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RESEARCH ARTICLE: ORIGIN AND EVOLUTION OF COASTAL LAGOONS FROM THE PAMPEAN REGION: MAR CHIQUITA, LAS BRUSQUITAS, RETA (BUENOS AIRES PROVINCE, ARGENTINA)

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Origin and evolution of coastal lagoons from the Pampean region: Mar Chiquita, Las Brusquitas, Reta (Buenos Aires province, Argentina)

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ABSTRACT

Low-lying coasts are specially conditioned for the origin and development of coastal lagoons. The Pampean region (Buenos Aires, Argentina) contains the surplus of a sea level fluctuation that occurred d during the last 6000 years. This report shows results from the study of three coastal lagoons at different stages of their evolution: Mar Chiquita coastal lagoon, Las Brusquitas estuarine lagoon, and the small coastal lagoon of Balneario Reta. The long-term evolution is considered in the case of Mar Chiquita and Las Brusquitas, while modern trends are also described for the Mar Chiquita silting problems and the urbanisation of the Reta village surrounding the lagoon. The study is based on radiocarbon datings, salinity analyses, and sedimentological records on outcrops and piston cores. At Mar Chiquita coastal lagoon, a shallow open bay has been restricting since the Middle Holocene, causing the development of marshes and tidal flats between cheniers and regressive spits. Its evolution is therefore conditioned to high-energy events that reworked bioclastic sands (cheniers and regressive spits) and the silting of fine sediments. The sequence cropping out at the outlet of the Las Brusquitas creek extended temporally between 6190 and 2380 ^{14}C years BP; the estuarine lagoon was located at the outlet of two creeks. New outcrops exhumed and radiocarbon datings indicated this new interpretation of the site as an estuarine lagoon silted in the last 2000 years. The small estuarine lagoon (“microalbufera”) of Balneario Reta is another wetland flooded by the increase in water discharge due to artificial channels. The connection to the sea depends on the effects of high tides and winds blowing from the south. The contents in diatom assemblages were interpreted as indicators of changes in salinity balances during the Late Holocene. Oligohaline specimens dominated at the three coastal lagoons; polihaline and mesohaline assemblages characterise some intervals at the Mar Chiquita and Las Brusquitas sedimentary sequences. In order to preserve these coastal lagoons and the natural reserves related, it is necessary to preserve their dynamics according to forecasted sea level rise, and the water balances between salt and fresh waters.

Keywords: coastal lagoons, estuarine lagoons, sea level, coastal dynamics

INTRODUCTION

The Holocene sea-level fluctuation induced flooded depressions with different depths and environmental dynamics along the coastal plains of Buenos Aires Province (Fig. 1). Where the water discharge was significant estuarine environments developed. Those enclosed with less water depth constituted coastal lagoons (Fig. 2). The evolution of these estuarine environments in Buenos Aires Province was therefore conditioned to the regional slopes and sedimentation rates (Isla, 1998; Isla and Espinosa, 1998). Coastal lagoons are more dominated by marine processes (longshore drift) while in estuarine lagoons fluvial processes are more important (Fig. 2). The extension of vegetated marshes is related to the slope of the coastal plain and the precipitations regimes (Isla *et al.*, 2010). The formation of spits or barriers is related to the availability of sand supplied by the longshore drift (Isla, 2017).

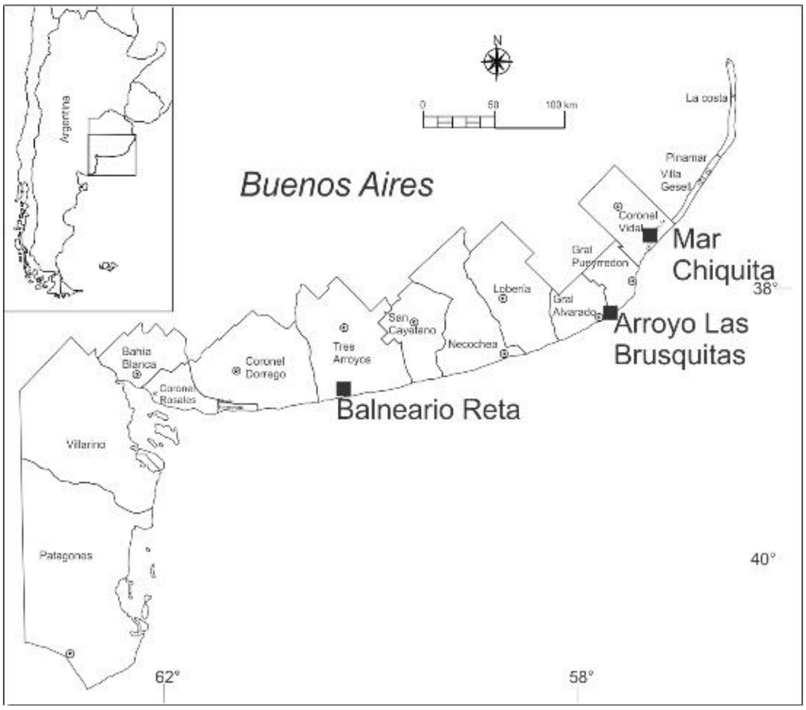

Figure 1. Location map of Mar Chiquita, Arroyo Las Brusquitas and Balneario Reta lagoons.

