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Past environmental changes during the Late Holocene sea-level fall (last 2.7 Ka) at Bahía Samborombón, NE coastal plain (Argentina)

Mariel S. Luengo[a,*], Emiliana Bernasconi[b], Isabel Vilanova[c], Enrique Fucks[d]

[a] CONICET-Centro de Estudios Integrales de la Dinámica Exógena (CEIDE), Universidad Nacional de La Plata, Calle 64 N° 3, 1900, La Plata, Argentina
[b] Delegación de Geología y Petróleo, INIBIOMA-CONICET, Universidad Nacional del Comahue, Quintral 1250, 8400, San Carlos de Bariloche, Argentina
[c] CONICET-Museo Argentino de Ciencias Naturales BR, Avda. Ángel Gallardo 470, 1405, Ciudad Autónoma de Buenos Aires, Argentina
[d] Centro de Estudios Integrales de la Dinámica Exógena (CEIDE) Universidad Nacional de La Plata. Calle 64 N° 3, Instituto de Ambientes de Montañas y Zonas Áridas (IAMRA- UNdeC), 1900, La Plata, Argentina

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ABSTRACT

Here we present a reconstruction of vegetation history and environmental changes at the central zone of Bahía Samborombón during the Late Holocene sea-level regressive phase (last 2.7 Ka) corresponding to MIS 1. This study is an integrative approach based on the combination of geomorphological and micropaleontological (pollen, non-pollen palynomorphs and foraminifera) proxy data. We found agreement among the environmental inferences from each proxy, which clearly show the evolution of the estuarine saltmarsh from an intertidal environment under significant marine influence towards a supratidal brackish-freshwater environment as sea-level was falling. The evidence of this evolution is (1) coastal progradation encompassing at least 5.7 km as revealed by relict shorelines. Saltmarsh elevation is another evidenced as a result of accretion due to fine sediments accumulation of at least 1.2 m thick. We posit based on these values, significant progradation and accumulation processes. (2) Plant succession, characterized by the replacement of low saltmarsh vegetation by that typical of high saltmarsh; which then is associated to brackish-freshwaters plant communities in shallow water-bodies environments. (3) A gradual decrease of dinocysts and foraminifera assemblages, the latter absent during the last millennium indicating a decrease in marine influence and the consequent lower salinity values. Bahía Samborombón coastal plains became a regional scale character during the last 2.7 Ka due to its surface increase, turning into one of the most extensive southeastern-South America saltmarshes, currently constituting a biosphere reserve.

1. Introduction

The NE coastal plains located adjacent to Río de la Plata estuary (Fig. 1), developed over several sea-level transgressive periods during the Quaternary; and acquired its present configuration in response to the interaction between eustasy and marine, coastal and fluvial factors during the Holocene sea-level transgressive-regressive cycle (Violante et al., 2001; Cavallotto and Violante, 2005). The sedimentary sequences along this plain, specifically from Bahía Samborombón area (Fig. 1), have a stratigraphic continuity and abundant fossil record characterizing different depositional environments e.g. coastal barriers, beach ridges, tidal flats and lagoons environments, among others. In this regard, these sedimentary sequences are considered as key archives for reconstructing the geomorphological history as well as past environmental conditions related to the Holocene sea-level changes and climatic conditions. Major contributions have been made in the stratigraphic, geomorphological and paleontological aspects as well as in the reconstruction of past relative sea-levels (e.g. Fidalgo et al., 1973; Figini et al., 2003; Cavallotto, 1995; Cavallotto et al., 2004; Violante et al., 2001; Codignotto and Aguirre, 1993; Aguirre and Whatley, 1995; Schnack et al., 2005; Fucks et al., 2006, 2010; Richiano et al., 2012).

In particular, concerning relative sea-level fluctuations (hereafter referred as sea-level) during the Holocene, several curves have been proposed for the Rio de la Plata estuary and adjacent coastal plain (e.g. Isla, 1989; Aguirre and Whatley, 1995; Cavallotto, 1995; Cavallotto et al., 2004). Most recently, Prieto et al. (2017) produced a Holocene sea-level curve for this region based on the analysis of the sea-level database, revealing that during the transgressive phase the sea-level rose to reach the present level at or before ∼7000 cal yr BP, with a highstand peak ∼ +4 m between ∼6000 and 5500 cal yr BP (depending on the statistical method used) or at ∼7000 cal yr BP according to the ICE-6G model prediction, gradually falling after this time

* Corresponding author.
E-mail addresses: msamluengo@gmail.com (M.S. Luengo), emibernasconi@yahoo.com.ar (E. Bernasconi), ivilanova@macn.gov.ar (I. Vilanova), efucks@fcnym.unlp.edu.ar (E. Fucks).

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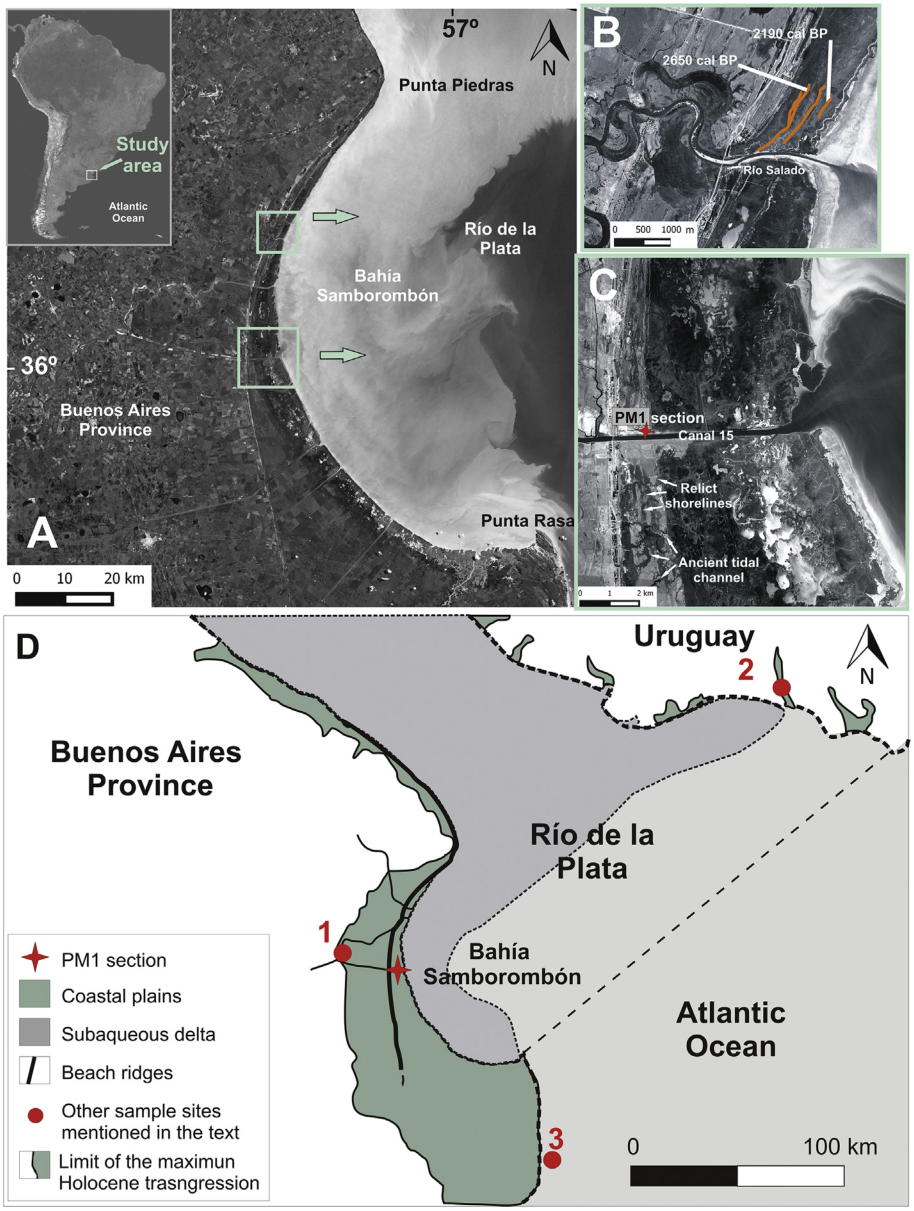

Fig. 1. Location map. A- Landsat 7 image from NE Buenos Aires province coastal sector. B- Spot 6 image from North sector of Bahía Samborombón, where it shows radiocarbon dates of cheniers (orange lines) from Río Salado mouth sector. C- Spot 6 image from the central zone of and sediment section site PM1 (red asterisk). C- regional geomorphologic map, modified from Cavallotto (2002) with others sample sites (red circles) mentioned in the present work: 1. (RS) Vilanova and Prieto (2012), 2. (ASG) Mourelle et al. (2015), 4. (T9) Vilanova et al. (2008). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

to the present position. However, the models provide no evidence to suggest a significant trend of change in the speed of sea-level fall or oscillations during the falling stage system tract (Prieto et al., 2017). Thus, additional data are needed for more details about sea-level fall, particularly during the Late Holocene.

