray coloration (5Y 5/2), which could be related to deposition under reducing conditions, and are eventually cut by small scale (0.2 × 1 m) pebbly lenses (Rs facies; Fig. 4B). Some articulated *Diplodon* sp. valves were found in these levels, as well as complete shells of the oligo-to meso-haline gastropod *Heleobia parchappii*. Clay mineralogy of Rs facies is very similar to Fl facies. Depositional processes in this environment include suspension fallout in still-stand water bodies and deposition from weak traction currents (Table 1).

Gasparini et al. (2016) assigned the *Heleobia* shells to *Heleobia australis*. A more detailed taxonomic analysis allowed to re-assign the shells to *Heleobia parchappii*. At the same time, the C and O isotopic composition of the analysed shells (δ^{13}C: −5.4, −7.6 and −7.1‰ δ^{18}O: −2.8, −3.0 and −1.1 respectively) is in agreement with the taxonomic reinterpretation, since they reflect the different salinity requirements of the different taxa (i.e. different salinity of the environments they lived in).

Sediments from Fl facies were sampled to analize the invertebrate fossil content. Calcareous microfossils (ostracods in particular) were studied in order to be used as a proxy for paleoenvironmental reconstructions. In three of the four analysed samples, a conspicuous association of brackish ostracods was registered. Diversity and abundance is low, and some specimens presented signs of transport and reworking. The ostracods assemblage is dominated by *Cyprideis salebrosa hartmanni* Ramírez; *Candonopsis* sp., *Herpetocypris* sp. and *Limnocythere* sp. appear in a low proportion. This assemblage is common in continental to brackish environments, from truly freshwater to saline ones. It is interpreted that this assemblage evolved in pools and ponds of a salt marsh, where salinity was higher than in the surrounding areas. *C. salebrosa hartmanni* supports ample salinity variations, and is associated with brackish environments such as coastal lagoons or estuaries (Ornellas and Würdig, 1983; Dias Brito et al., 1988; Calvo-Marcilese et al., 2014; Marquez et al., 2016).

Table 1
Sedimentary facies of the "Nicolás Vignogna III" quarry succession.

Facies	Features	Interpretation
Gh	Clast-supported gravel; crude horizontal bedding	Longitudinal bedforms, lag deposits.
Gg	Coarse to very coarse, poorly-sorted sand or gravel. Seldom normal grading. Abundant intraclasts.	Scour-fill sand. Rapid deposition of bed load; lag deposits
Rs	Rudstone. Mostly *Heleobia* shells, seldom *Diplodon.* Poorly sorted, with fine sand matrix. Rare normal grading. May be carbonatic gravel clasts and fossil mammal shards.	Scour fill. Rapid deposition of bed load; lag deposits.
St	Fine to medium sandstone, sometimes pebbly or bioclastic *(Heleobia).* Trough cross-bedding.	Sinuous-crested and linguoids (3D) dunes
Sp	Coarse pebbly sandstone. Planar cross-bedding, sets: 0.8 m high. Tabular to concave-up based bodies.	Transverse and/or linguoid bedforms (2D-dunes)
Sbp	Coarse bioclastic sandstone. Planar cross-bedding, sets: 0.3 m high. Tabular bodies.	Transverse and/or linguoid bedforms (2D-dunes)
Sh	Silty fine to medium sandstone with high content of carbonatic pebbles. Horizontal bedding. Tabular bodies, internally with horizontal lamination.	Plane-bed flow (critical flow)
Sbh	Silty fine to medium sandstone or medium to coarse bioclastic sandstone alternating with fine beds of *Heleobia* rudstone. Horizontal bedding. Tabular bodies.	Plane-bed flow (critical flow)
Sm	Fine sitly to medium sandstone. Seldom bioclastic *(Heleobia).* Massive or with (faint) lamination. Tabular bodies.	Plane-bed flow (lower flow regime)
Fl	Clayey siltstones or siltstone-fine sandstone. Massive or with faint lamination. Tabular bodies.	Suspension fallout in still-stand water and deposition from weak traction currents.
Fbl	Clayey siltstones. Massive or with faint lamination. Tabular bodies.	Deposition from weak traction currents.
Fm	Silty fine sand. Massive or with faint lamination.	Deposition from eolian suspension; loess.

Table 2
Summary of sample codes, radionuclide concentrations, De values and luminescence ages. Grain size of quartz extract was 90–180 mm for all samples.