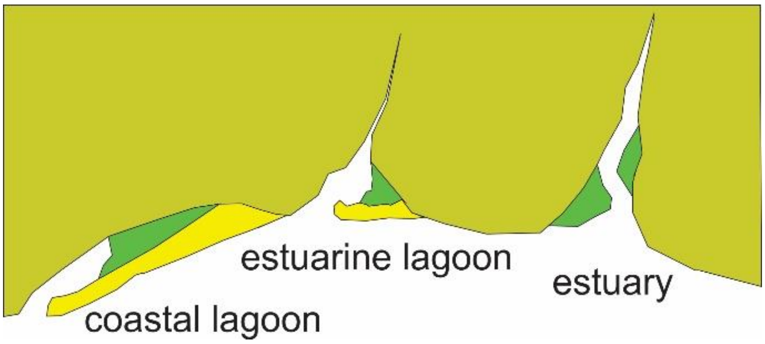

Figure 2. Geomorphological classification of coastal lagoons and estuarine lagoons with different development of marshes and sandy environments (modified from Davies, 1973).

Coastal lagoons can evolve in relation to the sea level trends. In the Northern Hemisphere, they migrate onshore in relation to the shoreline retreat (Swift and Moslow, 1982). However, at the coast of New York, drowned coastal lagoons and barrier facies on the continental shelf led to punctuated and rapid sea level rises (Sanders and Kumar, 1975). In South America, as in many other regions of the Southern Hemisphere, coastal lagoons evolved in a stable, or less than 2 m fluctuation of the sea level (Fig. 3). However, their dynamics and climate are determinant on their evolution (Roy, 1984; Kjerfve, 1994; Isla, 1995).

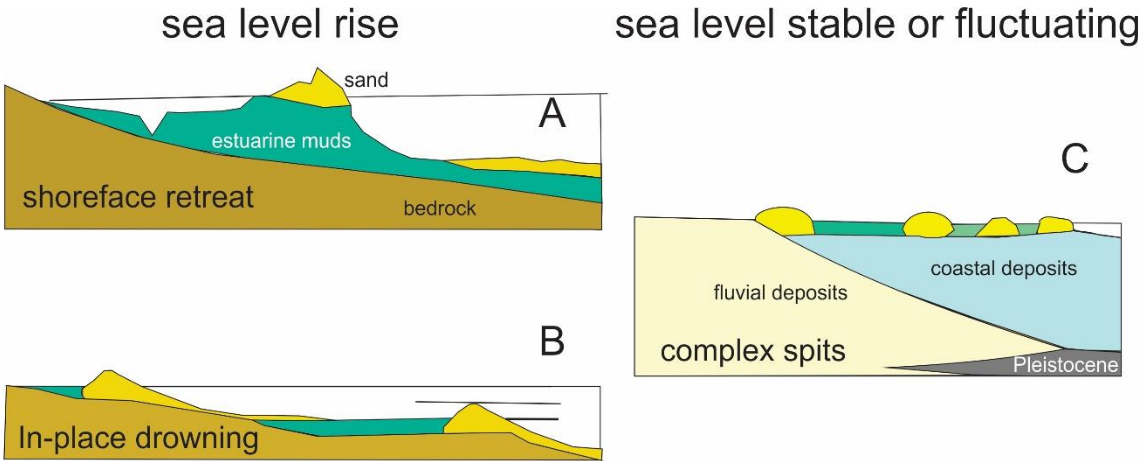

Figure 3. Coastal-lagoon evolution in terms of sea level variations. A. Shoreface retreat model. B. In-place drowning. C. Complex spits in a stable or fluctuating sea level (modified from Isla and Isla, 2022).

This manuscript describes three coastal lagoons from Buenos Aires Province, Argentina, at different stages of their evolution, and with different salinity regimes. The Mar Chiquita lagoon is today in the last stages of silting. Sedimentation has increased due to alterations in its dynamics caused mainly by human interventions. The Las Brusquitas estuarine lagoon was completely silted during the last Holocene sea-level drop. The Reta lagoon is handled as a coastal depression episodically flooded during high sea-level stands, and where the water discharge was modified by channels constructed during the XXI century. *In situ* salinity variations were measured at still operational coastal lagoons (Mar Chiquita, Reta). Salinity estimations from estuarine sequences (Mar Chiquita, Las Brusquitas) were estimated applying to transfer functions based on diatom assemblages (Hassan *et al*., 2009; Espinosa *et al*., 2012).