In contrast, only few palynological studies have been carried out from deposits located in the NE coastal plain, particularly in Bahía Samborombón and Río de la Plata connected sectors where coastal saltmarshes are the most representative ecosystem (Vilanova et al., 2006; Vilanova and Prieto, 2012). However, there are scarce studies combining or integrating paleoecological information from different indicators (proxy-records) e.g. Prieto et al. (2004); Vilanova et al. (2008), Vilanova et al. (2013) and Mourelle et al. (2015). This kind of studies can provide the appreciation of rates of environmental change and longer term integral perspective about how the vegetation and environmental conditions have evolved into their current state; which would help us to understand the inherent variability; providing a context to assess their future response. This information is relevant considering the extreme importance of this region in terms of its biodiversity, land use, and the ecological services given to both local and regional societies.

At present, in the littoral zone of Bahía Samborombón there are RAMSAR wetlands, mainly saltmarshes, encompassing aquatic and terrestrial ecosystems under the influence of mixing waters from tributary rivers, Río de la Plata estuary and Atlantic Ocean; and characterized by specific ecological conditions that give place to a high biodiversity. In the Río de la Plata and Bahía Samborombón estuarine conditions have prevailed since the early and mid-Holocene subjected to strong salinity variations under the influence of local, regional and global drivers, with the inherent spatial and temporal variability and the interplay of processes. This variability in space and time both, at small and large scale, involves almost any physical, chemical and/or ecological variables; and can be better studied by multiple approaches to understand function and change over time. In this regard, the integrative studies of Holocene saltmarsh sediments and microfossil assemblages contained are considered highest-precision proxies and can shed light of the Holocene relative sea level trends.

Moreover, the littoral zone of this region constitutes a buffer between land and aquatic ecosystems, thereby allow the Pampa grasslands to be sheltered from marine influence. Currently, the region is at risk of inundation and erosion processes due to human impact, warming climate and sea-level changes. Thus, the monitoring, management and

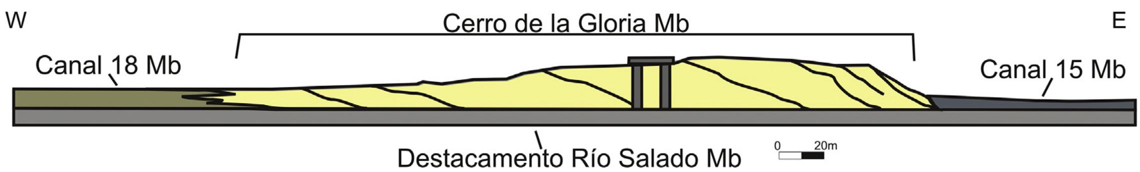

Fig. 2. Modified from Richiano et al., 2012; architectural scheme of the deposits from Canal de las Escobas Formation with their Members, situated in Cerro de la Gloria (35°58′25.01″S, 57°26′57.93″W).

conservation of the wetlands in this littoral zone would be beneficiated with the information from the long-term ecosystem dynamics. In this regard, the main question of our work is how vegetation and environments evolved during the Late Holocene sea-level decreasing phase; trying to understand the resilience of plant communities and the environments in response to sea-level fluctuations, hydroclimatic variability and human impact.

The aims of this paper are: (1) to reconstruct detailed vegetation history and environmental changes; (2) to identify the relict shorelines formed during the Holocene sea-level fall through the application of remote sensing; (3) to develop a geomorphological evolution model; and (4) To provide information relevant for the conservation of this region in terms of its biodiversity, land use, and the ecological services. To accomplish these aims, here we present an integrative approach based on the combination of geomorphological and micro-paleontological (pollen, non-pollen palynomorphs (NPPs) and foraminifera) proxy data from the central zone of Bahía Samborombón, spanning the last ~2700 cal yr BP at millennial to centennial time scale; a means the first detailed record for the region during the last part of the sea-level regressive phase. Also, we provide new radiocarbon dates for the Late Holocene of materials collected in some geomorphological landforms and litho-stratigraphic units from the Bahía Samborombón littoral zone. In this way, we contribute to enhance the chronological control of the area within the context of sea-level regressive phase.

2. Study area

2.1. General description

The Bahía Samborombón is located in the northeastern coastal plain of Argentina, adjoining to the outer part of the Rio de la Plata estuary (Fig. 1). It is a wide open bay towards the East of Buenos Aires Province, from Punta Piedras (35°27´´ S, 56°45´´ W) to Punta Rasa (36°17´´ S, 56°46´´ W). There are 3 mains rivers crossing the bay: Río Salado, R. Samborombón and R. Ajó; numerous artificial channels and shallow lakes and depressions of variable shape that are interconnected by tributary creeks. Specifically, at the center of the bay there is a coastal narrow strip of ~6 km wide (Fig. 1B) where an artificial channel (Canal Nº. 15) built in 1930′s decade had left exposed sediments whose genesis is linked to the sea-level last transgressive-regressive cycle, corresponding to Marine Isotopic Stage 1 (MIS 1).

The tidal range has very small amplitude being microtidal (0.46/0.52) (Servicio de Hidrografía Naval, 2002). The coastal plain has negligible slope (0.01%) and an average elevation of 1.6 m above mean sea level (Carol et al., 2008). The horizontal gradient of marine water salinity distribution goes from 5 psμ in Punta Piedras to 20–25 psμ in Punta Rasa (Guerrero et al., 1997). Rainfall recharge, continental water inputs, evaporation and long residence times define the hydrochemical and isotopical features of groundwater (Carol et al., 2013). From the coast towards inland, several sectors can be recognized water with and without sediments, tidal plains, saltmarshes and the Pampa plain (Bértola et al., 1998).

Climate is temperate (sub-humid to humid), with maritime influence decreasing to the west and south-west. The annual average temperature and precipitation are 16 °C and 950 mm respectively. The high amount of precipitation occurs during the summer; which is related to the influence of the South American Monsoon System (SAMS) and the South Atlantic semi-permanent high-pressure cell (Garreaud et al., 2009). The most representative winds are those from N, NE, E and SE, (Servicio Meteorológico Nacional, 1986); in particular, those from SE generate precipitation events called “sudestada”, which significantly affect the region by pushing waters toward inland. At decadal and multidecadal scale, El Niño episodes are typically associated with anomalously wet conditions in the southeastern South America; also, precipitation variability have been connected to atmospheric-ocean coupled oscillations over the Atlantic and the Pacific oceans (Garreaud et al., 2009).

2.2. Geomorphological and lithostratigraphic settings

As a result of the Holocene sea-level eustatic variations, deposition of the marine units grouped as Canal de las Escobas Formation took place in Bahía Samborombón (Fidalgo et al., 1973; Fucks et al., 2010), encompassing the transgressive, highstand and regressive stages (Violante et al., 2001; Violante and Parker, 2004; Richiano et al., 2012). Deposits of this Formation were discriminated into 4 members: Destacamento Río Salado, Canal 18, Cerro de la Gloria and Canal 15 (Fig. 2).

The sediments from Destacamento Río Salado Member consist of flaser and wavy stratified mud and represent intertidal–subtidal environments. Deposits of Cerro de la Gloria Member, composed by sand and organic material, represents coastal progradation and several littoral ridges related to storm events. These ridges prevented the tides to surpass and go further inland, with the consequently wetlands and coastal lagoon development; whose deposits correspond to Canal 18 Member. Eastward, as sea-level decreased, a series of marshes established composed by clayey organic sediments, whose deposits constitute Canal 15 Member (Fucks et al., 2010). Another deposit of Canal 15 Member corresponds to cheniers, defined as beach ridges composed by coarse material generated by storms, mainly bioclastics, resting on silty or clayey deposits that become isolated from the shore by a band of tidal mudflats (Otvos and Price, 1979). The cheniers deposits represent ancient shore lines and provide a sensitive record of environmental changes, e.g. in sediment supply, sea-level and storminess among others (Augustinus, 1989). Cheniers from Bahía Samborombón central area are composed almost exclusively by *M. isabelleana*.

2.3. Vegetation distribution and composition

The central area of Bahía Samborombón is characterized by extensive saltmarshes mainly regulated by tidal flows and topography; which also determine the dynamic and salinity of surface and underground waters (Boorman, 2003; Carol et al., 2009). As a consequence, there is a plant zonation related to their tolerance to floods and salinity, whose distribution pattern follows a gradient from the bay shoreline up to ~5 m. a.s.l (limit with Pampa grasslands). Generally, vegetation is dominated by *Spartina alterniflora*, *S. densiflora* and *Sarcocornia perennis* (Isacch et al., 2006). The saltmarshes have two main zones, low and high, which differ according to the frequency of tidal floods, sedimentology and floristic composition (Bértola et al., 1998; Cagnoni, 1999). The low-marsh is daily flooded and its extension is bounded to the limits of the influence of the daily tidal regime. The vegetation is composed mostly by *Spartina alterniflora* (Vilanova and Prieto, 2012). The high-marsh is irregularly flooded and its upper limit is conditioned for the extent of the flood produced by extreme high tides (Cagnoni, 1999). The vegetation is composed by *Sarcoccornia perennis* stands surrounded by *Spartina densiflora*, accompanied by *Limonium brasiliense* and *Juncus* aff. *acutus* patches (Vilanova and Prieto, 2012). Between the high and low zones, different vegetation pattern and composition allow the recognition of a transitional middle zone. In both, the middle and high zones *Spartina densiflora* and *S. perennis* can be distributed in three different patterns: (1) *S. densiflora*grasses only; (2) *S. perennis*stands only; and (3) a mixture of both species (Isacch et al., 2006). In addition, arboreal patches *Celtis tala* ('talares') develop on top of the beach ridges along with *Scutia buxifolia*, *Jodina rhombifolia*, *Schinus longifolius* and *Sambucus australis* (Torres Robles, 2009).