Sample	Th	U	K	Anual dose	Accum. dose	Age
(Lab code)	(ppm)	(ppm)	(%)	(μGy/year)	(Gy)	(yr)
2965	10.636 ± 0.383	3.332 ± 0.089	0.135 ± 0.020	1920 ± 75	72	37 550 ± 3280
2966	12.380 ± 0.446	4.354 ± 0.668	0.990 ± 0.143	3100 ± 350	186	60 050 ± 9840

This facies association is interpreted as coastal deposits in an inner estuarine environment, similar to a salt marsh associated with low-hierarchy channels, probably creeks. In addition, the occurrence of root casts suggest reworking by vegetation and deposition in freshwater floodplains or salt marshes (Pearson et al., 2012).

4.2. Facies association 2 (FA2): coastal creeks and associated deposits

This facies association includes the middle strata of the studied succession (1.5 m) and crops out at the CV-III and CV-VI sections (Fig. 3B). Sandstones that occur as tabular bodies and present a high bioclastic content characterize it. The predominant facies consist of silty fine to medium, or medium to coarse bioclastic sandstones with horizontal bedding that contain thin beds of *Heleobia parchappii* rudstone (Sbh facies, Table 1) (Fig. 4A). Compositionally, Sbh facies is classified as feldespathic wackes. Clay mineral composition is rich in illite and illite/smectite mixed-layers with subordinate amounts of smectite and chlorite. Sbh facies usually overlay a 3–5 cm thick rudstone, composed mostly of *Heleobia parchappii* and seldom *Diplodon* sp. shells (Rs facies; Table 1). Rs facies is poorly sorted, with fine sand matrix and rare normal grading, and is interpreted as the result of rapid deposition of bed load, namely as scour fill deposits. Clay mineralogy is represented by illite, illite/smectite mixed-layers, smectite and chlorite. Non-bioclastic sandstones are also found in FA2. They consist of tabular to concave-up based bodies of coarse pebbly sandstones with planar cross-bedding, sets are 0.8 m high (Sp facies; Table 1). Depositional processes in this environment are rapid deposition of bed load (lag deposits as scour fills), migration of transverse bedforms and plane-bed flow.

An outstanding characteristic of the outcrops in “Nicolás Vignogna III” quarry is the abundance and diversity of vertebrate fossils. FA2 is not an exception. Here, in deposits assigned to Sbh facies, remains of Glyptodontidae (*Glyptodon* sp.), Dasypodidae (*Eutatus* sp.), Megatheriidae (*Megatherium americanum*), Equidae (*Equus (A.) neogaeus*), Gomphotheriidae (*Notiomastodon platensis*), Camelidae (*Lama* sp.), Cervidae (*Ozotoceros* sp.), Toxodontidae (*Toxodon platensis*), Macraucheniidae (*Macrauchenia patachonica*) and a new genus and species of vultur (*Pampagyps imperator;* Agnolin et al., 2017), were collected (Table 4). All these fossils can be assigned to the Lujanian Stage (Cione and Tonni, 1999, 2005) based on the presence of *Equus (A.) neogaeus*. The vertebrate fauna is still under study and will be subject of future contributions.

The ostracod association found in FA2 deposits is similar to the one found in FA1 and points to continental to brackish environments, from freshwater to saline ones.

This facies association can be interpreted as deposited in low-hierarchy channels, such as coastal creeks that experienced crevassing during high-discharge periods and the development of splays. This would account for the abundant scouring (Rs facies) and the mixing of in-channel oligo-to meso-haline fauna (*Heleobia parchappii*) and ponds, where salinity was higher than in the surrounding areas (ostracods), and freshwater floodplain inhabitants (vertebrates). The vertical relationship between FA2 and FA1 confirms the occurrence of coastal creeks (FA2) developed in marshes (FA1) of an estuarine environment (Dashtgard and Gingras, 2005).

Some *Heleobia parchappii* and *Diplodon* sp. shells were dated (Gasparini et al., 2016), and the obtained ages were 31,040 ± 740 ^{14}C yr BP (LP2665) and 32,070 ± 1210 ^{14}C yr BP (LP2602). These ages are in accordance with the Lujanian Stage interpreted from the vertebrate fossil record.

4.3. Facies association 3 (FA3): beach-related deposits

This facies association groups some middle strata of the studied succession (1.5 m) and crops out mainly at the CV-VI section (Fig. 3B). Sandstones that occur as tabular bodies and present a high bioclastic content characterize it. The predominant facies is represented by coarse bioclastic sandstones with planar cross-bedding in sets of 0.3 m thick (Sbp facies; Table 1). Compositionally, Sbp facies is classified as feldespathic wackes with abundant vitric shards. Illite and illite/smectite mixed-layers with subordinate amounts of smectite and chlorite constitute the clay fraction. There are fragmented bioclasts and articulated *Ostrea* sp. shells (Gasparini et al., 2014) associated with vertebrate fossil remains assigned to terrestrial (*Equus (A.) neogaeus*) (Fig. 4C), freshwater (*Hydromedusa tectifera*) and to saline (marine-estuarine) (*Pogonias cromis*) fauna. Sbp facies is intercalated by fine beds of sitly fine bioclastic sandstones of the Fbl facies (Table 1). Fbl facies is classified compositionally as a lithic wacke with illite and illite/smectite mixed-layers as major components of the clay fraction. The main depositional process in this environment is migration of transverse 2D-bedforms, with subordinated deposition from weak traction currents.

