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ORIGINAL

Coastal landscape evolution on the western margin of the Bahía Blanca Estuary (Argentina) mirrors a non-uniform sea-level fall after the mid-Holocene highstand

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Abstract Sedimentary descriptions and radiocarbon ages from two cores obtained from coastal plains along the western margin of the Bahía Blanca Estuary (Argentina) were integrated with previous information on landscape patterns and plant associations to infer landscape evolution during the mid-to-late Holocene. The study area comprises at least two marine terraces of different elevations. The old marine plain (OMP), at an average elevation of 5 m above mean tidal level (MTL), is a nearly continuous flat surface. The Recent marine plain (RMP), 2 to 3 m above MTL, is a mosaic of topographic highs and elongated depressions that may correspond to former tidal channels. Mollusks at the base of the OMP core (site elevation 5.09 m above MTL), with ages between 5,660 ± 30 and 5,470 ± 30 years BP, indicate a subtidal setting near the inland limits of the marine ingression. The sandy bottom of the core is interpreted as the last stage of the transgressive phase, followed by a tight sequence of dark laminated muds topped by a thick layer of massive gray muds. The RMP core (site elevation 1.80 m above MTL) has a similar sedimentary sequence, but unconformities appear at lower elevations and the massive mud deposits are less developed. The thickness of the grayish mud layer is a major difference between the OMP and RMP cores, but deeper layers have similar ages, suggesting a common origin at the end of the transgressive phase. The overlying massive muds would correspond to rapid sedimentation during a high sea-level stillstand or slow regression. It is proposed that, after a rapid sea-level drop to about 3 m above MTL, a flat and continuous surface corresponding to the OMP emerged, and more recent coastal dynamics shaped the dissected landscape of the RMP. For the Bahía Blanca Estuary, smooth regressive trends have been proposed after the mid-Holocene highstand, but also stepped curves. A stillstand or slowly dropping sea level was described around 3,850 ± 100 years BP, as well as negative relative sea-level oscillations. In this study, the differentiation between the OMP and the RMP supports the occurrence of a stepped regressive trend that, at least locally, presented two different stages.

Introduction

Coastal settings in Atlantic South America commonly present the relative sea-level (RSL) signal of far-field regions, with a mid-Holocene highstand (sea-level maximum) above the elevation of present-day shorelines (Milne et al. 2005; Toscano et al. 2011). This Holocene marine transgression had a remarkable influence on the coastal landscape evolution of, for example, several estuaries such as those of the Río de la Plata and Bahía Blanca in Argentina.

Geomorphic evidence of the Holocene marine transgression has been reported in extensive studies of the Río de la Plata Estuary. For the coastal region between Uruguay and Argentina, a maximum RSL of 6.5 m above present at about 6,500 cal years BP was proposed (sea-level curve from southern Río de la Plata first published by Cavallotto et al. 2004, redrawn by Gyllencreutz et al. 2010 using the same sea-level index points but calibrated ^{14}C ages). The coastal landscape

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comprises a subaerial zone and the subaqueous delta of the Paraná River, as well as a series of coastal plains formed during the Holocene (Cavallotto et al. 2004). After the mid-Holocene highstand under a falling RSL, coastal progradation formed an extensive system of beach ridges. Protected environments behind the ridges transformed into tidal mudflats and marshes (Amato and Silva Busso 2009). According to Cavallotto (2002), the Paraná River delta began to form at ca. 1,800 cal years BP under intense fluvial–estuarine sedimentation related to an increase in precipitation. The progradation of the Parana River delta led to the occupation of the former estuarine environment and the establishment of the present-day fluvial conditions. The present geomorphic settings, combined with prevailing tidal or fluvial hydrologic regimes, allowed a differentiation of ten landscape units further characterized by their dominant plant associations (Kandus and Malvárez 2004).

Similarly, along the eastern and southern barriers in the Buenos Aires Province, Argentina, coastal processes related to RSL changes during the Holocene have produced extensive horizontal records of beach ridges interspersed with estuarine environments (Isla et al. 1996). During the later stages of the Holocene transgression, wide sand barriers developed as a result of high wave energy and abundant sand supply. During the subsequent regressive phase, the offshore supply of sand from the shelf diminished, and the seaward migration of shorelines created coastal lagoons, tidal flats, marshes, and cheniers (Isla and Espinosa 1995). Based on present-day landforms, a landscape zonation for the eastern and southern barriers has been proposed, and the regional and local geomorphic settings were further associated with different vegetation types (Celsi and Monserrat 2008; Monserrat 2010).