2.4. Bahía Samborombón ecological relevance and properties

According to Ramsar.org, the Bahía Samborombón is the biggest mixohaline wetland in Argentina, which is considered of international relevance for the conservation of biological diversity. Consequently; it was declared as a Ramsar Site in January 24th, 1997. It includes private lands, National Army lands, Wildlife Reserve and Natural Provincial Reserves. It covers a total of 2440 km^2 (between 0 m and 8 m above sea level), of which 1473 km^2 are land and the rest correspond to the open water to 3 m average depth. Moreover, this wetland provides numerous ecosystems services such as regulation of water, disturbance events (storminess protection, erosion control), climate (microclimate), sediment retention, nutrient cycling, surface water maintenance, wild life protection (refuges for migratory birds and Pampas deer).

3. Materials and methods

3.1. Remote sensing analyses

A Spot 6 image taken on September 14, 2015 was analyzed. The spectral resolution of bands B1 to B4 are; Green (0,530–0590 μm), Red (0,625–0695 μm), Blue (0,450–0520 μm), Near Infrared (0.760–0.890 μm), all which have a spatial resolution of 6.0 m; also a Panchromatic band was analyzed with spectral and spatial resolutions of 0,450–0745 μm and 1.5 m, respectively. This image was provided by the National Commission for Spatial Activities (CONAE). For the recognition and mapping of geomorphological features (relict shorelines and tidal channels, among others) the best information was provided by the Spot 6 image panchromatic band. The preprocessing consisted in the data radiometric correction. Spatial operations called convolution filters were carried out to improve visualization. Subsequently, vector data layers (polygons and/or lines of different colors) were generated to differentiate coastal geoforms throughout QGIS 2.2.0 program. Field work was necessary to corroborate the morphologies recognized by remote sensing image and for the description of exposed sections from quarries and artificial channels.

3.2. Sampling procedure of sediment section (PM1)

We sampled a 120 cm long sedimentary sequence (PM1), located at the left margin of the artificial channel named as Canal 15 (35°58'14.86″S, 57°24'49.72″W), at 5700 m from the present bay shoreline (Fig. 1). In the laboratory, the sequence was subsampled and described, considering texture, color, sedimentary structures and presence of macrofossils (gastropod and bivalves), and shell fragments. The subsampling was at 1 cm intervals. Subsamples were analyzed for pollen and spores; dinoflagellate cysts (dynocists), foraminifer's tests and mollusca valves (taphonomy). Palynological and foraminiferal analyses were every 3 and 4–5 cm, respectively.

3.3. Palynological analysis

For the recovery of palynological content (pollen, spores and dinocysts) a total of 38 levels of the sequence section were analyzed. Sediment (1 cm^3) was processed using the physical and chemical methods proposed by Faegri and Iversen (1989) and Mudie and Harland (1996); which include the use of KOH, HCL, HF and acetolysis. *Lycopodium clavatum* spore tablets (Stockmarr, 1971) were added before treatment to calculate pollen concentration. A minimum of 300 pollen grains per level were counted. The identification of pollen grains and spores was made according the atlases and published keys (Heusser, 1971; Markgraf and D'Antoni, 1978; Prieto and Quattrocchio, 1993; Mourelle and Prieto, 2016), and the reference collections at the BA_Pa (Museo de Ciencias Naturales) and Cátedra de Palinología, Universidad Nacional de La Plata, Argentina (Yáñez et al., 2014). Diagrams were drawn applying TGView 2.0.4 program and palynological zones were determined by CONNIS stratigraphical constrained cluster analysis (CA) (Grimm, 2004). Pollen types selected for this analysis were those whose mean value was at least 1% or whose maximum value was higher than5%. CA divided the pollen diagram from PM1 section into three zones (PM1-P1.1, PM1-P1.2 and PM1-P2). Pollen grains and spores were calculated as a percentage of the total pollen sum; whereas dinoflagellate cysts were calculated as the percentage of the pollen sum plus NPP sum.

3.4. Foraminifera analysis

Microfaunal collection and analyses were conducted following standard protocols of Boltovskoy (1966) for benthic foraminifera. A total of 26 levels of the sequence section were analyzed. These samples were water washed through a 63 μm mesh screen (Tyler Screen System Nº 230) and dried at room temperature. From the residue, 1 g of material was extracted; the entire available tests were picked and studied under binocular. Systematic analysis was based on Loeblich and Tappan (1992) on Boltovskoy (1954a, b); Boltovskoy et al. (1980); Calvo Marcilese (2011); Bernasconi and Cusminsky (2015), among others. There were estimated the total abundance (number of specimens per gram of dry sediment), relative species abundance (proportion of each species in the total assemblage) and diversity (species richness (S) and Shannon-Weaver (H) and Fisher's α indices). Shannon-Wiener (H) values greater than 3 would indicate normal marine conditions, while low values would suggest a highly unstable environment (Buzas and Gibson, 1969). Murray (1991) believes that values lower than 0.6 would reflect hyposaline lagoon environments and those higher than 2.5–3 would indicate normal marine conditions. For the other hand, Fisher's α values greater than 7 would indicate normal marine conditions from platform to abatial or hypersaline platform, while values less than 5 would suggest general hyposaline or marine hypersaline marginal conditions with a high predominance of one species (Murray, 1973, 1991). The diagram of the foraminiferal relative proportions was divided in several zones according to Coniss software included in the TILIA 2.0.4 statistic package (Grimm, 2004). The analysis considered only the species whose relative abundance was equal to or greater than 1%. Standardized Euclidian distance was applied as the distance coefficient, and data transformation by standardization to mean 0 and 1as typical deviation. Clusters formed according to the sum of squared error hierarchical clustering method (Grimm, 2004).

3.5. Chronology

The chronology of the section is based on three radiocarbon dates determined on *Mactra isabelleana* valves and bulk organic matter (Table 1). The summarized chronology indicates that the study section represents the last 2.7 ka BP. For radiocarbon dates based on *M. isabelleana*, we selected valves presenting well preservation state regarding the taphonomic attributes (fragmentation, abrasion and

Table 1
Radiocarbon dates from PM1 section, Canal 15 and cheniers. Material analyzed: *Mactra isabelleana* shells and bulk organic matter.

Profile (cm)/Geoform	Uncalibrated age (^{14}C yr BP)	Calibrated age weighted average/cal yr BP (1- σ interval)	Laboratory no.	Material
PM1 42-43	1489 ± 22	1223 (1218–1254)	D-AMS 016771	Bulk organic matter
PM1 85-86	1689 ± 23	1374 (1343–1406)	D-AMS 016770	*Mactra isabelleana*
PM1 107-108	2640 ± 80	2240 (2206–2444)	LP-3129	*Mactra isabelleana*
Chenier 01	2590 ± 80	2190 (2146–2344)	LP-3297	*Mactra isabelleana*
Chenier 03	3050 ± 100	2650 (2726–2941)	LP-3300	*Mactra isabelleana*