METHODOLOGY

Old nautical charts, aerial photographs, and satellite images were compared in order to document geomorphological changes though time. Vibracores were extracted from the plain surrounding the Mar Chiquita coastal lagoon. Radiocarbon datings were performed from molluscs and organic matter layers collected from these cores and outcrops. Salinity measurements were collected by a Horiba U10 water quality analyser, and were inferred from their diatom contents in sediments. At Las Brusquitas outlet, the sedimentary outcrops were described and sampled. In Reta Lagoon, a 31 cm piston core was drilled from a water depth of 0.7 m. These cores were split, sampled and the sediment content were analysed to concentrate frustules of diatoms.

Mollusc shells were collected from the coastal plain surrounding the Mar Chiquita coastal lagoon. Two bivalve species, *Mactra isabilleana* and *Tagelus plebeius,* were sampled from the same sites. They were collected from approximately the same depths (0.3-0.5 m) from the surface of the plain dominated by freshwater marshes. It was assumed that because of their narrowness and elongated shapes, *Tagelus plebeius* can dig to deeper levels than *Mactra isabelleana*. Most of the ^{14}C dates were already reported (Schnack *et al.*, 1982) and analysed at the LATYR Lab (Universidad Nacional de La Plata, Argentina). No reservoir effects were here reported as it is known that these watersheds are subject to differential supply of carbonate water (Glok Galli *et al.*, 2014). For the case of coastal lagoons the mixing between fresh and sea water is implicit in their definition.

The diatom assemblages were analysed according to laboratory and statistical procedures described in Hassan *et al.* (2009) and Espinosa *et al.* (2012). Diatom assemblages were related to salinity changes according to present salinity affinities, ranges, and applying transfer functions already published.

STUDY AREA

These three coastal lagoons were related to the evolution of the Eastern and Southern barriers of Buenos Aires. They are emplaced on a humid-subhumid climate. These barriers are wider than 1 km with lengths over 50 km (Isla, 2017). The Mar Chiquita lagoon is emplaced along the Eastern Barrier of Buenos Aires, whereas Las Brusquitas and Reta are related to the Southern Barrier (Fig. 1). Both barriers have different sedimentary histories: the Eastern Barrier grew in relation to the fluctuation of the sea-level during the Holocene; the Southern Barrier is composed of sand dunes perched on top of ancient cliffs. The Mar Chiquita and Reta lagoons are attached to touristic villages that are conditioning their environmental conservation issues.

Annual precipitations are slightly higher in Mar Chiquita and Las Brusquitas (844 mm) than in Reta (777 mm). In the Tres Arroyos County rains have been decreasing during the interval 2014-2020, as indicated by meteorological stations at Claromecó, Cristiano Muerto, Chacra Barrow and San Francisco Bellocq. Tidal ranges at Mar Chiquita and Las Brusquitas are less than 2 m. In Mar Chiquita the tidal ranges diminish significantly to the main body of the coastal lagoon (Isla and Gaido, 2001). In Balneario Reta tidal range reaches about 2 m.

Buenos Aires coastal plains are subject to significant interannual variations in precipitation, increasing during El Niño Southern Oscillation years and diminishing during La Niña years (Isla and Toldo 2013; Isla, 2018).

RESULTS

The Mar Chiquita coastal lagoon

The evolution of the Mar Chiquita coastal-lagoon is related to a sea-level fluctuation during the last 6000 years BP (Schnack *et al.*, 1982). During this interval, complex spits grew from north to south which caused the original bay to become a coastal lagoon that dwindled progressively from north to south (Fig. 4). The resulting shelly spits and cheniers were dated as Late Holocene (Isla, 2017).

