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MIDDLE–LATE HOLOCENE PALEOENVIRONMENTAL RECONSTRUCTION OF A SALADO RIVER SECTOR - SAMBOROMBÓN BAY USING BENTHIC FORAMINIFERA

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Abstract. The effect of Holocene sea-level changes and their impact on coastal environments have been well-preserved in different places worldwide. Several studies along the Argentine coastal margin have contributed to understanding the extent and magnitude of the marine ingression occurred during the Mid–Holocene Highstand and its effect on ecosystems. In this research, we present a benthic foraminiferal fauna analysis of an outcrop located in Samborombón Bay, Argentina, with the aim to evaluate the maximum extent of the Holocene marine transgression in the middle zone of the bay. Along the sedimentary section, *Cribroelphidium poeyanum*, *Cribroelphidium gunteri*, *Ammonia tepida*, *Elphidium galvestonense*, and *Ammonia parkinsoniana* were the most representative species, while *Quinqueloculina milletti* and *Haynesina germanica* were represented in less proportion in some levels. This assemblage indicates that the study area represents a marine marginal environment with brackish conditions between 6,261–5,919 cal. years BP and 1,725–1,511 cal. years BP. However, the diversity and abundance of the foraminiferal fauna reveals the transition from a shallow estuarine environment (6,261–5,919 cal. years BP) to a brackish marsh environment with floodable depressions and greater freshwater influence (1,725–1,511 cal. years BP). These changes are related not only to regressive and transgressive events that occurred during the Holocene, but also to the climatic, oceanographic, hydrological, and geomorphological characteristics of the middle zone of the Samborombón Bay.

Key words. Sea-level transgression. Mid–Holocene Highstand. Marginal marine environments.

Resumen. RECONSTRUCCIÓN PALEOAMBIENTAL DEL HOLOCENO MEDIO-TARDÍO EN UN SECTOR DEL RÍO SALADO - BAHÍA SAMBOROMBÓN UTILIZANDO FORAMINÍFEROS BENTÓNICOS. Las variaciones del nivel del mar durante el Holoceno y su efecto sobre los ambientes costeros se han preservado con muy buena calidad en diferentes lugares del mundo. Diversos trabajos realizados en el margen costero argentino han permitido entender el alcance y la magnitud de las ingresiones marinas ocurridas durante el máximo transgresivo del Holoceno Medio y su efecto sobre los ecosistemas. En esta investigación presentamos el análisis de la fauna de foraminíferos bentónicos en un afloramiento localizado en la Bahía Samborombón, Argentina, con el objetivo de definir el alcance máximo de la transgresión marina holocena en la zona media de la Bahía. A lo largo de toda la sección *Cribroelphidium poeyanum*, *Cribroelphidium gunteri*, *Ammonia tepida*, *Elphidium galvestonense* y *Ammonia parkinsoniana* fueron las especies más representativas, mientras que *Quinqueloculina milletti* y *Haynesina germanica* estuvieron representadas en menor proporción en algunos niveles. Este ensamble indica que el área de estudio representó un ambiente marino marginal salobre entre 6,261–5,919 cal. años AP y 1,725–1,511 cal. años AP. Sin embargo, la variación en la diversidad y abundancia de la fauna de foraminíferos evidencian el cambio de un ambiente estuarino somero (6,261–5,919 cal. años AP) a un ambiente de marisma salobre con depresiones inundables y mayor influencia de agua dulce (1,725–1,511 cal. años AP). Estos cambios están relacionados no solo con los eventos regresivos y transgresivos ocurridos durante el Holoceno, sino también con las características climáticas, oceanográficas, hidrológicas y geomorfológicas de la zona media de la Bahía Samborombón.

Palabras clave. Transgresión marina. Máximo nivel del mar. Ambientes marino-marginales.

Coastal Areas are strongly related to sea-level changes, especially those that occurred in the Late Holocene. These regions have sedimentary deposits that are well-preserved and offer great potential for paleoenvironmental studies and reconstruction of sea-level variations (Isla, 1989).

The continental zone of the Samborombón Bay is characterized by Quaternary outcrops of loess sediments, interspersed with Pleistocene and Holocene marine sedimentary deposits, which are the result of transgressive and regressive events driven by eustatic sea-level changes (Isla, 1989; Parker, 1990; Aguirre & Whatley, 1995; Isla *et al*., 2000; Violante & Parker, 2000, 2004; Violante *et al*., 2001; Cavallotto *et al*., 2004; Fucks *et al*., 2010). A recent model proposed by Prieto *et al.* (2017) revealed that relative sea levels (RSL) rose to reach the present level approximately before *ca*. 7,000 cal. years BP, with the peak of the sea-level highstand approximately +4 m between *ca*. 6,000 and 5,500 cal. years BP (depending on the statistical method used) or at *ca*. 7,000 cal. years BP according to the ICE-6G model prediction. After this time, sea levels gradually fell to the present position (Prieto *et al*., 2017).

Holocene marine deposits in the continental zone of the Samborombón Bay are grouped into the Canal de las Escobas Formation, formerly known as Las Escobas Formation, which consists of four members: Destacamento Río Salado, Canal 18, Cerro de la Gloria, and Canal 15 (Fucks *et al*., 2010). This Holocene sequence has been studied from various approaches (sedimentology, stratigraphy, paleontology, micropaleontology, and palynology) thanks to the stratigraphic continuity and the high abundance of fossils in the area. These studies made it possible to establish different depositional environments, such as coastal barriers, tidal flats, marshes, and coastal lagoons, among others.

The depositional environments of each member have been characterized based on the microfossil fauna record, specifically foraminifera and ostracoda. Bertels-Psotka & Laprida (1998a, 1998b, 1998c) analyzed ostracod assemblages from Holocene outcrops corresponding to the Cerro de la Gloria Member and the Canal 18 Member. Laprida & Bertels-Psotka (2003) determined the benthic foraminiferal fauna characteristic of the Cerro de la Gloria Member. Also, Laprida *et al.* (2011) studied the distribution, diversity, specific composition, and taphonomy of foraminifers in recent littoral environments. Ramos *et al.* (2019) analyzed the microfossil assemblages (foraminifera and ostracoda) of a Holocene sequence, extending the reach of the Mid–Holocene Highstand marine ingression. Most recently, Ballesteros-Prada *et al.* (2021) described the benthic foraminiferal assemblages and the paleoenvironment developed in the Canal 18 Member.

Furthermore, Vilanova & Prieto (2012) proposed a paleoenvironmental reconstruction for the Mid–Holocene on the right bank of the Salado River (Samborombón Bay), based on palynological data. On the other hand, Luengo *et al.* (2018, 2021) have carried out multiproxy analyses to integrate micropaleontological (foraminifera), palynological, and geomorphological information particularly from outcrops of the Canal 15 and Canal 18 members.

Holocene marine deposits have been found in the central zone of the Samborombón Bay, over the banks of the Salado River and Canal 15, located 50 km from the current shoreline (Ramos *et al*., 2019). These deposits suggest that the Holocene maximum transgression impacted on ecosystems further away than proposed by former studies (Violante & Parker, 2004; Prieto *et al*., 2017).