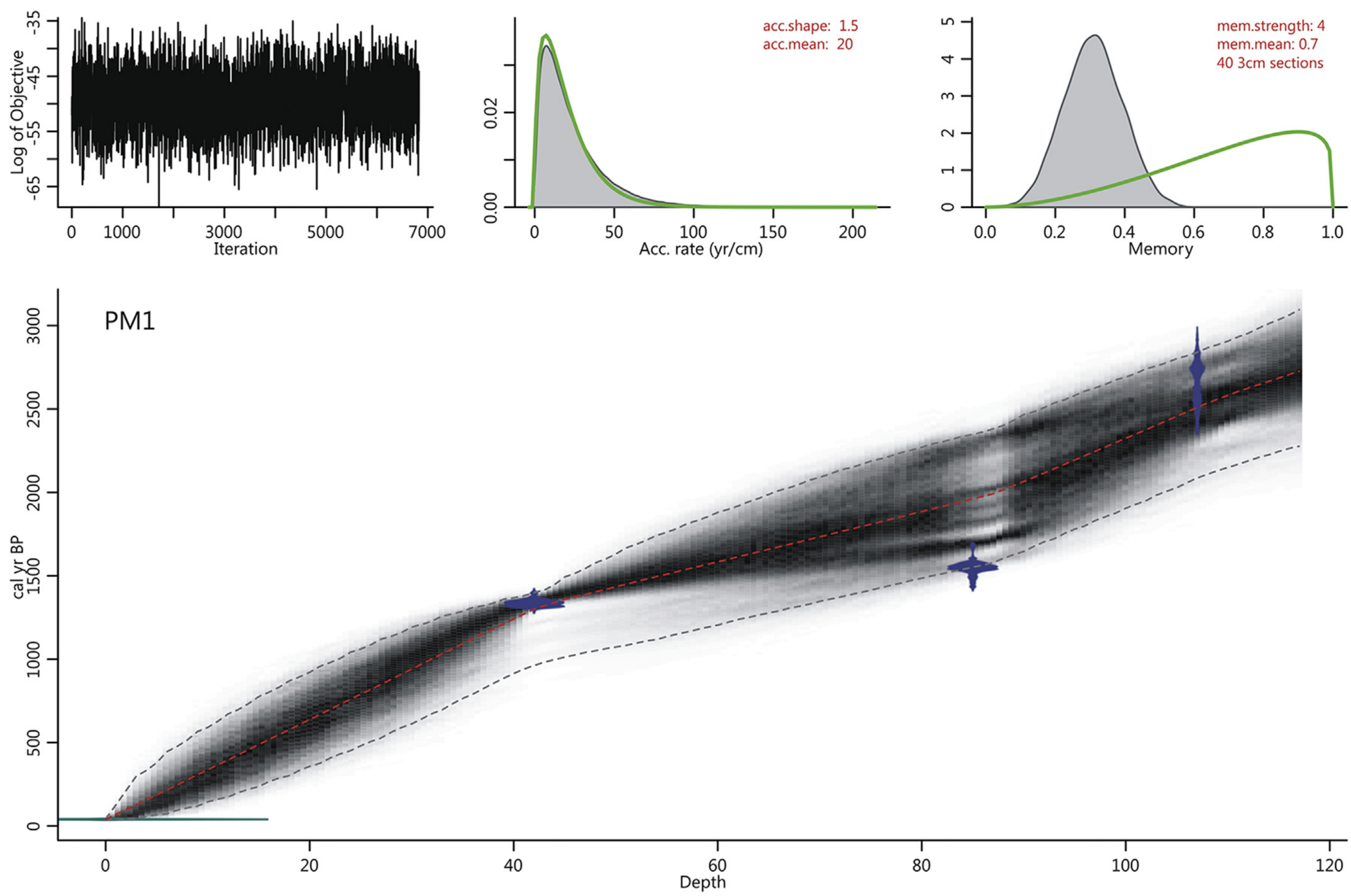

Fig. 3. The age-depth model for PM1 section using the program Bacon. Upper panels depict the Markov Chain Monte Carlo (MCMC) iterations (left), prior (green curves) and posterior (gray histograms) distributions of accumulation rate (middle panel), and memory R (right panel). The bottom panel shows the age-depth model (gray) and the calibrated14C dates (blue). Gray stripped lines indicate the 95% confidence intervals; the red curve shows the "best" fit based on the weighted mean age for each depth. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

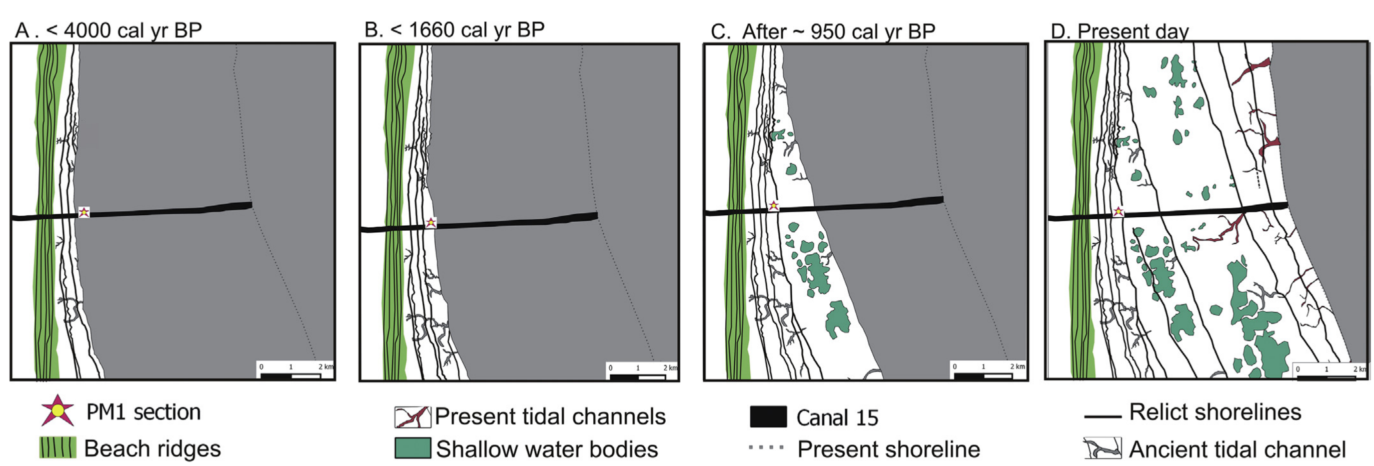

Fig. 4. Evolutionary sequence of coastal plain from central zone of Samborombón Bay constructing by mapped geomorphologycal features.

corrosion). These valves were entire and with signs of minimum reworking or transport. 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) and the Marine13 curve (Reimer et al., 2013). Age-depth model was constructed by Bayesian age-depth modeling approach using the program "Bacon" (Blaauw and Christen, 2011), (Fig. 3). Additionally, two more radiocarbon dates were obtained from cheniers located ~25 km North of the section in order to better constrain the regional chronological context (Fig. 1B, Table 1).

4. Results

4.1. Coastal relict shorelines

A total of 9 relict shorelines (not including the current one) were recognized and mapped in the central zone of the coastal plain of Bahía Samborombón, following E-W direction; from the coastline up to the main beach ridges (Cerro de la Gloria Mb), covering ~7 km (Fig. 4D). These relict shorelines are linear, parallel to sub-parallel, and were inferred by (1) the aligned water bodies and tidal channels mouths, all ending on a perpendicular line (relict shoreline); (2) through slightly topographic changes, (3) modifications in the current vegetation cover, and (4) cheniers; the latter with a chronology that reveals the regressive character (Fig. 1B). All these features are clearly distinguished because there were slightly affected by anthropic activity, except in those sectors where their materials were extracted from quarries.

The spacing of the relic shorelines varies along transect following W-E direction. In the vicinity of the most internal ridges (Cerro de la Gloria Mb.) formed between ~4200 and 2700, the distance among them range from 150 to 500 m, resulting in the divergence to the South (Fig. 4). Eastward, the recognition of the more recent relict shorelines as well as ancient tidal channels is complicated because they are not clearly seen; although the delimitation can be made based on the arrangement of the aligned water bodies.

4.2. Sedimentology, structures and macrofaunal analysis

At the base, the sedimentary sequence is characterized by muddy texture and heterolytic structure (clays and silts), which become homogeneous towards to the upper part. There are remains of entire and fragmented shells scattered throughout the section, but also concentrated in levels. The sequence is described based on its color, structures, pedogenetic characteristics and macro-fossils content (Table 2). Above the section, there is a uniform layer composed by debris resulted from the building of Canal 15 at the beginning of the twentieth century, in 1910 (Min. de Obras Públicas de la Provincia de Buenos Aires, 1911).

4.3. Palynological zones

The pollen diagram shows that Chenopodiaceae and Poaceae are the dominant taxa of the record reaching maximum values of 80% and 45%, respectively (Fig. 5). These taxa are accompanied by Cyperaceae with values up to 20% and Asteraceae up to 10%, along with *Celtis* sp. that is recorded with values ~5%. Regarding dinocysts, both *Operculodinium* and *Spiniferites* have the highest proportions at the base of the diagram ~60% and 15%, respectively; showing a decreasing trend towards the top. On the contrary, the aquatic fern *A. filiculoides* has an increasing trend up to 80%. According to CONISS cluster analysis three palynological zones and 2 subzones were defined, whose description is as follows:

Zone PM1-P1.1 (117-65 cm) **P1.1a** Chenopodiaceae values reach 55% and Poaceae 35%; accompanied by Cyperaceae and Asteraceae ranging 3–7%. *Azolla filiculoides* has values ≤ 10%; *Phaeoceros* and *Botryococcus* sp. are registered with ≤5%. *Operculodinium* and *Spiniferites* have the highest values up to 60% and 10%, respectively. **P1.1b** Chenopodiaceae and Poaceae have more variable 40–50% and 30–40%, respectively; accompanied by Cyperaceae and Asteraceae 3–7%. *Limonium brasiliense* appears here ≤5%. *Azolla filiculoides* reaches 15%; *Phaeoceros* and *Anthoceros* are recorded as traces and *Botryococcus* sp. as well. *Operculodinium* varies 25–50% and *Spiniferites* fluctuates between 5 and 15%.