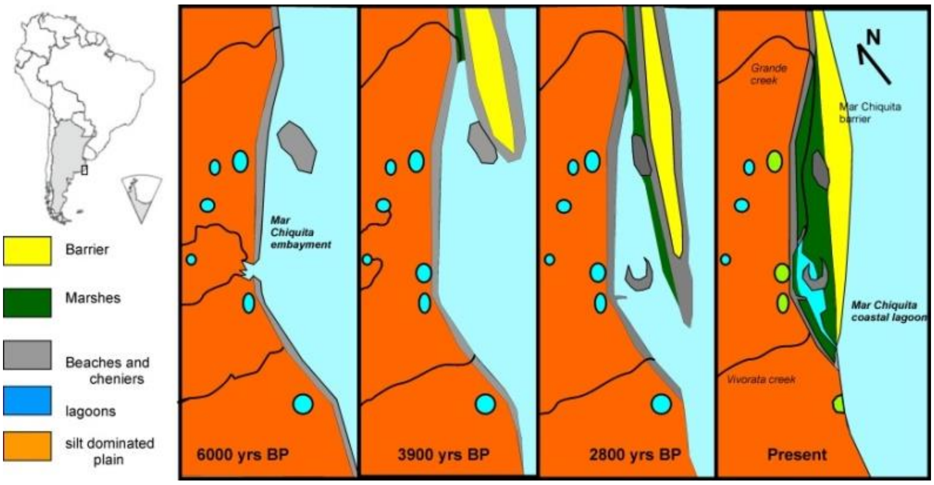

Figure 4. Evolution of the Mar Chiquita coastal lagoon in relation to the Late Holocene sea-level fluctuation and the progradation of complex spits (modified after Isla, 2017).

Radiocarbon datings were performed on mollusc shells sampled from the coastal plain (about 30-50 cm depth). According to these datings the lagoon enclosed between 5000 and 2800 years BP (Fig. 5). In all cases, specimens of *Mactra Isabelleana* were older than those of *Tagelus plebeius* sampled on the same sites. This fact was related to the differential Carbon uptake between both species, and the reservoir effect related to the mixing with carbonated water supplied from the caliche levels that characterised the watershed of Mar Chiquita plain (Glok Galli, 2014, Glok Galli *et al.*, 2014).

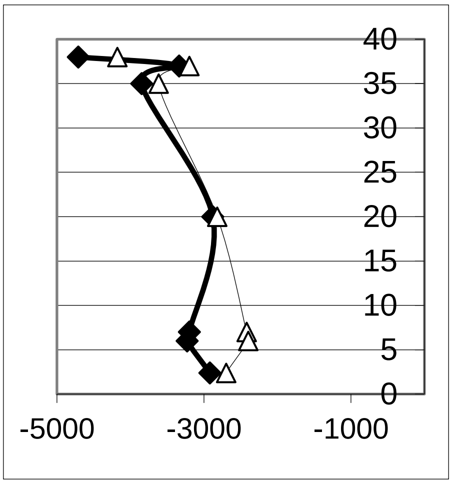

Figure 5. Radiocarbon datings (radiocarbon years before present; x axis) in relation to the distance to present inlet (in km, y axis). Squares represent datings performed on specimens of ***Mactra isabelleana*** *while triangles ages obtained from specimens of* ***Tagelus plebeius.***

Eight vibracores collected from the coastal plain surrounding the lagoon have recorded intervals to the formation of complex spits and cheniers (Fig. 6). During the sea level regression there was an alternation of mud and shelly deposits along and across the lagoon. In this sense, the aggradation was not uniform: cheniers were constructed during episodic processes across the plain (Price, 1955; Augustinus, 1980), and mud silted within restricted areas. This alternation of mudflats and cheniers are common in flat estuarine environments subject to periodic episodic effects (Isla and Bedmar, 2014). Examples from South America are described et the Paraná delta (Milana and Krohling, 2015; Colombo *et al.*, 2021), the coastal lagoons surrounding the Santa Marta Cape (Fornari *et al.*, 2012), and San Sebastián Bay (Isla *et al.*, 1991).

Some of the sediments from the cores were studied applying transfer functions, relating measured salinity and approximations inferred from transfer functions based on diatom assemblages (Hassan *et al.*, 2009; Espinosa *et al.*, 2012).