The sedimentary successions located in Samborombón Bay represent key records for reconstructing the geomorphological and environmental history, particularly those related to Holocene sea-level changes and climatic conditions. Previous studies in the area provided important information that aids in understanding and interpreting paleoenvironmental changes, especially the transgressive-regressive events that occurred in the bay, and contributed to refining the regional paleoclimatic reconstruction. However, it is necessary to carry out more detailed analyses to provide higher resolution and determine the events that occurred during the Holocene. Therefore, the use of additional proxies such as foraminifera will generate new data to enhance the precision of paleoenvironmental reconstructions in continental areas of the Samborombón Bay.

In this study, we present a micropaleontological analysis of foraminifera from a Holocene sedimentary section, located in the middle zone of the Samborombón Bay, approximately 35 km from the current coastline, with the aim of providing an overview of the environmental evolution of the zone.

STUDY AREA

Samborombón Bay is located in the northeast of Buenos Aires Province (Fig. 1.1). It is the most extensive myxohyaline wetland of Argentina (Volpedo *et al*., 2005), covering around 244,000 ha of which more than 65% are terrestrial ecosystems, the remaining correspond to aquatic systems extending 150 km along the Río de la Plata western coast, from Punta Piedras (35° 27′ S; 56° 45′ W) to Punta Rasa (36° 22′ S; 56° 35′ W). Its evolution was linked to the sea-level variation and the climatic changes occurred during the Holocene, between 11,650 and 7,000 cal. years BP, when sea level rose 60 m to global level (Guilderson *et al.*, 2000; Prieto *et al.*, 2017) and 4 m to the regional scale, especially in the Río de la Plata, near the Uruguay and Argentine zones (Prieto *et al.*, 2017). This sea-level rise is related to a fast increase of temperature and several environmental changes (Smith *et al.*, 2011; Prieto *et al.*, 2017).

The majority of the geoforms and sedimentary deposits present in the continental zone of the Samborombón Bay were originated by Late Pleistocene–Holocene sea-level fluctuation, particularly transgressive-regressive cycles related to MIS1 and MIS5e (Fucks *et al.*, 2010). Pleistocene marine sediments have been grouped into the Puente de Pascua Formation, whereas the Holocene marine sediments represent the Canal de Las Escobas Formation (Fig. 1.2). In the Late Holocene, the coastline reached a relative height of +4 m above sea level generating muddy deposits with flaser and wavy stratification in sub- to intertidal environments, represented in the Destacamento Río Salado Member (Fucks *et al.*, 2010). Following the maximum transgression that occurred between 5.5 and 6 ky cal. years BP, the sea began to recede to its current position (Prieto *et al.*, 2017), creating tidal flats in open environments that became restricted by the formation of storm ridges. This happened when the sea level was stabilized at an intermediate position between the current coast and the maximum transgression, corresponding to the Canal 18 and Cerro de la Gloria members, respectively (Fucks *et al.*, 2010). The Canal 15 Member was deposited east of the shell ridges

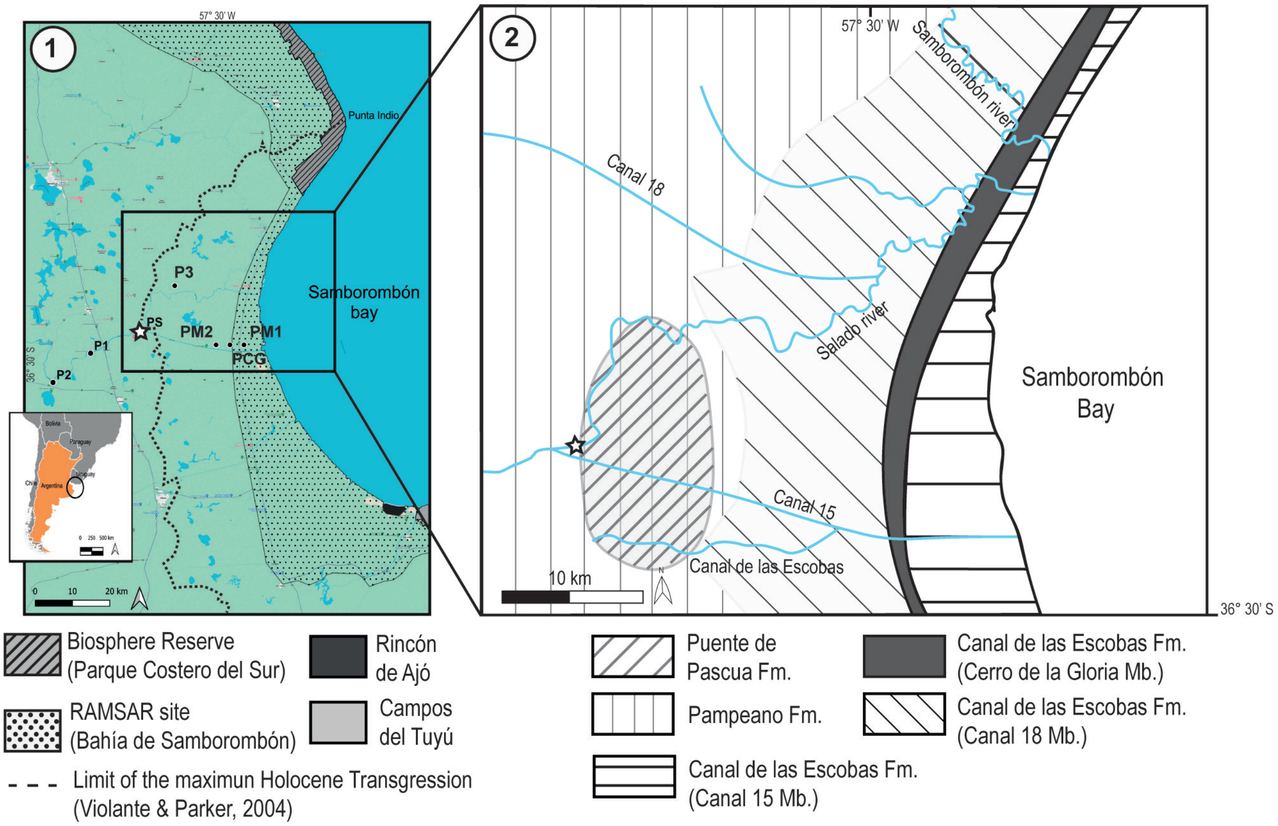

Figure 1. 1, Study area (Google Earth, access May 2024) and **2,** geological map proposed by Fucks *et al.* (2010). The outcrop analyzed in this work is marked with a star (**PS**) and the other outcrops mentioned in the text are marked with circles. Other sequences sources: **PM1** (Luengo *et al.*, 2018), **PM2** (Ballesteros-Prada *et al.*, 2021), **PCG** (Laprida & Bertels-Psotka, 2003), **P1** (Fucks *et al.*, 2015), **P2** (Ramos *et al.*, 2019), and **P3** (Fucks *et al.*, 2007).

during the regressive stage of the cycle, corresponding to environments ranging from tidal flats to marshes (Fucks *et al.*, 2010).