Sediments from Sbp facies were sampled for analysis of the invertebrate fossil content. Some forams such as *Ammonia* sp., *Elphidium gunteri* and *Elphidium poeyanum* were identified, as well as the ostracod *Cyprideis multidentata*. This assemblage is commonly found from near marine coasts to brackish environments (Cusminsky et al., 2006; Laprida, 2006; Ferrero, 2009; Calvo-Marcilese, 2011).

Radiocarbon dating of an *Ostrea* sp. specimen indicated an age of

Table 3
Radiocarbon ages in years BP and calibrated by CALIB Rev 7.0.4 program, range 1σ.

Sample	Dated material	Raw radicarbon age	Calibrated radiocarbon age	Author
(Lab code)		(14C yr BP)	(cal yr BP)	
LP-2399	Shells	8480 ± 130		Soibelzon et al. (2012)
LP-2675	Shells	29 070 ± 1490	31 448–34 278	Gasparini et al. (2016)
LP-2665	Shells	31 040 ± 740	34 242–35 632	Gasparini et al. (2016)
LP-2729	Shells	31 950 ± 830	34 633–36 294	Gasparini et al. (2014)
LP-2602	Shells	32 070 ± 1210	34 743–37 474	Gasparini et al. (2016)
LP-2660	Shells	32 580 ± 1520	35 085–38 397	Gasparini et al. (2016)