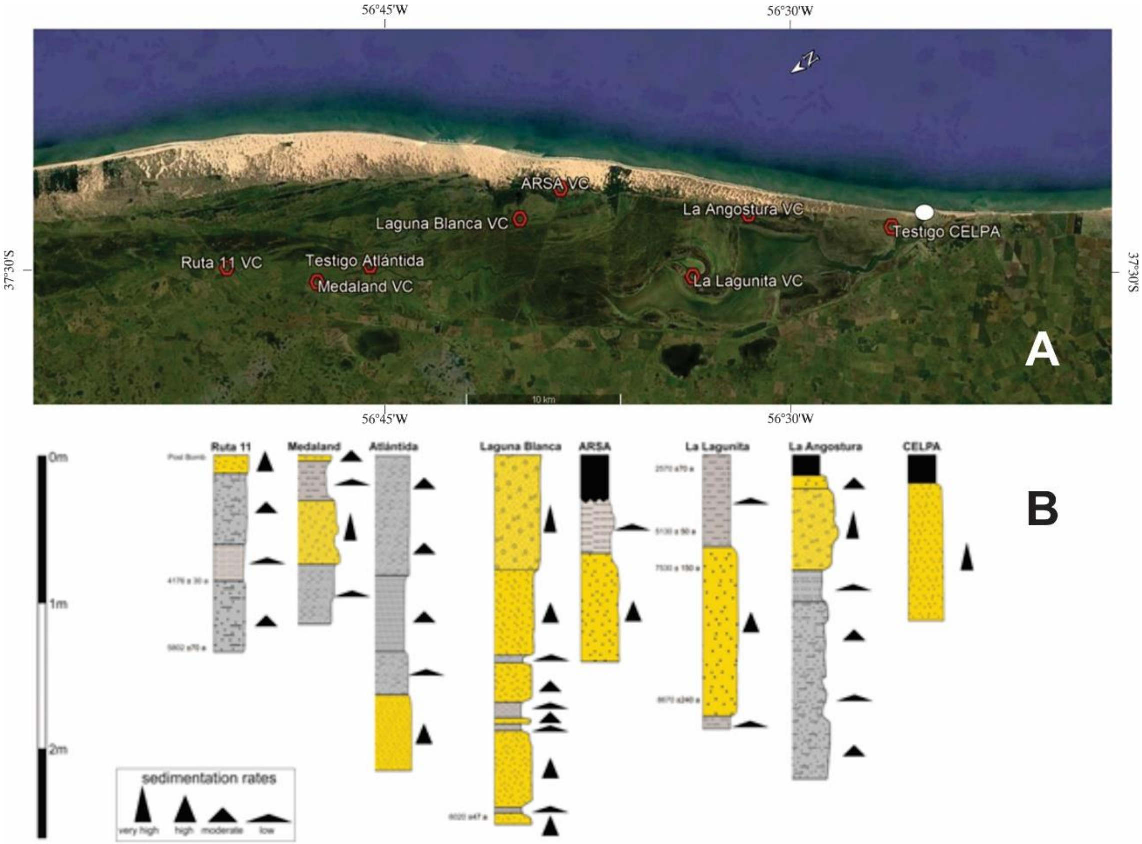

Figure 6. A. Cheniers, regressive spits, and location of virbacores at the Mar Chiquita coastal plain (references in figure 4). The white circle locates the site of the measurements of water quality. B. Vibracore descriptions with estimations of the different sedimentation rates.

The Mid to Late Holocene sea-level regression caused the Mar Chiquita lagoon to evolve into a choked type lagoon (Kjerfve, 1994). This coast is microtidal semidiurnal; during the day one high tide is higher than the other. The CELPA bridge (built during the 1960s) caused a narrowing of the discharge channel, and therefore restricted the action of both tides on the main body of the lagoon. Most of the lagoon dynamics were conditioned by a tidal wedge whose range diminishes towards the headlands (Isla and Gaido, 2001). As it is draining a wide coastal plain in a temperate climate subject to flooding periods, high and low water levels can alternate. Temperature and salinity were measured at the discharge channel during the interval from April 2009 to March 2010 (Fig. 7). Summer maxima fluctuate between 20 and 25°C while the winter minima drop to 5-10°C (Fig. 7a). Salinity was measured at the discharge channel trying to avoid tidal variations at the inlet. It was about 22 UPS average, but dropping episodically up to 0 due to dilution effects caused by rainfalls within the watershed (Fig. 7b).

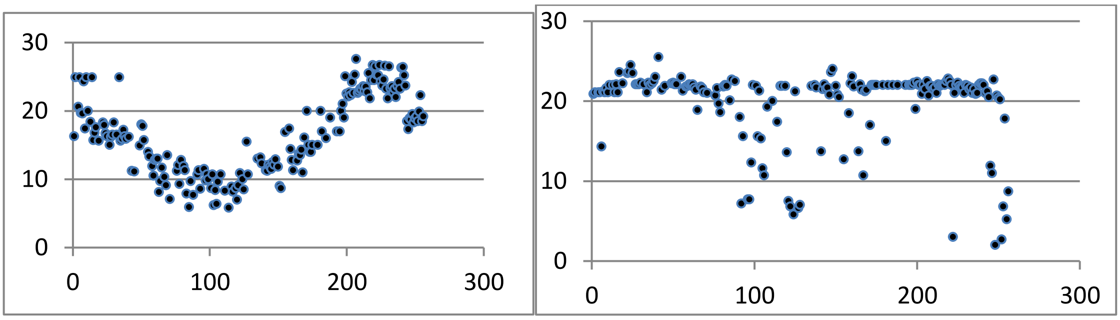

Figure 7. A. Daily water temperature variations along the discharge channel during the interval Apr 2009-Mar 2010. B. Daily salinity changes along the channel during the same interval.