MATERIALS AND METHODS

Sampling and chronology of the sediment

A 171 cm long sedimentary section (named PS from now on) was extracted in 2016 from an outcrop located at 34.43 km from the shoreline of the bay, at the right margin of the Salado River (35° 55′ 28.73″ S; 57° 43′ 59.41″ W; 5 masl). The sampling site was chosen following the previous study of Vilanova & Prieto (2012). The sampling was carried out using a 7 cm diameter plastic PVC pipe, which was sunk laterally into the outcrop after cleaning the exposed surface. This sedimentary section of 171 cm thick was subsampled in the laboratory every 5 cm from the base to the top and a total of 36 samples were obtained and analyzed (Fig. 2); each of them was labelled with the number of outcrop, section and level in cm (PS-T1-00-01). Also, the texture, color, sedimentary structure, and presence of gastropods and bivalves were described.

Chronological ages were based on those proposed by Vilanova & Prieto (2012). All ages were calibrated using Calib Rev. 8.1.0 software (Stuiver *et al.*, 1993), according to the calibration curve Marine 20 (Heaton *et al.*, 2020) and calibration curve SHCal 20.14c (Hogg *et al.*, 2020), with a 2σ error and zero equal to 1,950 BC.

Micropaleontological analysis

The samples were washed with water through a sieve with a mesh size of 63 µm (Tyler Screen System No. 230) and dried at room temperature; 100–300 individuals were selected from the dry residue when it was possible. Identification at generic and suprageneric level was based on Loeblich & Tappan (1988) and Sen Gupta (1999), whereas for infrageneric categories the literature by Boltovskoy *et al.* (1980), Laprida (1997), Bernasconi & Cusminsky (2007), Cusminsky *et al.* (2009), and Calvo-Marcilese (2011) was used.

Total abundance (individuals per gram of dry residue) and species richness (S) were estimated. Diversity indexes, such as Shannon-Wiener (H) and Fisher's alpha (α) were calculated in order to characterize the environmental conditions (α was estimated only in samples with more than 100 individuals). Diversity indexes have been suggested to be a useful method to categorize paleoenvironments on a broad scale. The H values < 2.5 indicate marginal marine environments, and values between 1.5 and 3.5 refer to shelf and deep-sea environments (Murray, 2006). The α index values < 4 generally indicate hypersaline marine marginal, except in normal marine and hypersaline lagoons (< 6), but may also indicate normal marine environments with a high dominance of single species. The majority of shelf and deep-sea assemblages have α values 5–15 or 5–20 (Murray, 2006).

The Palaeontological Statistical Program (Past), version 3.25, was used to calculate diversity indexes (Hammer *et al.*,

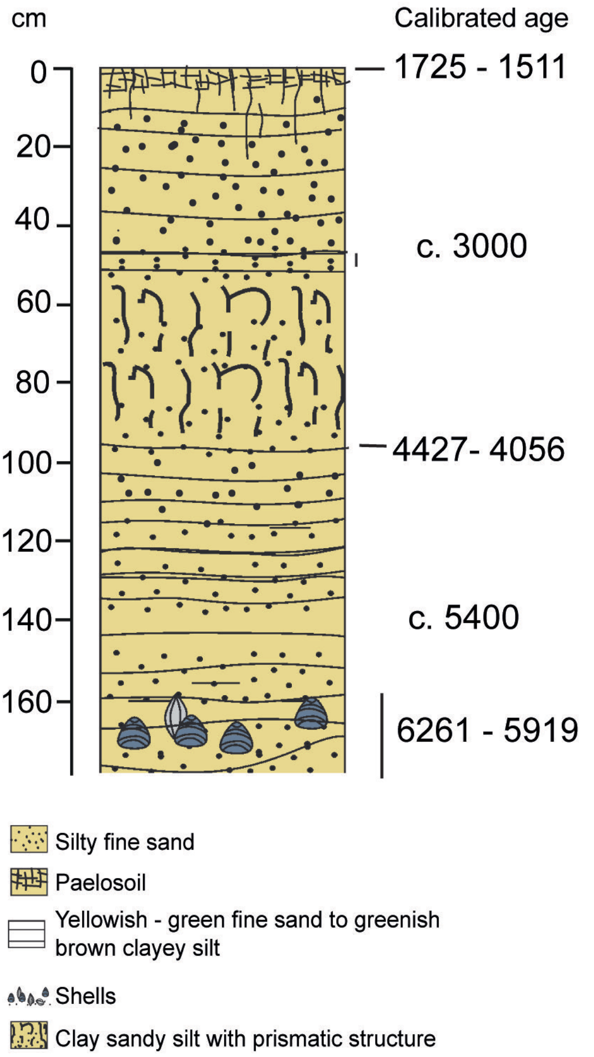

Figure 2. Lithological description of the **PS** sedimentary sequence.

2001). The proportions of agglutinated, porcelaneous, and hyaline individuals were calculated over the total number of specimens in each sample.

Paleoecological Indexes

Taphonomic analyses were performed in order to evaluate the degree of preservation of foraminifera. Four taphonomic groups were defined based on Brandt (1989) and Laprida & Bertels-Psotka (2003): (A) well-preserved shells, having at most the last chamber broken, (B) blackish shells with chamber fillings and/or with a polished coating in shades of black, (C) broken or fragmented shells, and (D) reworked shells.

Life position of the foraminifera (infaunal/epifaunal) was also determined to infer eutrophication and oxygen level in the environment. This interpretation was based on a literature review and the morphological observations of specimens (Supplementary Information). Infaunal individuals with biserial and triserial forms reflect low-oxygen environments, while epifaunal specimens are associated with high-oxygen environments (Corliss, 1985; Corliss & Chen, 1988). The percent of infaunal and epifaunal specimens was calculated based on the total of individuals in each group over the total of individuals per sample.

Paleo oxygen levels were calculated using the Benthic Foraminiferal Oxygen Index (BFOI; Kaiho, 1994, 1999) based on foraminiferal morphotype characteristics. Foraminifera were classified in three groups based on morphological characteristics: dysoxic (0.1–0.3 ml/L), suboxic (0.3–1.5 ml/L), and oxic (> 1.5 ml/L).

The *Ammonia-Elphidium* Index (AEI) has been used in the literature to study regions affected by hypoxia, due to large contribution of organic matter (Sen Gupta *et al.*, 1996; Sen Gupta & Platon, 2006; Eichler *et al.*, 2012a; Pregnolato *et al.*, 2018). This index is calculated as follows: $AEI= [NA/(NA+NE)]\times100$, where NA and NE are the numbers of *Ammonia* and *Elphidium* individuals, respectively.

Statistical analysis

A cluster analysis was performed to determine changes in foraminiferal assemblages throughout the sedimentary sequence; zonation was defined by stratigraphically constrained incremental sum of squares cluster method (CONNIS) performed with Tilia software 2.6.1 (Grimm, 2004). For this analysis, only species with a relative abundance equal to or greater than 2% were considered. Euclidean distance was applied as the distance coefficient, data was standardized with mean= 0 and standard deviation (SD)= 1 (Grimm, 2004).