Zone PM1-P1.2 (65-30 cm) Chenopodiaceae dominate and increase toward the top of the zone ranging 55–75%. Poaceae decrease to 15% with a peak of 35%. Asteraceae increase slightly ~10%. *Phaeoceros* is ≤ 5% and Ricciaceae appear here. *Azolla filiculoides* reaches up to 40–50%; whereas *Operculodinium* and *Spiniferites* have a gradual decreasing trend, the former to10-15% and the latter to ≤5%.

Zone PM1.P2 (30-0 cm) Chenopodiaceaevaries35-75% and Poaceae as well 10–40%. Cyperaceae and *Ambrosia* increase toward the upper part of the zone, reaching values of 20% and 10%, respectively). A notably rise in *A. filiculoides* is recorded, reaching 80%. In this zone, up to 4 pollen clumps of Chenopodiaceae, Poaceae, Asteraceae and *Ambrosia* are found. *Operculodinium* and *Spiniferites* diminish considerably, the former to≤5% and the latter to traces.

4.4. Foraminiferal zones

We determined 28 species of benthic foraminifera distributed among 16 genera. The individuals belong to five Orders, Rotaliida (98%), Buliminida (1.8%), Lagenida (0.1%), Spirillinida (0.04%) and Miliolida (0.01%). Total abundance ranged from 26 to 15683 individuals, S ranged from 3 to 17, values for H ranged from 0.8 to 1.8 and Fisher's α varied between 0.5 and 2.0 (Figs. 6 and 7).

The foraminiferal assemblage is mainly constituted by *Elphidium* aff. *poeyanum* (Balkwill and Wright), *Ammonia parkinsoniana* (d'Orbigny) and *Elphidium gunteri* Cole which represent more than 90% of the total fauna of the sequence. The analysis of clustering showed two zones PM1-F1 and PM1-F2, in the second one, three sub-zones were distinguished PM1-F2. a, PM1-F2.1. b and PM1-F2. c (Fig. 8). Species relative abundance is provided in parentheses:

Zone PM1-F1 (116–100 cm), it is mainly characterized by *Elphidium* aff. *poeyanum* (Balkwill and Wright) (34.3–58.4%), *Ammonia parkinsoniana* (d'Orbigny) (17.0–40.2%), *Elphidium gunteri* Cole (4.1–30.1%), *Bolivina ordinaria* Phleger and Parker (0–8.1%), *Buccella peruviana* (d'Orbigny) (1.4–3.7%), *Elphidium* sp. (0–5.8%), and *Bolivina pseudoplicata* Heron-Allen and Earland (0–3.6%). Total abundance ranged from 2388 to 15683 individuals. Values for S and H ranged from 8 to 16 and 1.0 to 1.8, respectively, and Fisher's α index from 0.9 to 2.0.

Zone PM1-F2. a (100–73 cm), it is represented mainly by *E.* aff. *poeyanum* (39.6–57.1%), *A. parkinsoniana* (9.2–42.3%), *E. gunteri*

Table 2
Sedimentary and macrofaunal descriptions of the PM 1 section.

Depth (cm)	Sediment, structural, pedogenetic and macrofaunal characteristics
0–20 cm	Dark brown silty-clay, plastic and adhesive soil is developed. Structured in prisms, with roots and abundant content in organic matter.
20–90 cm	Reddish brown muddy sediment (presence of organic matter and iron oxides). Massive structure observed in the field. Above, bioclastic fragments and isolated gastropods of the genus *Heleobia* are present.
90–118 cm	Grayish-greenish brown laminated silt and mud. Towards cm 107 there is a fossiliferous level, a few centimeters thick with remains of mollusks (*Mactra isabelleana*, *Heleobia australis*, *H. parchappii*) *Tagelus plebeus* is in life position.

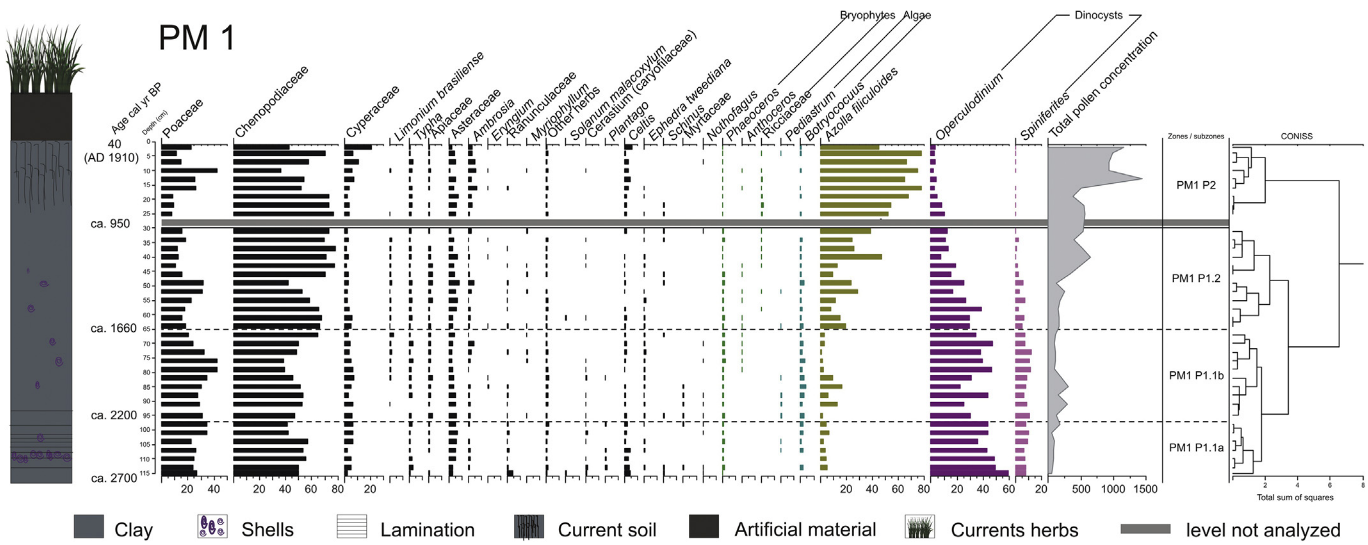

Fig. 5. Sedimentary sequence, radiocarbon dates, pollen and NPPs percentage diagram and palynological zones from PM1, Canal 15, Bahía Samborombón.

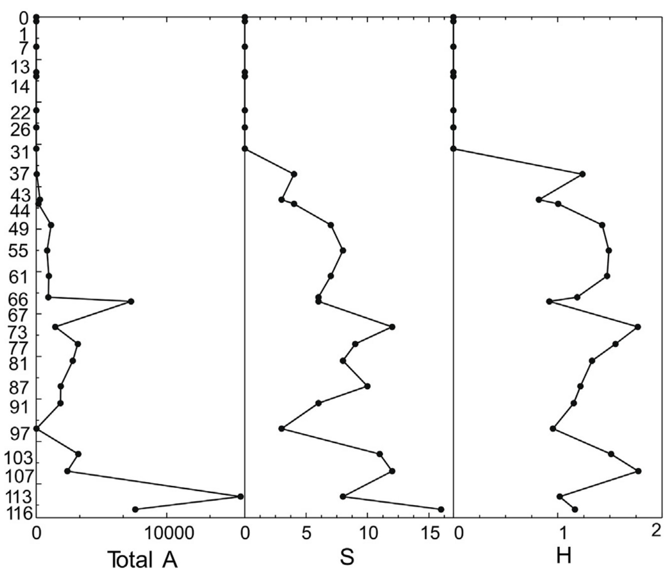

Fig. 6. Total abundance (Total A), Species richness (S) and Shannon-Weaver diversity index (H) of the PM1.

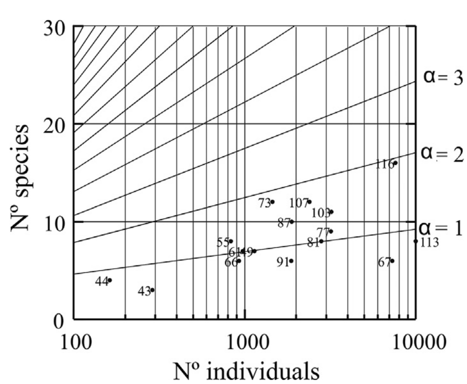

Fig. 7. Fisher index values from levels with more 100 individuals.

(9.0–32.4%), *Elphidium galvestonense* Kornfeld (0–15.5%), *B. ordinaria* (0–2.8%), and *B. peruviana* (0–1.6%) were found. The rest of the species were recorded in lower percentages. Total abundance ranged from 26 to 3192 individuals. Values for S ranged from 3 to 12; H from 1 to 1.8 and Fisher's α index from 0.8 to 1.8.

Zone PM1-F2. b (73–35 cm), it is mainly characterized by *E.* aff. *poeyanum* (20.5–64.1%), *A. parkinsoniana* (14.3–61.5%), *E. gunteri* (4.0–21.2%), *E. galvestonense* (0–18.4%), and *B. peruviana* (0–3.7%). Total abundance ranged from 39 to 7280 individuals. Values for S and H ranged from 3 to 7 and 0.9 to 1.5, respectively, and Fisher's α index from 0.5 to 1.3.