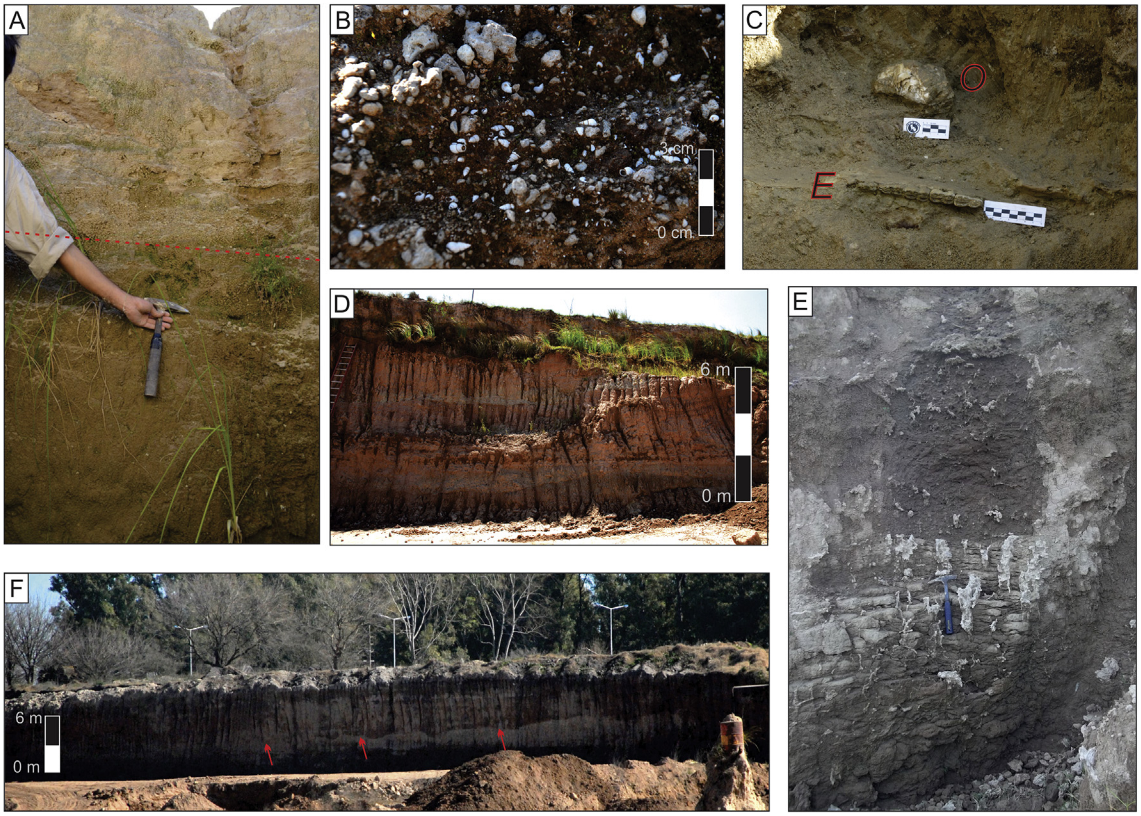

Fig. 4. Sedimentological features of the studied succession. A- Massive siltstones and fine silty sandstones (Fl facies) of FA1 in transitional contact (red dotted line) with and silty fine to medium bioclastic sandstones (Sbh facies) of FA2. B− Rs facies: rudstone of *Heleobia parchappii* shells, poorly sorted and with a fine sand matrix and carbonatic gravel clasts. C− FA3: Sbp facies with an assemblage of fragmented and articulated *Ostrea* sp. shells (red O in photo) and *Equus (A.) neogaeus* hemimandible (red E in photo). D- FA4: lithosomes with an irregular-concave-up base and a flat top surrounded by tabular sandstones. E− FA4: detail of the tabular sandstones. They show horizontal lamination, color mottles, root casts and some calcareous rhizoconcretions at the top of the different strata. F− FA5: two different lithosomes can be identified. The lower one presents an erosive and irregular base (red arrows) followed by St facies rich in carbonatic intraclast sand culminates with Sm facies deposits. The upper lithosome corresponds to the characteristic tabular silty mudstone assigned to Fm facies and its top is pedogenically modified by the development of the modern soil. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

31,950 ± 830 ^{14}C yr BP (LP2729) (Gasparini et al., 2014). Samples for OSL dating were taken from the lower levels of the CV-VI section (Fig. 3B). The obtained OSL age was 60,050 ± 9840 YBP (OSL 2966).

This facies association can be interpreted as beach-related deposits accumulated during storms in the inner estuary. Large waves might have transported suspended sediment, bed-load sediment and marine fauna (forams, turtles and fishes) into the salt marsh, where they got mixed up with terrestrial fauna (e.g. *Equus*) and sediments.

4.4. Facies association 4 (FA4): fluvial channels

This facies association characterizes the middle and upper strata of the studied succession (~8 m) and crops out at the CV-I, CV-IV, CV-V and CV-VII sections (Fig. 3A). It is composed mainly of light brown (5 YR 6/4) to dark yellowish brown (10 YR 4/2), medium to coarse sandstones. Two different types of stratal architecture can be found in FA 4. The first one is characterized by tabular bodies of medium sandstones with horizontal lamination, color mottles, root casts and some calcareous rhizoconcretions at the top of the different strata (Sm facies; Table 1) (Fig. 4E). Sm facies is compositionally classified as a feldespathic wacke. Similarly to the previously described facies, clay mineral composition of Sm facies is rich in illite and illite/smectite mixed-layers, with subordinate smectite and chlorite. At times, these tabular bodies can be composed of silty fine to medium sandstones with high content of carbonatic pebbles and horizontal bedding and lamination (Sh facies; Table 1). The second architectural type is characterized by lithosomes with an irregular concave-up base and a flat top (Fig. 4D). They are made of medium to coarse sandstones (lithic wackes rich in vitric shards) with planar and through cross-bedding (Sp and St facies; Table 1). Clay minerals of St and Sp facies are mainly illite and illite/smectite mixed-layers. The lower 15–20 cm are represented by sub-rounded carbonatic pebbles with normal grading (Gg facies; Table 1). Clay mineralogy of Gg facies is similar to Sp and St facies. Although the clasts are reworked, their low mechanical resistance suggests that the transport and mobilization was little.

FA 4 is very rich in vertebrate fossils (Table 4). The main taxa represented are Glyptodontidae (*Glyptodon* sp., *Panochthus* sp., *Neosclerocalyptus* sp.), Dasypodidae (*Eutatus* sp.), Pampatheriidae (*Pampatherium* sp.), Megatheriidae (*Megatherium* sp.), Mylodontidae (*Lestodon armatus*), Chinchillidae (*Lagostomus* sp.), Cavidae, Equidae (*Equus (A.) neogaeus*), Gomphotheriidae (*Notiomastodon platensis*), Camelidae (*Lama* sp.), Cervidae, Tayassuidae (*Tayassu pecari*), Toxodontidae (*Toxodon platensis*), Macraucheniidae (*Macrauchenia patachonica*), Canidae (*Dusicyon* sp.), Mephitidae (*Conepatus mercedencis*), Didelphidae (*Lestodelphys* sp.), Rheidae and Testudinidae.

Some *Heleobia parchappii* shells found at St facies were dated and the obtained ages were 32,580 ± 1520 ^{14}C yr BP (LP2660) and 29,070 ± 1490 ^{14}C yr BP (LP2675) (Gasparini et al., 2016). Samples for OSL dating were taken from the upper levels of the CV-IV section (Fig. 3A); the obtained age was 37,550 ± 3280 YBP (OSL 2965). These ages are consistent with the biostratigraphic interpretation of the vertebrate fauna, characteristic of the Lujanian Stage.