The Bahía Blanca Estuary of Argentina is a major coastal system in Atlantic South America (Fig. 1), and numerous studies have reported geomorphic evidence of the Holocene marine transgression based on sedimentological and paleontological analyses of fossiliferous horizons and sand-shell ridges along the coastal region north of the Canal Principal, as well as acoustic seismic investigation of the marine bottom and sub-bottom of this channel (e.g., González 1989; Aliotta and Farinati 1990; Spagnuolo 2005; Giagante et al. 2011; Aliotta et al. 2013, 2014; Calvo-Marcilese et al. 2013). The present-day landscape dynamics was also evaluated in different coastal sections north of the Canal Principal, and major geomorphic processes were inferred from variations in various types of marshes (Pratolongo et al. 2013).

Contrastingly, raised Holocene environments that occupy the gently sloping western margin of the estuary have been less studied. Significant contributions are limited to the geomorphic description of marine terraces of Holocene origin (González-Uriarte 1984), paleontological studies of storm deposits at the inland limits of the marine transgression (Farinati 1983), and soil-vegetation surveys at five scattered locations on the coastal plains (Kruger 1989; Kruger and Peinemann 1996). More recently, plant associations were regionally described and mapped, and further related to geomorphic units and landscape patterns (Piovan 2016; Pratolongo et al. 2016).

The present study provides sedimentological descriptions and radiocarbon dates of two cores obtained on the wide coastal plains of the northwestern margin of the Bahía Blanca Estuary. The aim is to propose a model of coastal landscape evolution for the western margin of the estuary during the mid-to-late Holocene, based on new information from these cores combined with previous results on geomorphic units, landscape patterns, and their associations with major vegetation types in this area.

Study area and vicinity

The coastal landscape of the Bahía Blanca Estuary has been deeply molded by the Holocene marine transgression. Based on several cores from the Argentinean continental shelf, a progressive sea-level rise was described during the late Pleistocene between 9,750 and 8,200 years BP (Guilderson et al. 2000), and further supported by foraminiferal records from a core retrieved on the inner shelf in the coastal region off the Bahía Blanca Estuary (Bernasconi and Cusminsky 2015). On the steeply sloping northern shore of the Canal Principal, the oldest and highest deposits occur in the inner section of the estuary, and form a spit composed of several sand-shell ridges up to 10 m above present sea level (Aliotta and Farinati 1990). González (1989) studied a succession of Holocene beach ridges and tidal flat deposits in this area, corresponding to high- and low-energy depositional periods. Based on ^{14}C dates, González (1989) described at least five beach ridges representing major episodes of high wave energy during the regressive phase after the Holocene transgression maximum. These episodes were named “transgressive stages” I to V, dated at between 5,990 ± 115 and 3,560 ± 100 years BP (uncorrected and uncalibrated measured ages). The term “transgressive stage” was used by González (1989) because each beach ridge appeared in a discordant relationship over older deposits, but not necessarily representing “… transgressions of thermoeustatic, tectonoeustatic or other origin …” (González 1989, p. 69).

In the middle zone of the Canal Principal, Holocene deposits appear about 6 to 7 m above mean sea level, and form relatively continuous sand ridges parallel to the northern shore (Aliotta and Farinati 1990). In this area, two well-marked sand-shell ridges were identified, and a ^{14}C age of 4,615 ± 110 years BP (uncorrected and uncalibrated measured age) was considered to be the upper age limit for the inland ridge. According to Aliotta and Farinati (1990), this ridge indicates the culmination of the transgressive episode, after which a regressive pulse may have occurred. The second (seaward)