Zone PM1-F2. c (35–0 cm), this zone is represented by the total absence of foraminifera, all of levels were sterile.

5. Discussion

5.1. Paleoenvironmental reconstruction

After the mid-Holocene highstand (~6 ka), as the sea-level regressive phase began, lagoons, marshes, and tidal flats enclosed by beach ridges developed in an incipient proto-Bahía Samborombón (Violante et al., 2001, Violante and Parker, 2000; Fucks et al., 2010). In the central bay area, the regressive beach ridges of ~400–500 m wide most probably occurred within the ranges ~5200–4900 cal yr BP and 4450–4150 cal yr BP (Fucks et al., 2010). Moreover, after 4 ka, coastal progradation occurred determined by in relation to high sediment supply from the Río de la Plata (Violante et al., 2001); this phenomenon is detected by the increasing distance among the successive relict shorelines prograding eastward (Fig. 4). According to our data, during the 2650-2190 cal yr BP period disaggregated and isolated cheniers developed north from the central bay area (Fig. 1B). Within this framework, sedimentation processes occurred in a subtidal-intertidal environment of low energy; simultaneously, sand and bioclastic sediments deposited over the successive shorelines related to high energy storm events (Fig. 9).

The multi-proxy record from this sedimentary deposits allow us to interpret several environmental scenarios during the last stage of the Late Holocene sea-level regressive phase at different intervals, which can be described as follows:

Between 2700 and 1660 cal yr BP halophytic salt marsh vegetation predominated near an intertidal-subtidal depositional environment. This vegetation was characterized by Chenopodiaceae (most probably representing *Sarcocornia perennis*) and Poaceae (likely *Spartina* spp.); accompanied by Asteraceae (*e.g. Baccharis*, *Ambrosia*, among others). *Sarcocornia perennis* and *Spartina* are key colonizing plant species of intertidal mudflats due to their tolerance of being covered by salt water for long periods. *Celtis*, an arboreal species, could be associated to the beach ridges that developed in the vicinity. The paludal species *Typha*

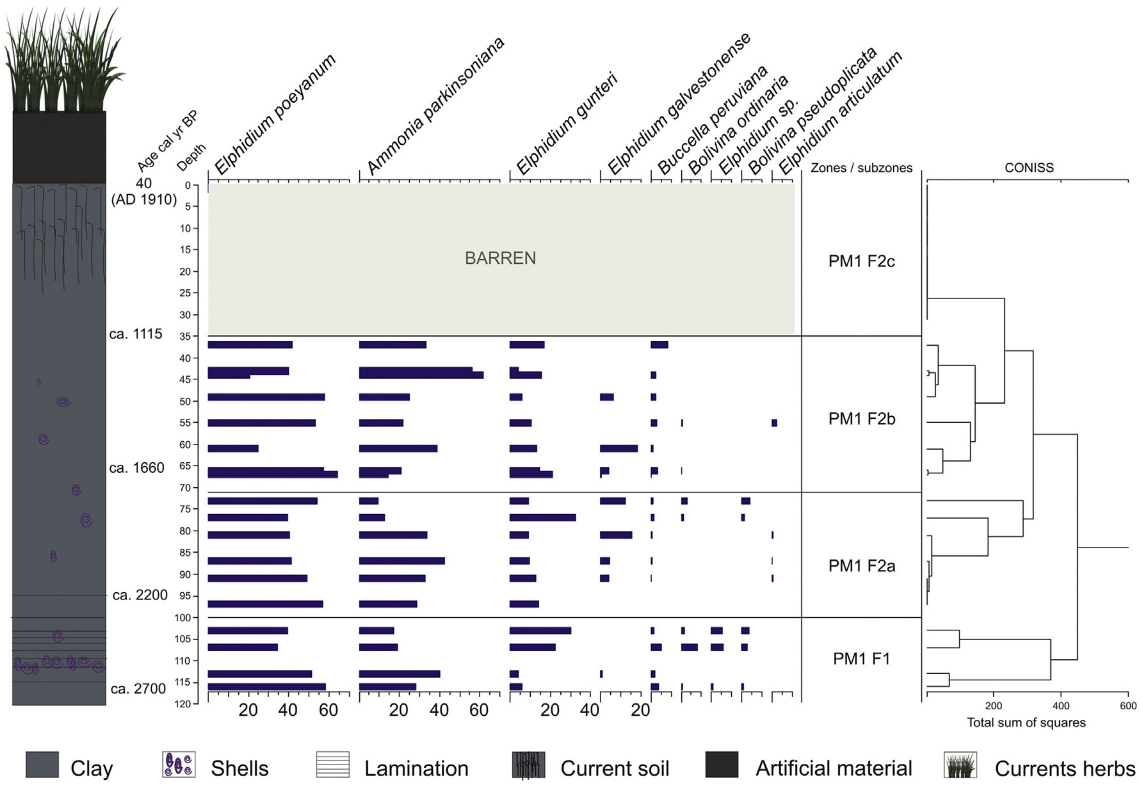

Fig. 8. Distribution of foraminiferal species in PM1, Canal 15, Bahía Samborombón, with 1% of relative abundance at least.

sp. and Cyperacecae (e.g. *Carex*, *Schoenoplectus*), along with the aquatic fern *Azolla* and the colonial algae *Botryococcus* suggest alkaline brackish-fresh waters influence (Fig. 5).

The dinoflagellate cysts, such as *Operculodinium* and *Spiniferites,* have the highest percentages that reflect significant marine influence; which is coherent with a similar record from the inner shelf at the south of Bahía Samborombón at ~2900 cal BP (Vilanova et al., 2008). The foraminiferal assemblage is characterized by well representation of *Elphidium* and *Ammonia* genera. The former, is a free-living epifaunal genus whose individuals were reported by Murray (1991) living on sandy substrate typical of the inner shelf and shallow waters (0–50 m depth), and in brackish environments, marshes and lagoons. The latter is a genus that supports high variations of both temperature and salinity (Walton and Sloam, 1990). The association *Elphidium – Ammonia* inhabits the inner shelf, brackish to hypersaline waters as lagoons (Murray, 2006), and environments under oligohaline to mesohaline conditions, with salinities between 5‰ and 18‰ (Brewster-Wingard and Ishman, 1999). In Argentina, this association is found in modern estuarine environments (Calvo Marcilese et al., 2013), lagoons (Márquez et al., 2016), and tidal flat at the south of Bahía Samborombón (Laprida et al., 2011); and also in fossil Holocene associations from inner shelf, southward from the bay (Laprida et al., 2007). Here, our records of *Elphidium* aff. *poeyanum* in association with *Ammonia parkinsoniana* are reflecting estuarine conditions in a shallow marginal marine environment (Fig. 8). On the other hand, the presence of two infaunal species that belong to *Bolivina* genus (*B. ordinaria* and *B. pseudoplicata*) could be associated to mud sediment and low oxygen levels (Corliss and Chen, 1988). The high abundance during this period is probably related to good conditions for the foraminifer development and significant marine influence (Figs. 6 and 7). In addition, the mollusks record, such as *Mactra isabelleana* (dated in 2240 cal yr BP) and *T. plebeius* with articulated valves and in life position; along with alternating and thinly laminated silt-clayey sediment, suggest low energy, intertidal subaqueous estuarine environment.

Within this period, at ~2050 cal yr BP, the presence of *Limonium brasiliense* indicates a middle to-high saltmarsh zone, with variations in salinity and aerial exposition related to a reduction in the frequency and duration of tidal inundation as a saltmarsh developed by the accumulation of new material raising the marsh surface level. This enabled species less tolerant of inundation to colonize, and more complex plant communities of mature saltmarsh to gradually grow; in fact, the development of mature saltmarsh depends on sediment supply and the rate of sedimentation and typically takes between 40 and 80 years (Boorman, 2003). In summary, palynological and foraminiferal records, along with lithology and stratigraphy suggest an estuarine environment under significant marine tidal influence but subjected to brackish-fresh waters input; and the onset of a mature saltmarsh. This significant marine influence is evidenced by the highest values of dinocyst and foraminiferal taxa (Fig. 10); in fact, standardized values of those proxies, with the exception of *Elphidium galvestonense* and *E. articulatum*, show positive anomalies during this period; which reflect favorable conditions for the marine-coastal organisms (Fig. 11).

During this period, the cheniers located northward constitute the evidences for the progradation processes at ~2650 and 2190 cal yr BP from W to E (Fig. 1B). This environment developed 6 km inland from the present shoreline (Fig. 4A).