The Las Brusquitas estuarine lagoon

An ancient estuarine lagoon was reported from the sedimentary deposits attached to Las Brusquitas creek (Isla *et al.*, 1986; Isla and Espinosa, 1998). The original description was based on the sequence cropping out at the northern shore of the creek (Espinosa *et al.*, 1984; Fig. 8a) and was later subject to many studies (Isla *et al.*, 1986; Marquez *et al.*, 2016). Radiocarbon datings from this outcrop spanned from 6380 ± 60 yrs to 2040 ± 80 yrs BP (Marquez *et al.*, 2016).

This new report incorporates a new outcrop exposed after a storm that occurred in 2019. Blackish-greyish laminated muds are spatially more extended, and lying close to the storm berm of the present beach. These new outcrops allow estimating an extension of approximately 400 m of the lagoon along the present shore (Fig. 8b). New radiocarbon datings performed on an oyster specimens gave a radiocarbon age of 6320±110 years BP (LP3693; with a reservoir correction age of 5920±110 years BP).

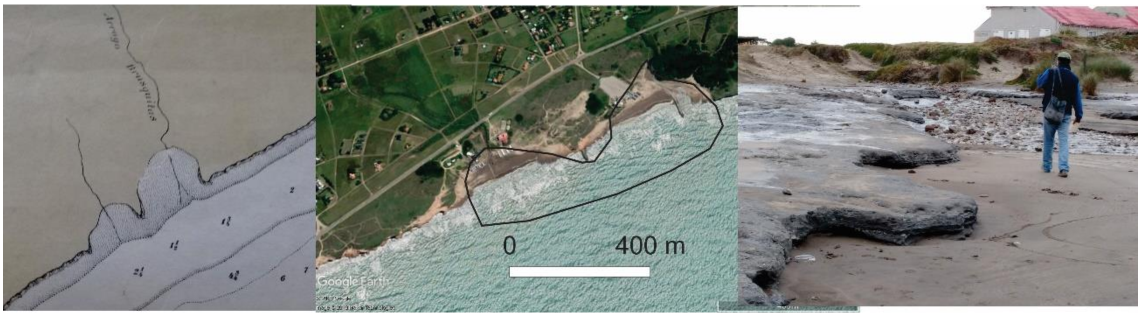

Figure 8. A. The depression of the Las Brusquitas estuarine lagoon was drafted at the Miramar nautical chart of 1916. B. Estuarine sequence cropping out at the upper beach of the Las Brusquitas beach.

The Reta estuarine lagoon

Attached to the Balneario Reta village there is a sandy depression that is episodically flooded by sea waves. The depression is related to an ancient cliff formed during the maximum transgression of the mid Holocene highstand (Fig. 9). The Reta village has grown in relation to touristic purposes and its urban sprawl has increased environmental problems (Piccinali, 2013).

At Reta Lagoon, a piston core 31 cm long was extracted from the middle of this shallow water pond (at a lagoon depth of 0.7 m). The diatom content was analysed in order to infer the maximum salinity recorded along the sediments of the core.

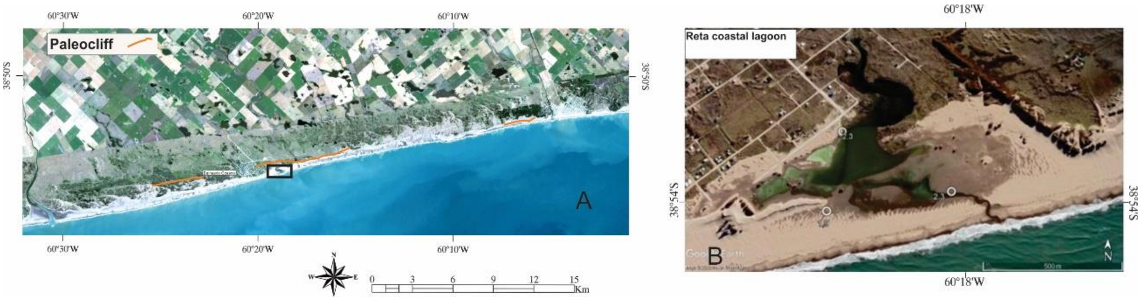

Figure 9. The Reta estuarine lagoon. A. Mid Holocene coastline (paleocliff) between Reta and Claromecó. Inset locates the Reta estuarine lagoon. B. Reta estuarine lagoon with three measurement locations, where salinity was always below 2.3 ‰.

Channels performed on this plain increased the discharge draining isolated ponds towards this estuarine lagoon (Fig. 10). Salinity measurements were performed at different moments and locations; it never surpassed 2.3 ‰. The village has been expanding towards the lagoon during La Niña drought of 2021-2022. These conditions would be changing according to forecasted climate (Magrín *et al*., 2014).