FA4 is interpreted as the in-fill deposits of fluvial channels. Their width/depth ratio (W/D) varies between 11 and 15; this allows to

Table 4
Vertebrate fossil assemblages of the different facies associations described for the "Nicolás Vignogna III" quarry. South American stages according to Cione and Tonni (2005).

Facies association	Vertebrate fossil assemblages	Huayquerian	Montehermosan	Chapadmalalan	Barrancalobian	Vorohuean	Sanandresian	Ensenadan	Bonaerian	Lujanian	Platan	Recent
		Miocene	Pliocene					Pleistocene			Holocene	
					Marplatan							
FA 5	*Eudromia sp.*	—	—	—	—	—	—	—	—	—	—	—
	Tolypeutes sp.							—	—	—	—	—
	Pampatherium sp.							—	—	—		
	Lestodon armatus								—	—		
	Eutatus sp.			—	—	—	—	—	—	—	—	
	Glyptodon sp.							—	—	—		
	Toxodon platensis								—	—		
FA 4	*Pampatherium sp.*							—	—	—		
	Lestodon armatus								—	—		
	Lestodelphys sp.						—	—	—	—	—	—
	Panochtus sp.			—	—	—	—	—	—	—		
	Neosclerocalyptus sp.					—	—	—	—	—		
	Tayassu pecari								—	—	—	—
	Dusicyon sp.					—	—	—	—	—	—	—
	Conepatus mercedensis							—	—	—		
	Lagostomus sp.		—	—	—	—	—	—	—	—	—	—
	Eutatus sp.			—	—	—	—	—	—	—	—	
	Glyptodon sp.							—	—	—		
	Megatherium americanum								—	—		
	Lama sp.				—	—	—	—	—	—	—	—
	Equus (A.) neogaeus									—		
	Notiomastodon platensis							—	—	—		
	Macrauchenia patachonica							—	—	—		
	Toxodon platensis								—	—		
FA 3	*Pogonias cromis*	—	—	—	—	—	—	—	—	—	—	—
	Hydromedusa tectifera		—	—	—	—	—	—	—	—	—	—
	Equus (A.) neogaeus									—		
FA 2	*Eutatus sp.*			—	—	—	—	—	—	—	—	
	Glyptodon sp.							—	—	—		
	Megatherium americanum								—	—		
	Lama sp.				—	—	—	—	—	—	—	—
	Equus (A.) neogaeus									—		
	Notiomastodon platensis							—	—	—		
	Macrauchenia patachonica							—	—	—		
	Toxodon platensis								—	—		
	Ozotoceros sp.									—	—	—
	Pampagyps imperator									—		

classify them as ribbon channels (Friend et al., 1979; Friend, 1983; Gibling, 2006). The absence of lateral migration surfaces and the channel architecture suggests they were low-sinuosity channels with low mobility. The vegetation cover of the channel banks and of the floodplain might have acted as a stabilising agent, preventing the lateral migration of the channels (Nichols and Fisher, 2007). The colors registered in these deposits are interpreted as the result of oxidizing conditions during deposition.

4.5. Facies association 5 (FA5): loess

This facies association characterizes the upper section of the studied succession (~3 m) and was identified in CV-I, CV-II, and CV-VII sections (Fig. 3A). In general terms, this FA corresponds to brown (5 YR 4/4 and 5 YR 6/4) silty mudstones and fine sandstones with thin lamination (Fm facies) and tabular geometry. Locally (CV−I section), FA5 can be sub-divided into two different lithosomes (Fig. 4F). The lower one is ~1.5 m thick and presents an erosive and irregular base with limited scouring (< 2 m), followed by St facies rich in carbonatic intraclasts (presumably they correspond to the calcic paleosol developed in the top of the underlying FA4). This lithosome culminates with Sm facies deposits. The upper lithosome corresponds to the characteristic tabular silty mudstone assigned to Fm facies and its top is pedogenically modified by the development of the modern soil. The last meter of the succession is rich in *Biomphalaria* shells, which were dated with ^{14}C, obtaining an age of 8480 ± 130 ^{14}C yr BP (LP2399) (Soibelzon et al., 2012).

Several vertebrate fossils were recovered from the upper lithesome of this facies association (Table 4), such as Glyptodontidae (*Glyptodon* sp.), Dasypodidae (*Eutatus* sp.), Pampatheriidae (*Pampatherium* sp.), Mylodontidae (*Lestodon armatus*), Chinchillidae, Camelidae, Cervidae, Toxodontidae (*Toxodon platensis*) and Tinamidae (*Eudromia* sp.). The persistence of extinct large and megafauna in the Holocene was previously reported for the study area by Soibelzon et al. (2012) and for the Pampean Region by Politis and Gutiérrez (1998) and Gutiérrez et al. (2010).