RESULTS

The PS section was characterized by poorly stratified, fine greenish-yellow sandy to brownish-green clayey silts. At the base, a fossiliferous layer of 20 cm composed of mollusc shells was observed (*e.g.*, *Mactra isabelleana*, *Heleobia australis*, *H. parchappii*). There is a fossiliferous level towards 100 cm, a few centimetres thick, with live-positioned valves of *Tagelus plebeius*. These shells recorded a radiocarbon age of 6,261–5,919 cal. years BP (Figini *et al.*, 2003). Between 90 and 60 cm, there was a level of sandy-silty material with prismatic structure. The radiocarbon age of this unit corresponded to 4,427–4,056 cal. years BP (Vilanova & Prieto, 2012). The study section culminates with the development of a paleosoil (0–20 cm). It presented an age of 1,725–1,511 cal. years BP according to Fucks *et al.* (2007) (Fig. 2; Tab. 1).

TABLE 1 – Radiocarbon dates po PS outcrop

Outcrop	Uncalibrated age (^{14}C years BP)	Calibrated age	Laboratory n°	Material
0	1,710 ± 60	1,725–1,511	LP 1766	*Pomacea* sp.[1]
90	4,311 ± 42	4,427–4,053	AA 814111	Organic matter[2]
160–172	5,870 ± 50	6,261–5,919	LP 1211	*Tagelus plebeius*[3]

References: 1. Fucks *et al.* (2007); 2. Vilanova & Prieto (2012); 3. Figini *et al.* (2003).

Foraminiferal diversity and abundance

All 36 samples corresponding to PS showed good recovery of foraminifera. The samples only contained benthic foraminifera, planktonic foraminifera were not found. In general, shells showed a good state of preservation (Taphonomic group A), while 1–25% of the specimens were broken (Taphonomic group C) and 100% of the shells were broken at the 25 cm level. The top of the outcrop presented 1–50% of shells with abrasion and/or reworking (Taphonomic group D). Also, 1–7% of the shells exhibited black or brown coloration (Taphonomic group B) (Fig. 3).

Total abundance varied between 2–826 individuals per gram of dry sediment, and the highest value was in the middle zone of the sedimentary section between 85–125 cm and 160–170 cm. On the other hand, the lowest values were shown at the top of the sequence, between 2–32 cm (Fig. 3).

The micropaleontological analysis allowed identifying 31 species of benthic foraminifera grouped into 12 genera, primarily belonging to the Order Rotaliida. The most abundant species were *Cribroelphidium poeyanum*, *Cribroelphidium gunteri*, *Ammonia tepida*, *Elphidium galvestonense*, and *Ammonia parkinsoniana* (Tab. 2, Fig. 4). Hyaline shells predominated throughout all the sequence (> 93%). Porcelaneous forms were present in lower proportions (< 7 %), from the 75 cm level to the base of the sequence (Fig. 3). Agglutinated shells were not observed along the sequence. Hyaline shells were mainly represented by species of the genera *Cribroelphidium*, *Elphidium*, and *Ammonia* and porcelaneous shells were mainly represented by species of the genus *Quinqueloculina* (Tab. 2, Fig. 4).

Species richness (S) varied between 1–23 throughout the sequence, showing a tendency to decrease towards the top. The values of H ranged between 0 (27 cm) and 2.5 (106 cm) and α index ranged from 2.5 to 6.1 at levels 61 cm and 137 cm, respectively (Fig. 3).

Paleoecological Indexes

The percentage of infaunal species was above 90% in most of the sequence. The BFOI ranged between -0.4 and 0, while the AEI showed values between 10 and 77 (Fig. 3).

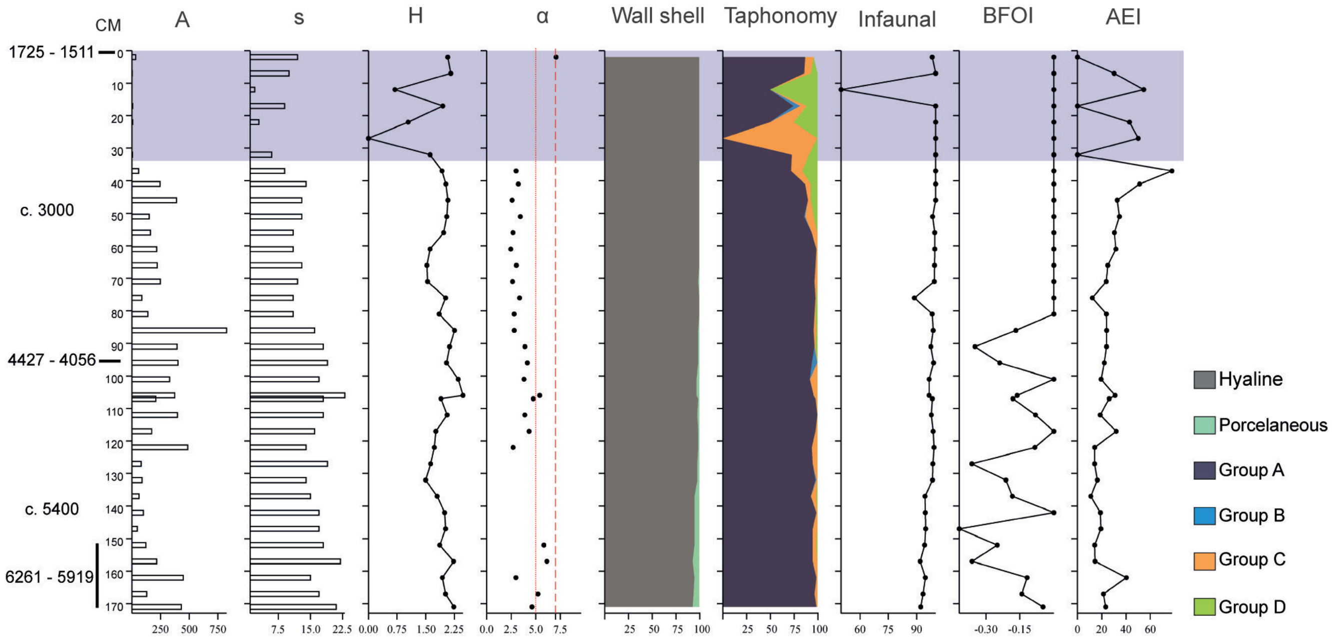

Figure 3. Diversity indexes, wall composition, and taphonomic groups from the studied assemblage. Abbreviations and references: **A,** Total abundance; **S,** Species richness; **H,** Shannon-Wiener index; **α,** Fisher index; Taphonomic group A, well preserved; Taphonomic group B, dark colour; Taphonomic group C, broken and fragmented; Taphonomic group D, reworking; **BFOI,** Benthic Foraminifera Oxic Index; **AEI,** *Ammonia-Elphidium* Index.