Between 1660 and 950 cal yr BP the established mature saltmarsh is shown by the dominance of Chenopodiaceae ~70% (Fig. 5). The gradual increase in *Azolla* (glochidia, spores and massulae), and Ricciaceae (spores) record indicate shallow freshwater bodies in the area related to higher freshwater input; which is in agreement with the lowering salinity suggested by the gradual decreasing trend of dinocysts (Figs. 5 and 10). The advanced vegetation development is also evidenced by the higher organic matter contained in the muddy sediments (Table 2). Regarding the foraminiferal assemblage the variable percentages of *Elphidium* aff. *poeyanum* and *Ammonia parkinsoniana* reflect large salinity variations (Figs. 8 and 10). On the other hand, the gradual increase of freshwater influence is suggested by the rare frequency of *Bolivina* and *E. gunteri*, and the absence of *E. articulatum* and *Elphidium* sp; as well as by the dramatic lowering of foraminiferal abundance and

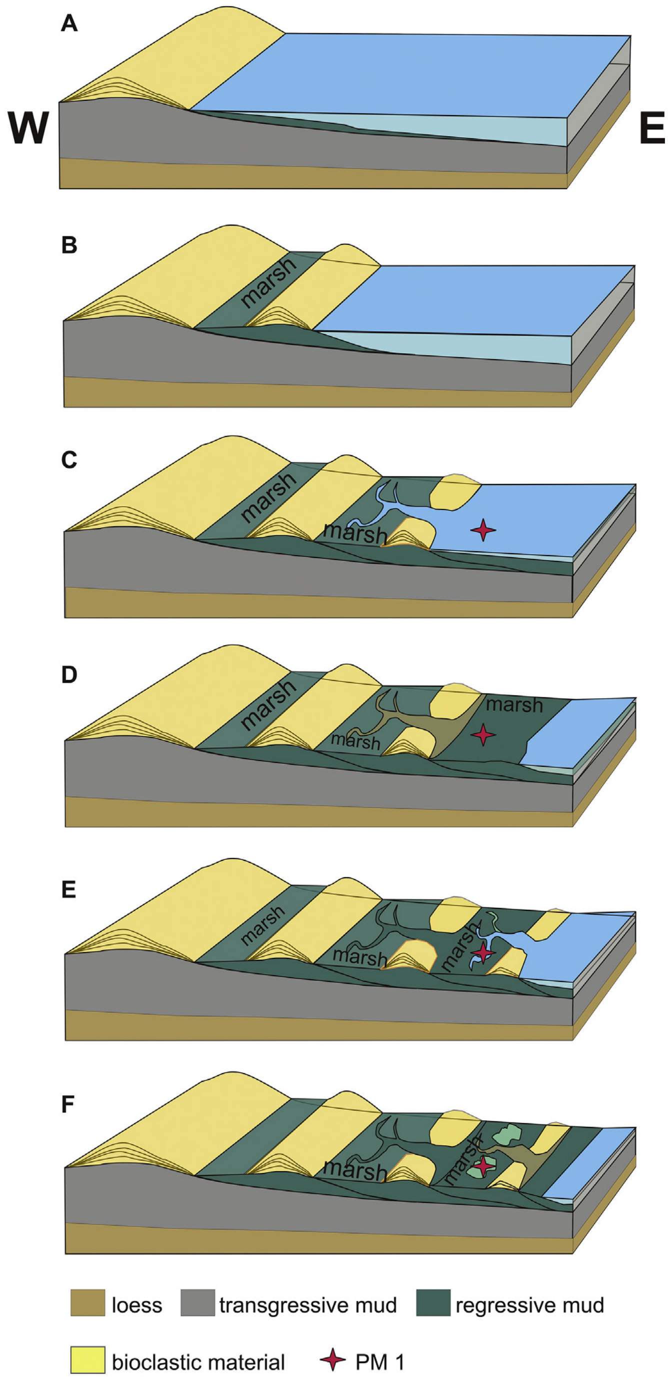

Fig. 9. Geomorphological evolution model of Bahía Samborombón during the regressive phase (MIS1); showing mudflat progradation and cheniers formation.

diversity, even reaching zero values towards ~1110 yrs BP (Figs. 6 and 7). The standardized values of dinocysts changed from positive to negative suggesting unfavorable conditions between 1535 and 1520 cal. BP, which related to higher freshwater input and the gradual sea-level fall; also, the foraminiferal taxa have fluctuating values (both, positive and negative ones) reflecting variable salinity conditions (Fig. 11).

These palynological and foraminiferal changes, along with another relict shoreline eastwards, suggest coastal progradation that progressively leaved behind isolated environments from the direct tidal-marine influence, although possibly connected through tidal channels (Figs. 4B and 9B – E). The coastal progradation might be related to the processes that accompanied the sea level fall and fluvial–estuarine sedimentation, and to intense deposition of the Parana river in Rio de la Plata estuary (Cavallotto et al., 2004). Consequently, these processes might have favored fine sediment transportation and deposition in Bahía Samborombón; which ultimately provoked saltmarsh accretion as more of the incoming sediment was intercepted and trapped, along with organic matter added to the marsh surface and by roots growth below it; all of which lead to a steady build-up in the surface level of the marsh.

From ~950 to 40 cal yr BP (AD 1910) the mature saltmarsh vegetation continued predominating in coexistence with freshwater communities that developed in shallow water bodies (Figs. 4D and 9F). Water salinity changed as it is shown by the dramatically decrease of dinocysts that almost disappeared, and by the highest *Azolla* values (up to 80%), whose normalization show positive anomalies (Figs. 10 and 11). *Azolla*, most likely *A. filiculoides* is a species widely distributed both, as a buoyant plant and fixed to margin zones from channels and ponds, inhabiting lentic waters (Medeanic et al., 2006). The almost disappearance of dinocysts and the absence of the former foraminifera assemblages imply the rarely marine tidal influence and the gradually predominance of brackish-freshwater conditions (Fig. 10). Good preservation of the palynomorphs (e.g. entire *Azolla* massulae) and the presence of pollen clumps suggest a low energy depositional environment and lack of transport, probably deposited "in situ". The increase in total pollen concentration toward the end of this period could be related to the closed distance from the source within the mature saltmarsh (Fig. 10).

These local water bodies were progressively got dried and desiccated at 6 km from the present shoreline, probably due to changes in groundwater level related to coastal progradation and sea level fell; with the consequent displacement of the saltmarsh to a location closer to the shoreline. Afterwards, pedogenetic processes took place, evidenced by prismatic structure and the highest pollen concentration. Over the soil, grassland settled as evidenced by root remains and predominant Poaceae pollen; this soil was buried later by debris resulted from the Canal 15 building in 1910.

Probably, during this interval (last millennium) as sea-level reached its present position, the climatic shift signal began to be noticed through fluvial input and water bodies in the wetland related to higher and variable precipitation regime, with the consequently salinity decrease. The precipitation regime, possibly more frequent, and higher but variable intensity would have contributed to the increase in water discharge of Río de la Plata plume and Río Salado; causing lowering in salinity, and the onset of present wetland environment. In summary, coastal progradation acting in tandem with sea-level retreat, under variable but more humid hydroclimatic conditions led into the present Bahía Samborombón geomorphological configuration (landscape) (Fig. 4D). The precipitation regime during this time has been associated with SAMS intensification and ENSO phenomenon (Razik et al., 2013), which is recognized here once the marine influence left to be superimposed with the climatic signal.

5.2. Late Holocene regional evolution

During the Late Holocene (last ~3.0 Ka) as sea-level decreased, significant geomorphologic and environmental changes occurred in the coastal plains of Bahía Samborombón and other sectors of the Río de la Plata estuary e.g. northeastern coast (Uruguay), adjacent inner shelf and the Paraná delta; which were configuring their respective geomorphology and present environments (Fig. 1D). In addition, the climatic conditions were another forcing; which were particularly variable over the last millennium. According to Gyllencreutz et al. (2010), the modern type of ENSO activity that established around 5000 cal yr BP was further strengthened towards present amplitude fluctuations around 3000–2000 cal yr BP causing increased Paraná discharge during El Niño years and northwards extensions of the low-salinity of Río de la Plata plume up to ~25°S during La Niña. Also, the SAMS and the austral trade winds intensified during the Late Holocene that favored sediment transport to the western South Atlantic (Razik et al., 2013).