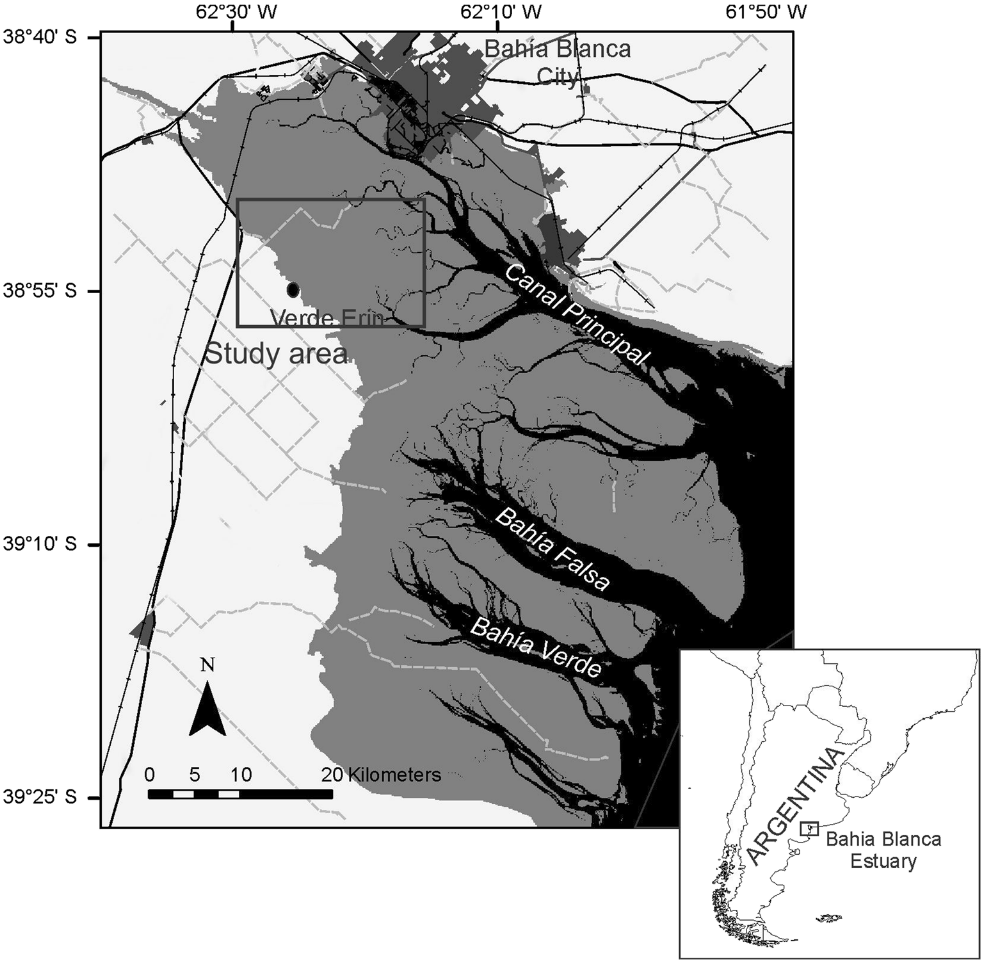


Fig. 1 Geographic location of the study area within the Bahía Blanca Estuary

ridge, at lower elevation, was assigned to "… a new transgressive pulse (that) produced some shelf abrasion, where ridge II stands discordantly …" (Aliotta and Farinati 1990, p. 359). Under a falling sea level during the regressive stage in the late Holocene, extensive coastal flats prograded seaward from the second ridge. Their radiocarbon ages range between 3,300 and 3,900 ^{14}C years BP (uncorrected and uncalibrated measured age), determined from fossils in life position (Farinati et al. 1992).

Sea-level oscillations have also affected the hydrological, morphological and sedimentary characteristics of old fluvial environments in the Bahía Blanca Estuary, as indicated by, for example, palynological and sedimentological data from river terraces in the continental area north of the estuary (Quattrocchio et al. 2008). Calvo-Marcilese et al. (2013) studied paleoenvironmental conditions during the beginning of the Holocene transgression based on sedimentological and micropaleontological analyses of samples from the mouth of the Napostá Grande River, debouching in the middle section of the Canal Principal. Those authors identified three estuarine paleoenvironmental stages: an estuarine environment with stronger marine influence at the base of the sequence, followed upward by massive silty-clays and sandy silty-clays with microfossil assemblages suggesting more restricted estuarine conditions with higher freshwater input. Finally, the upper part of the succession represents the establishment of modern continental freshwater conditions for the river.