TABLE 2 – Total abundance per 1gr of sediment of representative foraminifera (abundance > 2% of the total assemblage in more than two samples). The species are ordered from most to least abundant.

	cm	*Cribroelphidium poeyanum*	*Cribroelphidium gunteri*	*Ammonia tepida*	*Elphidium galvestonense*	*Ammonia parkinsoniana*	*Elphidium* spp.	*Cribroelphidium excavatum*	*Elphidium articulatum*	*Elphidium advenum*	*Haynesina germanica*	*Haynesina* sp1	*Haynesina* spp.	*Quinqueloculina* spp	*Ammonia* spp.	*Quinqueloculina milletti*	*Nonion* spp.	*Quinqueloculina patagonica*	*Quinqueloculina seminulum*	*Haynesina depressula*	*Elphidium discoidale*	*Elphidium margaritaceum*	*Buliminella elegantissima*	*Nonion pauperatum*	*Buccella* spp.
PS T9 12-11	2	7	3	8	4	1	1	3	0	1	0	1	0	0	1	0	0	0	0	1	1	0	0	0	0
PS T9 06-07	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PS T8 01-02	17	1	0	2	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
PS T8 13-14	22	1	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PS T8 08-09	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PS T8 03-04	32	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PS T7 17-18	37	11	6	17	4	8	0	3	0	0	0	6	0	0	1	0	1	0	0	0	0	0	0	0	0
PS T7 13-14	41	60	49	55	18	13	1	13	0	3	3	20	0	0	3	0	2	0	0	3	0	0	0	0	0
PS T7 08-07	46	102	46	94	24	19	33	0	0	24	0	20	0	0	9	0	0	0	0	7	0	0	0	6	1
PS T7 03-04	51	24	42	29	14	11	10	0	0	6	4	0	0	0	3	0	0	0	0	2	0	0	0	0	2
PS T6 13-14	56	41	36	34	5	8	5	4	0	9	0	11	0	0	5	0	0	0	0	0	0	0	0	0	0
PS T6 08-09	61	91	46	43	2	8	2	5	0	6	9	3	0	0	0	0	0	0	0	0	0	1	0	0	0
PS T6 03-04	66	85	62	47	3	3	5	4	0	1	6	1	0	0	0	0	0	0	0	0	1	0	0	0	0
PS T5 12-13	71	142	25	25	9	4	0	16	4	4	14	0	0	1	0	0	0	0	0	0	0	0	0	0	0
PS T5 07-08	76	7	26	17	0	1	2	4	6	3	0	12	0	0	0	0	0	0	0	0	8	2	0	0	0
PS T5 02-03	81	23	51	28	0	4	1	5	4	13	4	5	0	0	0	0	0	0	0	0	3	0	0	0	0
PS T4 20-21	86	126	218	135	21	35	32	28	65	56	39	39	0	0	0	0	14	6	0	5	0	0	0	0	0
PS T4 15-16	91	117	94	44	10	9	9	21	12	8	26	5	0	0	0	0	0	0	5	0	4	0	0	0	0
PS T4 10-11	96	131	80	60	15	8	14	26	24	1	0	0	25	2	2	0	9	0	1	0	0	1	0	0	0
PS T4 05-06	101	46	51	64	11	19	13	30	30	18	29	0	0	2	8	1	0	9	1	0	0	3	0	0	0
PS T4 00-01	106	63	70	60	13	12	11	13	34	12	25	30	0	6	7	1	3	2	5	0	0	1	0	0	1
PS T3 23-24	107	67	59	32	4	0	3	6	10	6	10	0	0	1	4	1	4	0	2	0	0	1	1	0	0
PS T3 18-19	112	96	104	79	12	7	20	0	0	0	0	18	13	0	13	1	15	12	1	0	0	0	0	0	0
PS T3 12-13	117	69	45	20	5	3	4	2	6	6	0	0	8	1	0	2	0	0	0	0	0	0	0	0	0
PS T3 07-08	122	175	146	55	11	2	44	10	9	0	0	0	21	0	8	4	0	0	0	0	0	0	1	1	0
PS T3 02-03	127	43	10	10	5	2	2	0	1	1	0	0	3	1	0	1	0	0	0	0	0	0	2	0	1
PS T2 21-22	132	49	15	7	6	2	0	3	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
PS T2 16-17	137	28	8	8	3	2	0	0	0	4	0	0	3	0	0	3	0	0	0	0	0	0	3	0	0
PS T2 11-12	142	37	20	13	6	4	1	4	5	0	0	0	5	8	0	1	0	11	1	0	0	0	0	0	0
PS T2 06-07	147	16	10	4	5	1	1	1	0	0	0	0	3	6	0	1	0	0	1	0	0	0	0	0	0
PS T2 00-01	152	55	24	8	8	7	5	2	0	0	0	0	2	6	1	3	1	0	2	0	0	0	0	0	0
PS T1 15-16	157	52	28	44	15	24	3	5	0	0	0	0	19	3	3	10	1	5	3	0	0	2	4	0	0
PS T1 10-11	162	160	93	67	41	16	17	0	0	0	0	0	24	20	3	10	1	0	6	0	0	0	1	0	0
PS T1 05-06	167	39	34	14	10	11	2	0	2	0	0	0	5	6	1	4	0	0	3	0	0	0	0	0	1
PS T1 00-01	171	113	77	67	55	28	6	9	6	1	16	0	14	21	5	20	0	4	5	0	0	2	0	0	0

Zonation

Based on the cluster analysis, three zones were differentiated: the first zone, PS-Z1, which extends from the base to the 117 cm level, the second zone, PS-Z2, located between levels 112 cm and 35 cm, and the third zone, PS-Z3, covering from the 32 cm level to the top of the sequence (Fig. 4).

PS-Z1 (171–117 cm). A maximum of 22 species were identified in this stage, with *Cribroelphidium poeyanum* (55.7%–23.8%), *Cribroelphidium gunteri* (30%–12.8%), *Ammonia tepida* (20.2%–6.8%), *Elphidium galvestonense* (12.8%–2.3%), and *Ammonia parkinsoniana* (11.2%–0.4%) as the most abundant. This assemblage also included a few individuals corresponding to the genera *Haynesina* spp. (9%–1.1%) and *Ammonia* spp. (3.4%–0.5%), which could not be determined at species level due to their small size. Individuals of the species *Elphidium articulatum* (4.9%–0.40%), *Cribroelphidium excavatum* (3.7%–1.3%), *Elphidium advenum* (6.7%–0.13%), *Quinqueloculina milletti* (4.7%–0.8%), and *Quinqueloculina seminulum* (2%–0.5%) were also recognized. Abundances ranged from 46 to 486 ind/g. Values of H varied between 1.4 and 2.3; α values ranged from 2.7 to 6.1; AEI values ranged from 10 to 40, while BFOI varied between -0.4 and 0. Infaunal species varied between 91% and 99%.

PS-Z2 (112–31 cm). Between 9 and 23 species were determined in this zone of the outcrop. The assemblage was primarily composed of *Cribroelphidium poeyanum* (57.9%–7.9%), *Cribroelphidium gunteri* (36.9%–9.8%), *Ammonia tepida* (29.4%–10%), *Elphidium galvestonense* (9.4%–0.9%), and *Ammonia parkinsoniana* (5.7%–1.7%). In smaller proportions, species from the genus *Haynesina*, such as *H. germanica* (8.8%–1.3%) and *Haynesina* sp. 1 (13.9%–1.2%) were found, along with *Elphidium articulatum* (9.15%–1.43%), *Cribroelphidium excavatum* (9.1%–1.7%), and *Elphidium advenum* (9.1%–0.4%). Abundance varied between 55 and 826 ind/g. Values of H ranged from 1.5 to 2.5; α index varied between 2.5 and 5.4; AEI values ranged from 12 to 77; and BFOI ranged from 0.3 to 0. Infaunal species varied between 86% and 100%.