This facies association can be interpreted mainly as eolian deposits, i.e. loess deposits (Zárate, 2003). The lower lithosome was assigned to a brief fluvial reactivation period before the establishment of a loessic deposition (Zárate, 2003). As with the fauna recovered from FA4, the fauna recovered from this FA suggests arid and semiarid grasslands, with warm temperate to cold temperate climatic conditions.

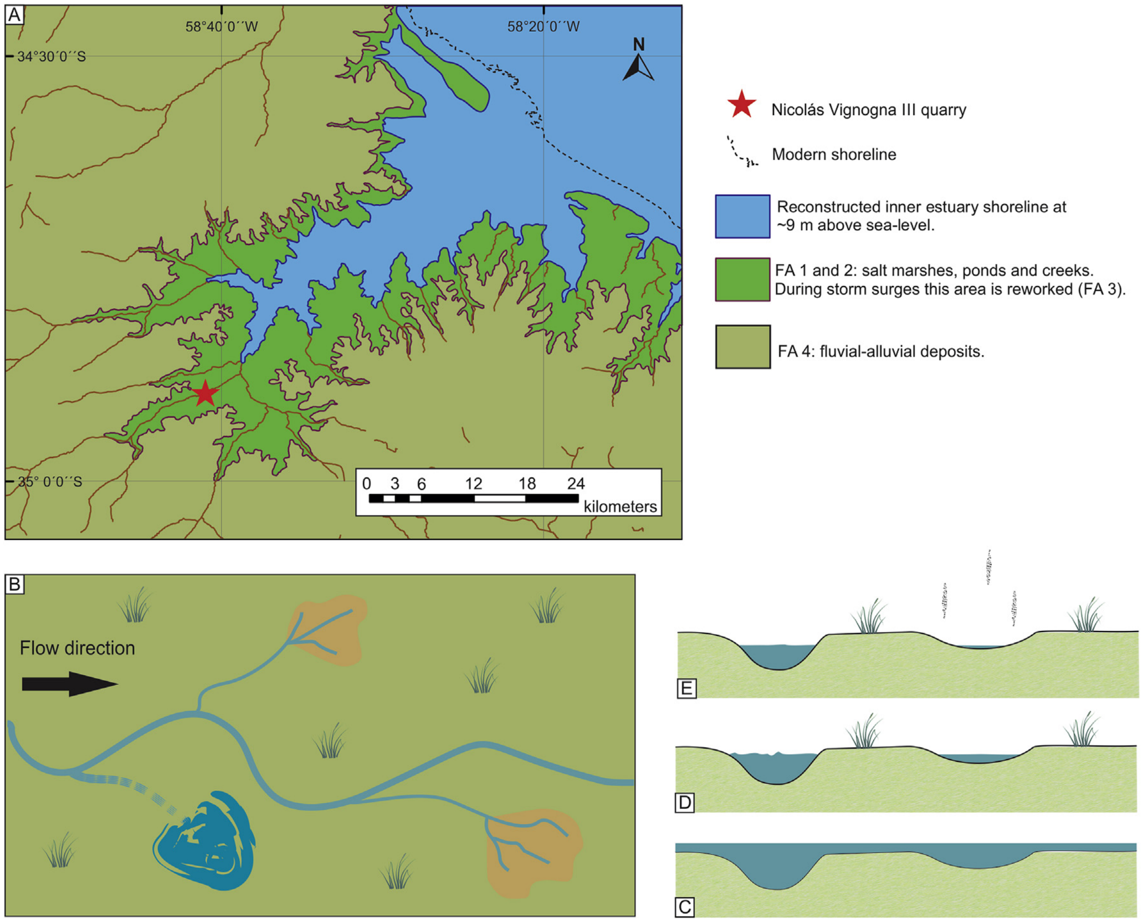

Fig. 5. Paleoenvironmental interpretation for the studied succession. A- General reconstruction of the Matanza-Riachuelo basin. Inner estuary coastline reconstructed at 9 m above present sea-level as suggested by Martínez et al. (2016). B— Scheme for the Matanza river at "Nicolás Vignogna III" quarry and the associated processes and environments (salt marshes and creeks). C— Flooding event, overflow in floodplains. D- Relative high base-level (humid season?): pools and ponds were ostracods flourished reflect groundwater level being higher than the topographic surface at some places. E — Relative low base-level (dry season?): disconnection of pools and ponds with running water. They become small closed systems subject to evapotranspiration and stressing conditions for the fauna that they sustained.