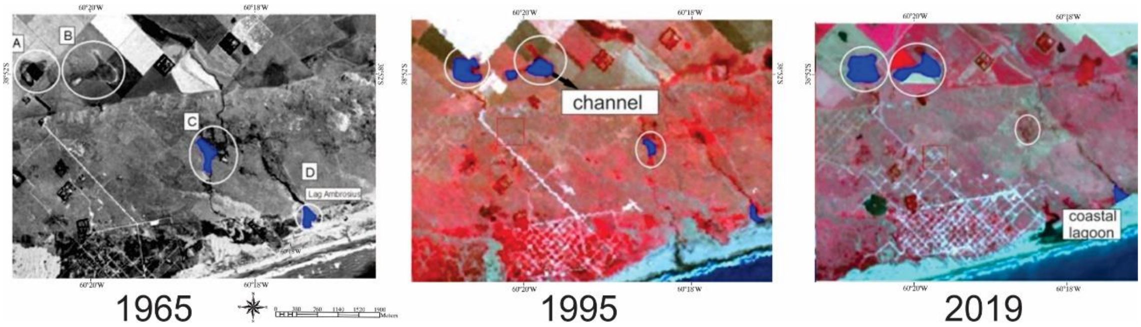

Figure 10. Changes of the drainage network of the Reta depression according to an aerial photograph of 1965, and satellite images from 1995 and 2019. Circles denote changes in small ponds.

A 31 cm piston core was collected from this site from a depth of 0.7 m. The lagoon is dominated by macrophytes. The bottom of the core is dominated by epifitic and benthic diatoms assigned to a brackish environment. At 18 cm depth, the marsh is assumed to be more saline with a higher content of *Diploneis interrupta*. Towards the top of the core (6 to 1 cm depth), diatom assemblages have an increase in tychoplanktonic specimens indicating an increase in salinity (Fig. 11).

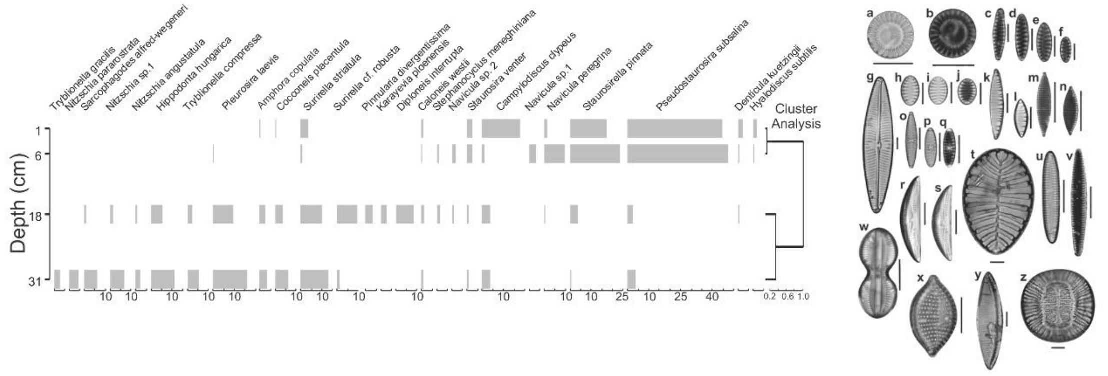

Fig. 11. Abundance diagram of the dominant diatoms in the sediment core from Reta lagoon: (a-b) *Stephanocyclus meneghiniana*; (c-f) morphological variability of *Staurosirella pinnata;* (g) *Navicula peregrina*; (h-j) morphological variability of *Staurosira venter*; (k-l) *Denticula kuetzingii*; (m-n) *Nitzschia angustatula*; (o-q) *Hippodonta hungarica*; (r-s) *Amphora copulata*; (t) *Surirella striatula*; (u-v) *Pseudostaurosira subsalina*; (w) *Diploneis interrupta*; (x) *Tryblionella compressa*; (y) *Tryblionella gracilis*; (z) *Campylodiscus clypeus*. Scale bars = 10 µm, 5 µm (Figs. c-f; h-j), 20 µm (t and z).

DISCUSSION

The described estuarine sedimentary successions were deposited during the Late Holocene sea-level fluctuation. According to radiocarbon dating of molluscs or peat horizons, it was possible to estimate sedimentation rates (Isla and Espinosa, 1998). These sedimentation rates not only depend on the input rate of sediments to these lagoons, but also on the inherited depths and the episodic processes that dominate these depressions.