PS-Z3 (32–0 cm). In this zone, species richness varied between 6 and 12. The assemblage was characterized by individuals of *Ammonia tepida* (50.2%–25%), *Cribroelphidium poeyanum* (25.1%–1.2%), *Elphidium galvestonense* (100% in one sample), *Ammonia parkinsoniana* (27.3%–3.70%), and *Haynesina* sp. 1 (14.8%–3.6%). Total abundance ranged from 1 to 31 ind/g, while values of H varied between 0 and 2.1; AEI ranged from 0 to 50; and BFOI values were equal to 0. Infaunal forms varied between 50% and 100%.

DISCUSSION

The sedimentary sequence PS was deposited during the Mid–Late Holocene, between 6,261–5,919 cal. years BP and 1,725–1,511 cal. years BP. The presence of benthic

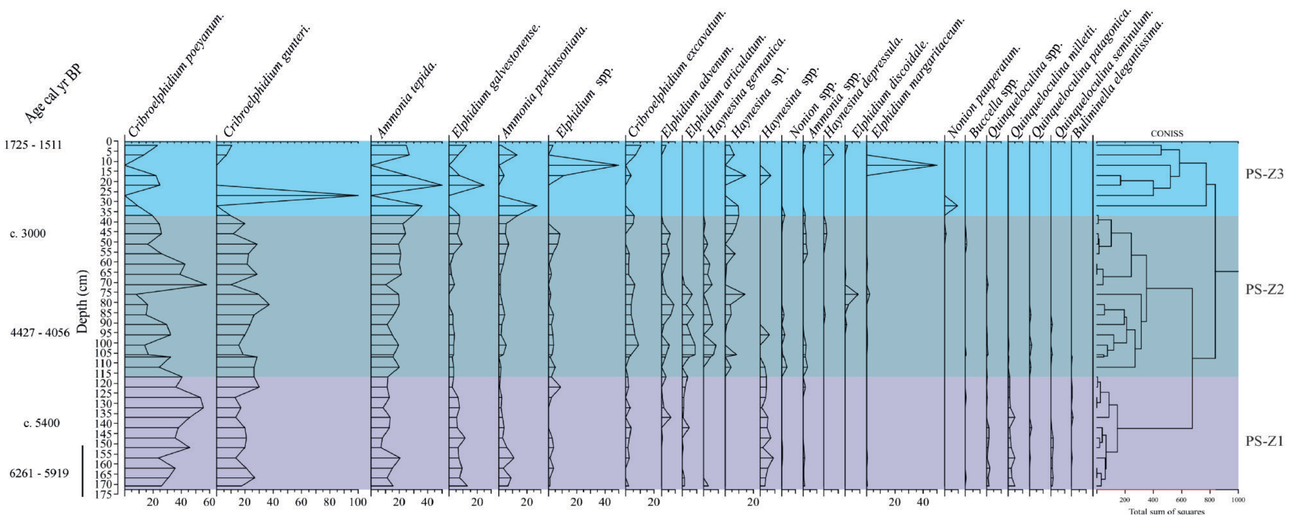

Figure 4. Species distribution and CONNIS analysis during the three stages: PS-Z1, PS-Z2, and PS-Z3.

foraminifera suggests that the sea-level rise impacted up to 35 km inland from the current coastal margin.

Taphonomic analysis indicated that the shells were well preserved along the sedimentary sequence. From the base to the 51 cm level there was a high percentage of well-preserved shells (Taphonomic group A) and a low percentage of broken shells (Taphonomic group C). These characteristics suggest that the foraminifera assemblage is mainly autochthonous and that this was a low energy environment. From 51 cm to the top, there was an increase in the percentage of fragmented and reworked shells (Taphonomic groups C and D), which would indicate that these shells had a different source.

The sedimentary sequence had a predominant percentage of hyaline shells and a low percentage of porcelaneous shells; they correspond to species characteristic of marginal marine environments. The absence of agglutinated shells is a recurring theme in Holocene marginal marine sequences studied in the area (Calvo-Marcilese *et al.*, 2011, 2013; Márquez & Ferrero, 2011; Márquez *et al.*, 2016; Luengo *et al.*, 2018; Ballesteros-Prada *et al.*, 2021). This pattern may be attributed to taphonomic, biostratinomic (microbial degradation of cement), or ecological processes (Berkeley *et al.*, 2007).

Total abundance and S exhibited low values throughout the profile, comparable to Holocene sediments of the Bahía Blanca estuary (Calvo-Marcilese *et al.*, 2011) and the Northeast of Buenos Aires Province (Laprida & Bertels-Psotka, 2003), which are associated with marginal marine depositional environments.

According to Murray (2006), H values obtained suggest that a marginal marine sedimentary environment was predominant throughout the sequence (H= 0–2.5). The highest values for the α index (5–6.1) were observed at the base of the section, indicating the presence of an environment with normal saline conditions or a hypersaline lagoon. Values below 5 were obtained at the 120–30 cm level, which implies a generally brackish or marginal marine sedimentary environment.

There was a prevalence of infaunal specimens (> 90%) throughout the sedimentary sequence, suggesting low oxygen conditions. Conversely, BFOI values along the section showed greater variation from the base to the 86 cm level (-0.41 to 0.04). From this level to the top, the value is equal to 0. In general terms, these values would indicate suboxic conditions between 0.3 and 1.5 ml/L. Low oxygen levels at the sediment surface are often related to high productivity caused by the oxidation of organic matter (Corliss & Chen, 1988).

AEI values were consistently low throughout the section (< 50), remaining between 10 and 26 from the base to 76 cm, with occasional peaks not exceeding values of 40. Beyond 76 cm, there was a slight increase in values, ranging from 24 to 77 at 32 cm. These AEI values indicate the lower influence of hypoxia.

Species as *C. poeyanum*, *C. gunteri*, *A. tepida*, *E. galvestonense*, and *A. parkinsoniana* were the most abundant throughout the sequence. On the other hand, *E. articulatum*, *C. excavatum*, *E. advenum*, *Q. seminula*, *Q. milletti*, and *H. germanica* were less abundant and were limited to certain levels. These species have been reported in Holocene sediments of the coastal plain in Buenos Aires Province, in areas near the study site of this work, including sediments from Samborombón Bay (Laprida & Bertels-Psotka, 2003; Laprida *et al.*, 2011; Luengo *et al.*, 2018; Ramos *et al.*, 2019; Ballesteros-Prada *et al.*, 2021; Luengo *et al.*, 2021), Mar Chiquita Lagoon (Márquez & Ferrero, 2011; Márquez *et al.*, 2016), and Bahía Blanca estuary (Cusminsky *et al.*, 2009; Calvo-Marcilese *et al.*, 2011, 2013).