5. Discussion

5.1. Paleoenvironmental and paleoclimatic interpretations

The facies associations identified at the "Nicolás Vignogna III" quarry show the temporal and spatial evolution of the late Pleistocene–Holocene depositional systems of the SW Río de la Plata margin. This evolution can also be interpreted in terms of relative rise and fall of sea level. FA 1 and 2 are interpreted as an inner estuarine environment, representing salt marshes, creeks and associated processes that cut through it (Fig. 5A). These environments reflect a relative high base-level, which could be related to a period of relative high sea-level. In this case, the pools and ponds where ostracods flourished might be the reflection of the groundwater level, being higher than the topographic surface at some places (Fig. 5B–E). Their disconnection with running water mean that they were small closed systems subjected to evapotranspiration and stressing conditions for the fauna that they sustained. The waterlogging conditions suggested by the olive gray coloration of the sediments can also be related to a relative high base-level (Dashtgard and Gingras, 2005). Sporadic storms or storm surges might have risen the estuary level even higher, leading to the flooding of the salt marsh and leaving behind sedimentological and biological evidences. In this way, FA3 can be interpreted as storm beach-related deposits and the co-existence of aquatic, saline tolerant species (*Pogonias cromis*, foraminifers) and terrestrial fauna (*Equus (A.) neogaeus*) can be understood as the result of reworking, mixing and may be even drowned continental fauna during the episode. These storm events could also be responsible for the flooding of the pools and ponds, and of making them brackish (in addition to the effect of evapotranspiration). Nowadays, storm surges in the Río de la Plata (known as "*sudestadas*") lead to a relative rise in the estuary water level of ~1.20 m, but the observed level can reach ~ 4.4 m above estuary level (D'Onofrio et al., 2008). The studied coastal and estuarine deposits can be correlated with the near-by Ezeiza (Martínez et al., 2016) and Pilar (Fucks et al., 2005) sites, where similar estuarine and marine sediments and mollusk assemblages have been described. The age superposition of FA3 with FA1 and FA2 could be related to a high sedimentation rate along with a rapid environmental evolution.

The salt marsh and estuarine deposits of FA1, 2 and 3 are followed by the fluvial deposits of FA4, with an erosive surface between them. This facies association has a distinct continental signature from the sedimentological and paleontological points of view. It is interpreted that the fluvial deposits correspond to the paleo-Matanza river, which also debouched in the Río de la Plata estuary during the late Pleistocene. Vertebrates found here are representative of grassland environments. In the Pilar site, Fucks et al. (2005) also describe fluvial deposits overlying the marine ones, with a characteristic erosive surface between them, concluding that the fluvial rejuvenation event was of regional importance, as would be expected if the forcing factor was indeed a sea-level drop. This fluvial environment evolved into an eolian one, from which FA5 is an example. These loess deposits can be correlated to the Holocene loess deposits described for the region by

Iriondo (1997), who interpreted them as the result of a stational anticyclonic center that produced semiarid climatic conditions and dry winds. FA5 deposits also contains fauna adapted to open environments with semiarid conditions (e.g. *Tolypeutes matacus*).

The dominance of illite and illite/smectite mixed-layers through the analysed succession suggests, in general terms, cool/temperate, dry, and seasonal climate conditions. This interpretation is based in the fact that illite typically occurs during the first stage of chemical weathering of feldspathic rocks and under low-hydrolyzing weathering regimes (Nesbitt and Young, 1984; Thiry, 2000); meanwhile, illite/smectite mixed-layers result from moderate chemical weathering (Chamley, 1989), mainly due to pedogenic processes under seasonal conditions during the transformation from smectite (Raigemborn et al., 2014 and cites therein). Illite/smectite mixed-layers and also smectite can be produced by the alteration of volcanic materials (e.g. vitric shards) under alternating wet and dry conditions. Although in low proportion, the occurrence of chlorite suggests an arid climate under which physical weathering prevailed. Dry and seasonal climatic conditions are also inferred from the presence of carbonate (calcite) as cement, matrix, and pedogenic features throughout the analysed succession (Adamson et al., 2015; Gallagher and Sheldon, 2016).

5.2. Sea level changes during the late Pleistocene in Argentina

According to the global sea-level chart (Miller et al., 2005) (Fig. 2), during the late Pleistocene, high-stand conditions developed following the Last Interglacial Maximum (MIS 5e). For the Argentinian Atlantic coast, the deposits related to this episode are regularly found at 3–9 m above sea-level (Martínez et al., 2016), and are characterized as coastal and/or beach deposits of the 'Belgranense' stage (Isla et al., 2000; Fucks et al., 2005; Schnack et al., 2005; Fucks et al., 2010; Martínez et al., 2016 amongst others). After that, global sea-level began to fall, until it reached its lowest point during MIS 2 (Fig. 2); a climatic deterioration (cooler and drier conditions) accompanied this sea-level fall that culminated with the Last Glacial Maximum (circa 18 ky) (Fig. 2). In this general trend of sea-level fall, MIS 3 deposits (ca. 30–60 kyr) reflect a relative sea-level rise. The corresponding MIS 3 high-stand deposits have been described in the Argentinian continental shelf, at depths of more than 50 m below modern sea-level (Isla and Schnack, 2016).