Conventional radiocarbon dates should be corrected in order to translate radiocarbon years into sideral years. This is performed by referring to a chronology based on tree rings from long-living species. As the atmosphere of the Southern Hemisphere is assumed to have a greater pre-industrial latitude-dependent ^{14}C offset than the Northern Hemisphere's, there is another correction recommended for the Southern Hemisphere (SHCAL04; McCormac *et al*., 2004). On the other hand, marine radiocarbon dates are particular sensitive to a time lag due to the differential C uptake between the atmosphere and the sea at different places (Stuiver and Baziunas 1993). This was commonly referred to as Reservoir effect. Different regional reservoir effects have been calculated for different coastal areas (Hughen *et al*., 2004) although these effects are known to vary also in time (Spennemann and Head, 1996; Ulm, 2006 a), and particularly in relation to local upwelling effects (Ulm, 2006b; Turney and Palmer, 2007). The coastal plain of Buenos Aires developed on a former desert environment rich in caliche levels. Present groundwater studies are estimating the flow of carbonated-rich water (biased to old carbon proportions) that mixes with modern carbon in estuarine environments such as the Mar Chiquita coastal lagoon (Glok Galli *et al*., 2014).

Based on diatom assemblages, it is possible to recognise that the Mar Chiquita lagoon had more sea water influence. On the other hand, Las Brusquitas lagoon had more mesohaline conditions; the Reta lagoon, on the other hand, has never received salt water to contain polihaline assemblages (Fig. 12).

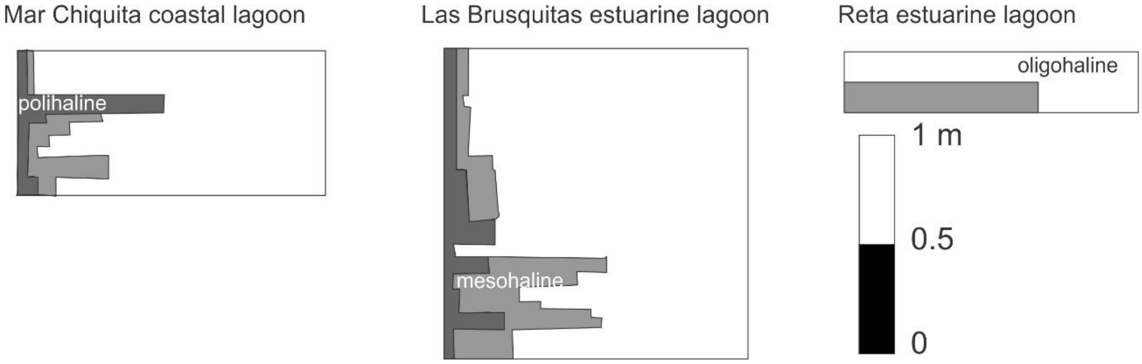

Figure 12. Comparisons of Mar Chiquita coastal lagoon to Las Brusquitas and Reta estuarine lagoons (modified from Isla, 1998). Salinity estimations are based on diatom assemblages (Hassan et al., 2009; Espinosa et al., 2012).

Present coastal lagoons can be subject to changes induced by climate variations, either direct or indirect (Chapman, 2012). They are expected to be threatened by the forecasted sea level rise and the increase in the recurrence and energy of storms

(Oppenheimer *et al*., 2019). Coastal lagoons are also liable to impacts triggered along the watershed (Mateus *et al*., 2016). In this sense, the Buenos Aires plains are particularly sensitive to floods and droughts in relation to El Niño and La Niña cycles (Isla, 2018). Some variations at these coastal lagoons can have direct social impacts on the surroundings (Carrasco *et al*., 2016) causing also changes at the land uses (Lopez-Dóriga and Jimenez, 2020). Regarding these lagoons, Balneario Reta village is growing without a territorial planning, very close to the estuarine lagoon and subject to variations triggered from the drainage basin or the temporal connection with the sea (Piccinali, 2013). These impacts should be considered in urban plans for the touristic village.

CONCLUSIONS

1. Coastal lagoons and estuarine lagoons originated and evolved in Buenos Aires coastal plain in relation to the Holocene sea-level fluctuation, and will continue to evolve in relation to the anthropogenic sea-level rise.
2. Their infilling rates depend on the sediment supply to these depressions, the depth of the flooded area and the dominant processes that conditioned them during the regression.
3. In temperate coastal lagoons, where the mixing of fresh and salt water can vary during their evolution, the diatom assemblages are sensitive to these changes. The reservoir effect can also vary where there were differences in the supply of carbon from old sediment sources.
4. The mid-Holocene cliffs between Reta and Claromecó were reported and mapped.
5. The impacts of the variations of the forecasted physical factors should be considered to preserve these lagoons and the reserves related to them in order to manage the sprawl of the villages attached.

Acknowledgements

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