Also, these assemblages of species have been observed in current sediments in the littoral and coastal zones of Argentina and the South Atlantic Ocean (Boltovskoy *et al.*, 1980; Cusminsky *et al.*, 2006; Calvo-Marcilese & Pratolongo, 2009; Eichler *et al.*, 2012a, 2012b; Bernasconi *et al.*, 2018; Ballesteros-Prada & Bernasconi, 2019; Bernasconi & Cusminsky, 2020; Márquez *et al.*, 2022). *Cribroelphidium poeyanum* was observed in oceanic saline water in combination with deriving freshwater from continental discharge found as far as a depth of 50 m (Eichler *et al.*, 2012a, 2012b), and polyhaline environments (18–30 psu) in estuarine channels (Eichler *et al.*, 2007). Specimens morphologically similar, denominated as *Elphidium* aff. *poeyanum*, have been reported in the Argentinean continental shelf, near to the la Plata River, at depths greater than 70 m (Bernasconi *et al.*, 2018; Bernasconi & Cusminsky, 2020). *Cribroelphidium gunteri* is found in different coastal lagoon zones (Márquez *et al.*, 2022), it was observed frequently in low marsh and tidal flats in Bahía Blanca estuary (Calvo-Marcilese & Pratolongo, 2009) and it is often associated with typical marshes vegetation, such as *Sarcocornia ambigua* and *Spartina densiflora* (Márquez *et al.*, 2022). Besides, this species was found in the backshore of littoral localities in Mar de Ajó, Argentina (Laprida *et al.*, 2011) and the continental shelf of Argentina (Bernasconi *et al.*, 2018). *Elphidium galvestonense* is a species characteristic of marginal marine environments, such as coastal lagoons and estuaries, as well as continental shelf (Boltovskoy *et al.*, 1980; Murray, 2006).

Specimens of the genus *Ammonia* inhabit muddy-sandy sediments, especially in environments with low salinity like marshes and brackish lagoons (Murray, 2006). This genus is common in continental shelf of Brazil and to the north of Argentina (Bernasconi *et al.*, 2018; Pregnolato *et al.*, 2018; Bernasconi & Cusminsky, 2020). *Ammonia parkinsoniana* is widely distributed across various marginal marine environments, such as coastal lagoons, estuaries, and salt marshes, as well as the inner continental shelf (Bernasconi & Cusminsky, 2020; Márquez *et al.*, 2022). This species has been reported in unvegetated mudflats in marine lagoons (Berkeley *et al.*, 2007).

Ammonia tepida was commonly found in vegetated samples from the coastal plain of the Mar Chiquita Lagoon (Márquez *et al.*, 2022) and in vegetated intertidal environments of estuarine marshes (Calvo-Marcilese & Pratolongo, 2009). This species has also been reported in low intertidal vegetated and unvegetated mudflats (Berkeley *et al.*, 2007).

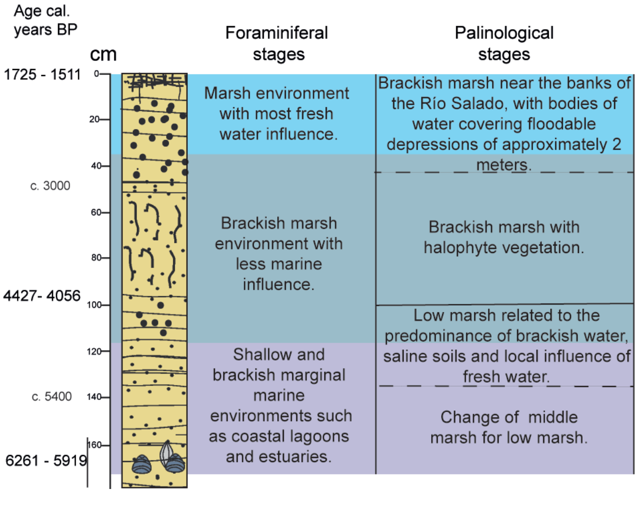

Figure 5. Paleoenvironmental reconstruction of the **PS** sedimentary sequence based on foraminifera (this study) and palynology (Vilanova & Prieto, 2012).

The dominance of *C. poeyanum*, *C. gunteri*, *A. tepida*, *E. galvestonense*, and *A. parkinsoniana* through the sedimentary sequence indicates a prevalence of marginal marine environments similar to coastal lagoons, estuaries or/and marshes between 6,261–5,919 cal. years BP and 1,725–1,511 cal. years BP. However, the presence of taxa with more restrictive distributions in the section such as *Quinqueloculina* and *H. germanica* suggests an environmental change in this period.

Paleoenvironmental evolution

Three stages of paleoenvironmental evolution were identified for the area, ranging from 6,261–5,919 cal. years BP to 1,725–1,511 cal. years BP (Fig. 5).

The oldest stage (PS2-Z1, 171–117 cm) is equivalent to the period between 6,261–5,919 cal. years BP and before 4,427–4,056 cal. years BP, which corresponds to the end of the maximum transgressive phase and the beginning of the regressive phase. The presence of *C. poeyanum*, *C. excavatum*, *C. gunteri*, *E. galvestonense*, and *Q. seminulum* are related to coastal lagoon or estuarine environments (Boltovskoy *et al.*, 1980; Murray, 2006; Calvo-Marcilese & Pratolongo, 2009; Márquez *et al.*, 2022) and indicate a restricted-shallow environment. Additionally, occurrences of *A. tepida* and *A. parkinsoniana* in lesser proportions and the diversity values (α < 6) indicate a marine marginal environment with normal salinity. During this period, marine ingression covered much of the land in the middle zone of Samborombón Bay, particularly in the Salado River area where the meeting of seawater and fresh river water created an estuary. These conditions were conducive to the proliferation of mollusks characteristic of these environments, such as *Tagelus plebeius* and *Mactra isabelleana*. The vegetation assemblage associated with the study area indicates brackish waters, saline soils, and local influence of freshwater (Vilanova & Prieto, 2012).

The second stage (PS-Z2, 112–31 cm) covers the period after 4,427–4,056 cal. years BP and preceding 3,000 cal.

years BP (Vilanova & Prieto, 2012), corresponding to the regressive phase. During this stage, the sea level decreased and the coastline retreated. This event changed the landscape and the environmental conditions in the study area. Even though the foraminiferal assemblage is similar to that of the previous phase, it shows a decrease in the diversity (< 5) and the abundance of *C. poeyanum*, *E. galvestonense*, and species of the genus *Quinqueloculina*. At the same time, the abundance of *A. tepida*, *C. excavatum*, and the occurrence of *H. germanica* and *Hainesina* sp. 1 increase. This composition of calcareous species associated with agglutinate species such as *Trochammina inflata*, *Jadammina macrescens*, and *Miliammina fusca* are related to estuarine environments (Calvo-Marcilese & Pratolongo, 2009). Nevertheless, increased abundance of *H. germanica* and *A. tepida* suggests the presence of vegetated intertidal environments of estuarine marshes (Calvo-Marcilese & Pratolongo, 2009), characterized by the dominance of Chenopodiaceae associated with Cyperaceae along with Asteraceae and *Ambrosia* (Vilanova & Prieto, 2012). *Cribroelphidium poeyanum* is more abundant in environments with normal salinity than *A. tepida* (Supplementary information; Debenay *et al.*, 1998; Brewster-Wingard *et al.*, 1996). Therefore, the decrease of *C. poeyanum* and increase *of A. tepida* indicated changes in salinity levels derived from a decrease in estuarine conditions, as well as an increase of the Salado River influence (Fucks *et al.*, 2015; Pommarés *et al.*, 2021). This relationship between the abundance of *C. poeyanum* and *A. tepida* is reflected in the increase of AEI; however, the change of the AEI in this section is not related to the variation of oxygen levels but in salinity levels.