When analysing the "Nicolás Vignogna III" quarry deposits, the lower levels of the studied section (Fig. 3A and B) correspond to salt marsh and estuarine deposits of FA1, FA2 and FA3. These levels are between 0 and 6 m above present sea level and can be correlated with a period of relatively high sea-level hereby assigned to the MIS 5e. This assumption can be made based on paleontological and geomorphological evidences, and is also supported by chronological data. In this sense, we present an OSL age of 60,050 ± 9840 YBP (OSL 2966, Fig. 3 profile CV-VII) for the lower FA3 deposits. FA1 and FA2 can therefore be interpreted as deposited during high-stand sea-level conditions older than 60 kyr. The presence of Lujanian vertebrate fauna in FA2 deposits (section 4.2) indicates that the high-stand conditions could not be older than 125 Ky, strongly suggesting a correlation with MIS 5e (Fig. 2). In the middle section of studied sections, the posterior development of a fluvial system (FA4) can be associated to a relative sea-level fall during MIS 4, 3 and 2, leading to a diminished water-table and oxidizing conditions reflected in the color of the deposits. Paleontological data found at these levels also suggest that a climatic degradation occurred during this period, which is in agreement with global climatic reconstructions of the late Pleistocene (Fig. 2). When considered all together, the relative base-level drop that took place in the continental environments might have been the trigger that led to the fluvial reactivation recorded by the fluvial deposits of FA4.

The initial work conducted in "Nicolás Vignogna III" quarry (Gasparini et al., 2014) assigned the studied deposits to the MIS 3, mainly due to the radiocarbon ages (Table 3). As recently noted by Martínez et al. (2016), several ^{14}C ages that range between 30 ky and 40 ky have been reported in coastal Argentina and Uruguay for deposits that are between 3 and 9 m above present sea level, and assigned to the MIS 3. In a more recent study of the "Nicolás Vignogna III" quarry, Gasparini et al. (2016) reviewed their data and stated that the lower levels of the quarry might represent either the MIS 3 or the MIS 5e high-stand. In this contribution, the OSL age (60,050 ± 9840 YBP) obtained for the lower FA3 deposits supports this assumption. The upper levels of FA3 had been previously dated with ^{14}C, obtaining an age of 31,950 ± 830 14C yr BP (LP2729) (Gasparini et al., 2014). The discrepancy between these two ages can be interpreted as the depositional time between lower and upper FA3 or could be related to the 50 and 30 ky low-stands, and the possibility that the concomitant erosion might have reworked MIS 5e deposits and caused the rejuvenation of the ^{14}C ages (Toledo, 2011). The OSL age of 37,550 ± 3280 YBP (OSL 2965, Fig. 3 profile CV-IV) for FA4 deposits is in accordance with previous ^{14}C ages and supports the MIS 3 assignation for those levels.

6. Conclusions

The facies associations identified at the "Nicolás Vignogna III" quarry show the temporal and spatial evolution of the late Pleistocene–Holocene depositional systems of the SW Río de la Plata margin, from an inner estuarine environment (salt marshes, creeks and associated processes that cut through it) affected by sporadic storm surges (FA 1, 2 and 3) to a fluvial environment (FA 4) that evolved into an eolian one (FA5).

The mineralogical analysis (the dominance of illite and illite/smectite mixed-layers throughout the studied succession), as well as the presence of pedogenic carbonates, suggests cool/temperate, dry and seasonal climate conditions.

The initial work conducted in "Nicolás Vignogna III" quarry assigned the studied deposits to the MIS 3, mainly due to the radiocarbon ages. In this contribution, we present OSL ages that, alongside with sedimentological, paleontological, and geomorphological data evidence that the lower levels of the studied deposits are older than previously thought.

The paleoenvironmental evolution of the "Nicolás Vignogna III" quarry can also be interpreted in terms of relative rise and fall of sea level, and the age interpretation allows to relate it with the global sea-level curve. The salt marsh and estuarine deposits of FA 1, 2 and 3 are related to a period of relatively high sea-level, that is, to the MIS 5e. After that, global sea-level began to fall, until it reached its lowest point during MIS 2; the development of a fluvial system (FA4) is associated to a lowering of the relative sea-level during MIS 4, 3 and 2, leading to a diminished water-table and oxidizing conditions reflected in the color of the deposits. During MIS 1, dry winds deposited the eolian sediments of FA5.

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