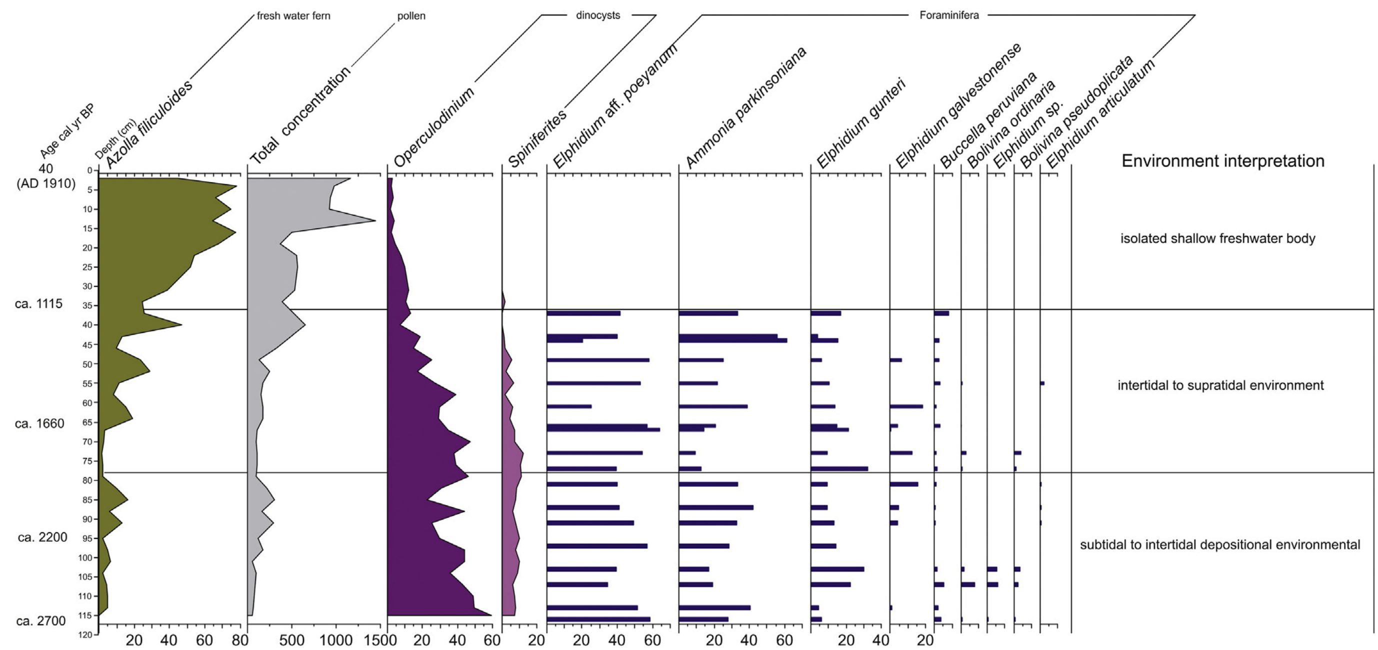

Fig. 10. Summary of micropaleontological zones and paleoenvironmental stages from PM1 sequence.

Between 2700 and 1660 cal yr BP in central Bahía Samborombón area, at 5.7 km from the present shoreline (PM1, Fig. 1), halophytic salt marsh vegetation predominated near an intertidal-subtidal environment, while at ~30 km (RS, Fig. 1), a transition from estuarine to fluvial conditions was occurring along with the terrestrialization of the environments (incipient pedogenetic processes) with the grasslands as dominant vegetation (Vilanova and Prieto, 2012). These different environmental conditions and vegetation are related to the distance from the shoreline and the geomorphologic configuration; inland locations became isolated by beach ridges and were left behind with the consequent stabilization; whereas the locations closer to the shoreline were subjected to the dynamic coastal conditions. In the northeastern coast of Río de la Plata (ASG), after 2900 cal yr BP there were brackish marshes accompanied by shallow pond environments related to sea-level fall, developed in reduced coastal strips (Mourelle et al., 2015); whereas southward from Bahía Samborombón, psammophytic vegetation developed over coastal barriers and the current inner shelf conditions were established (Vilanova et al., 2006).

Between 1660and 950 cal yr BP, as the coastal progradation proceeded high saltmarsh vegetation predominated with progressively development of freshwater communities in shallow water bodies located in central Bahía Samborombón, at 5.7 km from the present shoreline. At the Río de la Plata northeastern coast (AGS), brackish marshes continued, although subjected to a reduction in the estuary area and gradual water-level fall. The water-level reduction related to the sea-level fall and the sand bar formation generated protected areas behind barriers with stagnant shallow waters that favored the development of halophytic communities. There are not records at ~30 km inland from the present coastline after 1660 cal yr BP. At ~1700 cal yr BP intense deposition of the Paraná River occurred with the consequently Paraná delta formation as a result of the increasing fluvial discharge and sediment transport.

From 950 cal yr BP to the present (~last millennium), stabilization process continued at 5.7 km from the present shoreline which was subjected to human modification since AD 1910 by Canal 15 built and the recreation, fishing, agricultural and cattle raising activities; thereby restricting the mature saltmarsh to areas closer to the present bay shoreline, including wetlands and freshwater bodies, the latter occupying land depressions left by the sea as it decreased. In Río de la Plata northeastern coast (Uruguay) present-day marshes behind the sand bar

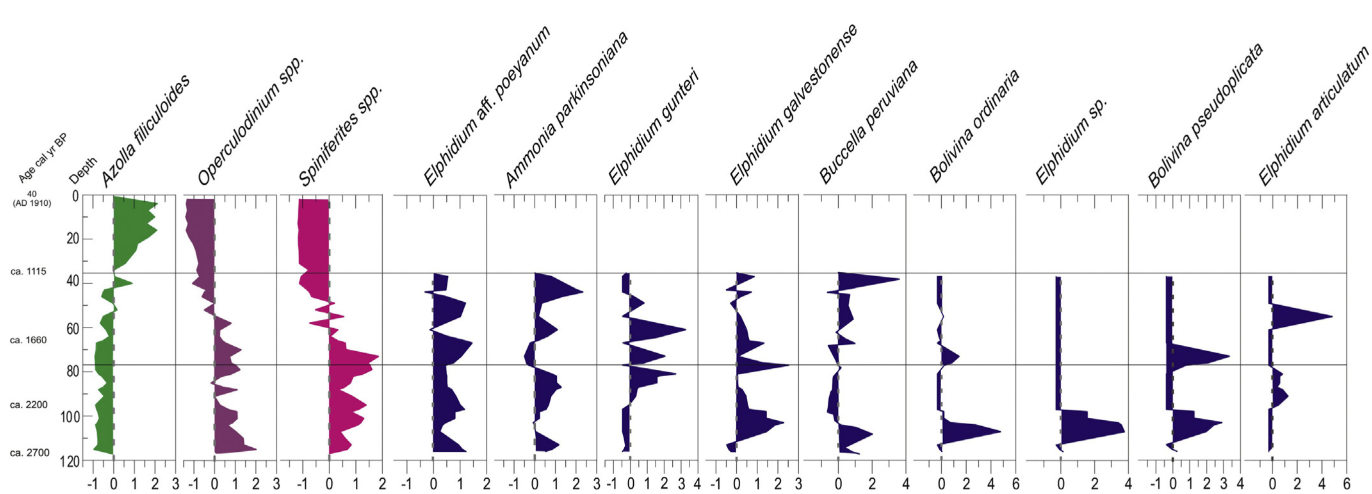

Fig. 11. Standardized data of different proxies from PM1 sequence.

located at the shoreline; along with stable dunes fixed by vegetation characterized the last 1000 cal yr BP (Mourelle et al., 2015).

6. Conclusions

During the last 2.7 yr BP there is coherence among the environmental inferences from each proxy, which clearly show the evolution of the estuarine saltmarshes from an intertidal environment under significant marine influence towards a supratidal brackish-freshwater environment as sea-level was falling. The evidences of this evolution are:

Coastal progradation, encompassing at least 5.7 km as revealed by the following geoforms recognized in the analyzed remote sensing image (1)relict shorelines inferred by the cheniers whose chronology support their regressive character; (2)recognition of aligned tidal channel mouths over a same relict shoreline, and (3) changes in vegetation cover. Saltmarsh elevation is another evidenced as a result of accretion due to fine sediments accumulation of at least 1.2 m thick. Consequently, despite of the highly dynamic and open conditions of Bahía Samborombón, we posit based on these values, high progradation and accumulation processes that provided the most detailed and longest record for the last 2.7 ka studied in the region; which can roughly be representing ~0.2 m/yr in coastal progradation and 0.83 m/yr in sediment accumulation.

- Successional processes through the replace of typical vegetation of low saltmarsh zone by vegetation corresponding to high saltmarsh zone; which then is associated to brackish-freshwaters communities.
- Gradual decrease of dinocysts and foraminifera assemblages, the latter absent during the last millennium indicate lowering marine influence and the consequent salinity values. The foraminifera absence could be consider the main change of the record probably related to lowering salinity and terrestrialization processes.
- During the last millennium, as sea-level retreated, hydrological changes due to climatic regime shift towards higher precipitation rate can be recognized by increasing aquatic freshwater components in water body environments.

Our results are relevant for the conservation and management for the Ramsar site because they provide information regarding the resilience capacity of saltmarsh plant communities, adapted to changing environment as reflected by their ecological thresholds (e.g. tolerance range to salinity, floods, sediment accretion, among others). In turn, this information can be applied to the ecosystem services for the sustainable use of mixohaline wetland (bird refuge, fishes spawning protected area, land sector destined to agricultural and cattle human activities).

Bahía Samborombón coastal plains became as a regional scale character during the last 2.7 Ka due to the increase in space, where one of the most extensive saltmarsh of southeastern-South America developed and became a biosphere reserve.

During the last millennium climatic forcing was clearly registered due to it is disentangle from the marine tidal influence as sea-level retreated and reached its present positions.

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