The third stage (PS-Z3, 32–0 cm) corresponds between 3,000 cal. years BP and 1,725–1,511 cal. years BP. The abundance of foraminifera decreases drastically and species of *Ammonia* become the most prevalent, while species of *Cribroelphidium* decrease. Moreover, there is a higher proportion of reworked foraminifera shells, implying a shift towards a medium to high marsh environment. Vilanova & Prieto (2012) state that the rise in Poaceae, Cyperaceae, Asteraceae, and *Ambrosia*, together with traces of *Alternanthera*, would represent grassland and marsh environments in the vicinity of the Salado River's banks. Water bodies in the floodplain depressions are indicated by the greater proportions of algae residue and the remains of shells of *Heleobia parchappii* and *Biomphalaria*, which are linked to aquatic ecosystems (Vilanova & Prieto, 2012).

Local paleoenvironmental evolution

The Salado River Basin is the most important hydrographic unit of the Buenos Aires Province, which flows NW–SE into the Samborombón Bay. Along its course, the river traverses various geomorphological formations and sedimentary deposits (Fucks *et al.*, 2007, 2015). Some of these deposits are associated with marginal marine environments, resulting from the sea-level rise during the Holocene Maximum Transgressive phase (Laprida & Bertels-Psotka, 2003; Fucks *et al.*, 2007, 2015; Luengo *et al.*, 2018; Ramos *et al.*, 2019; Ballesteros-Prada *et al.*, 2021).

During the period of maximum transgression (6,261–5,919 cal. years BP), a notable portion of Samborombón Bay was flooded. The waters of the Salado River mixed with the saline waters of the Atlantic Ocean, generating suitable conditions for the formation of an estuarine environment in the middle zone of the Samborombón Bay, extending approximately 28 km inland (Fucks *et al.*, 2007). The low slope of the coastal plain and the reduction in river flow derived from a dry period contributed to the estuarine waters advancing upstream for up to approximately 35 km (Piovano *et al.*, 2009; Fucks *et al.*, 2015; Ramos *et al.*, 2019). This event can be observed in a sediment wedge interbedded between the Gorch Member and Las Gaviotas Member (both from the Luján Formation). The foraminifera composition of this sedimentary wedge is less diverse than that studied in this work (PS), exclusively reporting higher proportions of *A. tepida* and *C. gunteri* and lower proportions of *A. parkinsoniana* (Ramos *et al.*, 2019). We could infer that this environment has more freshwater influence than marine influence (Fig. 6).

This wedge was previously observed by Fucks *et al.* (2015) and was associated with the maximum MIS 1 transgression during the Mid–Holocene. These sediments belong to the Canal de las Escobas Formation (Fucks *et al.*, 2010) and represent a marine ingression in the continent through the Salado River (Fucks *et al.*, 2015). Based on the results obtained in this study and the work conducted by

Ramos *et al.* (2019), it is likely that these intermediate deposits between P1 and PS correspond to marine marginal environments with brackish waters (Fig. 6).

Between 4,427 and 4,056 cal. years BP, the regressive phase resulted in a lowering of the sea level, leading to the creation of ridges as the coast receded. Additionally, an increase in freshwater from the Salado River contributed to a decrease in saline water, generating a muddy intertidal environment with shallow conditions. This change to fluvio-lacustrine environments was also observed by Fucks *et al.* (2007) in a sequence located nearby to the PS sequence.

The coastline shifted to its present position about 3,000 years ago. During this period, the influence of freshwater from the Salado River was predominant and the riverbanks were characterized by grasslands and brackish marsh grasses (Vilanova & Prieto, 2012). These fluvial depositional environments were observed closer to the shoreline (Fucks *et al.*, 2007), indicating the greater advance of freshwater over the river (Fig. 6).

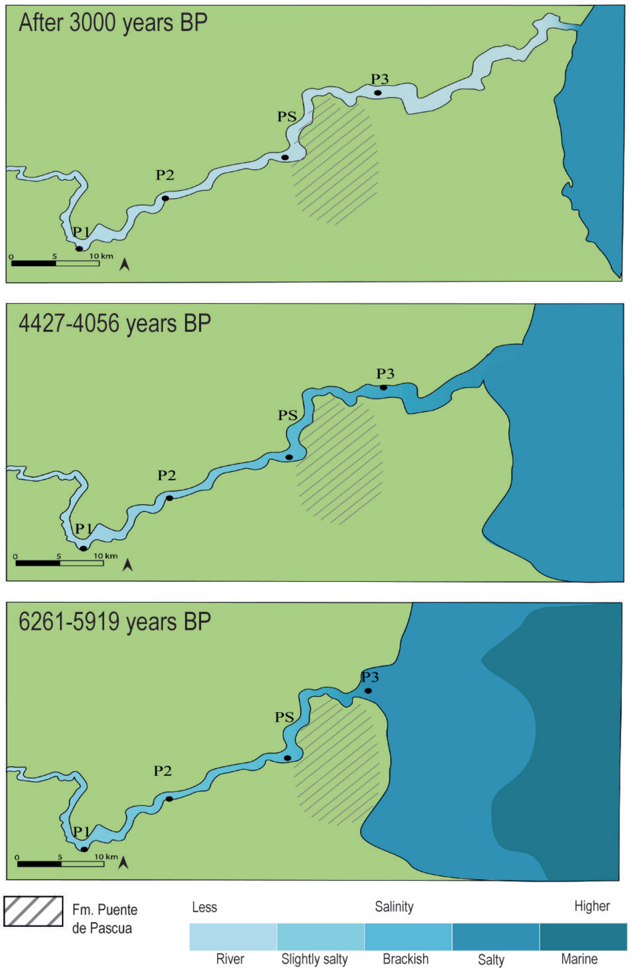

Figure 6. Paleoenvironmental evolution model of the Salado River during the transgressive phase and sea-level highstand. Sources: P1 (Ramos *et al.*, 2019), P2 (Fucks *et al.*, 2015), PS (this work), and P3 (Fucks *et al.*, 2007).

CONCLUSIONS

The PS sedimentary sequence under analysis was deposited during a period ranging from 6,261–5,919 cal. years BP to 1,725–1,511 cal. years BP. These ages coincide with marginal marine settings that were affected by an increase in sea level and marine ingression during the Mid–Late Holocene.

The benthic foraminifera assemblage described indicates a confined brackish depositional environment that encountered a decline in salinity through time. It transitioned from a shallow, confined brackish environment to a brackish swamp or high marsh environment with freshwater influence.

The fluctuations of the sea level in the Holocene, the coastal geomorphology of Samborombón Bay and the climatic changes that occurred during the Middle to Late Holocene influenced the dynamics and characteristics of the Salado River.

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