Fluvial events as well as paleochannel structures were described along the Canal Principal (Spagnuolo 2005; Giagante et al. 2008, 2011) and the continental shelf (Aliotta et al. 1999) by means of seismostratigraphic analyses. In the middle section of the Canal Principal, Giagante et al. (2011) studied a sub-bottom sedimentary deposit related to an ancient mouth of a river forming an ample alluvial cone or fan-like plain during the mid-to-late Pleistocene under a semiarid to arid climate (Quattrocchio et al. 2008). The beginning of sea-level rise during the Holocene changed the base level of the hydric system, and the coastal front migrated to the continent, partially burying the alluvial sequence with marine and tidal plain sediments. Similarly, Aliotta et al. (2014) described a fluvial–deltaic environment associated with old deposits of deltaic lobes that were part of a large Pleistocene drainage system. According to those authors, during the mid-Holocene sea-level rise the deltaic deposits were partially covered with medium sand and biogenic detritus, as well as compacted silty clay sediments in shallower zones. The advance of marine sediments as well as the reworking and redistribution of fluvial–estuarine sediments filled the paleochannels, until the establishment of a large estuarine–marine environment characterized by numerous tidal channels separated by emerged sectors forming the present-day banks and islands.

In the present study area, the northwestern margin of the Bahía Blanca Estuary has a gentler slope. Nevertheless, at least two marine terraces of different elevations can be distinguished (Fig. 2), which would correspond to different stages during the regressive phase (González-Uriarte 1984). According to Kruger (1989), an old marine plain that may have formed between 7,500 and 6,000 years BP extends at a higher elevation, and a Recent marine plain with a slightly convex relief and elongated depressions extends slightly above the present tidal influence. Below this elevation, Kruger and Peinemann (1996) described an upper intertidal zone today affected by tides during storm surges. In Verde Erin, Farinati (1983) described a shelly ridge at the base of a paleo-cliff that would correspond to storm deposits indicating the inland limit of the marine transgression at a ^{14}C age of 5,406 ± 227 years BP (uncorrected and uncalibrated measured ages). Unfortunately, most of the studies cited above do not specify their choice of vertical datum, and have not considered that dates corresponding to radiocarbon measured ages may present uncertainties due to isotopic fractionation or reservoir effects.

Based on the geomorphic map by González-Uriarte (1984) and surface elevation profiles constructed from sample points collected during the years 2013 and 2014 with real time kinematic (RTK) GPS units, Piovan (2016) identified five major landscape units in the present study area. Landscape units reflect dominant geomorphological processes associated with the marine transgression (Fig. 2a). The raised Holocene deposits in the coastal zone north of the Canal Principal outline the base of a frontal scarp. South of the scarp is a narrow depression containing an elongated salt flat locally known as *Salitral de la Vidriera*. On the coastal plain extending along the western margin of the estuary south of the Canal Principal, two successive levels were identified (Fig. 2b). The old marine plain (OMP), at an average elevation of 5 m above MTL, is an elevated and nearly continuous flat surface. The Recent marine plain (RMP), 2 to 3 m above MTL, is a mosaic of topographic highs and elongated depressions that may correspond to former tidal channels. From this latter unit, the gentle slope creates a gradual transition to the present marine plain (PMP) comprising active tidal channels, mudflats and salt marshes affected by modern estuarine dynamics. Remains of a highly dissected RMP typically form small elevated islands within the PMP, which are today exposed to rapid erosion (Piovan 2016; Pratolongo et al. 2016).

Considering hydrological characteristics, the study area can be broadly classified into intertidal and supratidal environments. An intertidal zone extends from the mean low tide (MLT) to the mean high tide (MHT) elevation, and corresponds to the area frequently inundated by tides entirely within the PMP. In the RMP, a supralittoral zone can be defined in an intermediate position, above the elevation of MHT and below the limits of the highest astronomical tide (HAT). Supralittoral environments are irregularly inundated by sea water during spring high tides and storm surges. Within the RMP, these supralittoral environments form a gently sloping continuum through supratidal environments, beyond the influence of tidal inundation. The RMP is dissected by narrow depressions that may correspond to former tidal channels, presently draining rain water. The OMP is entirely occupied by supratidal environments, not affected by tidal flooding (Pratolongo et al. 2016).

Piovan (2016) identified seven plant associations for the study area based on a field survey of 230 sites carried out from 2012 to 2014. A vegetation map was constructed by on-screen digitalization of major plant associations identified in recent (2010–2015) high-resolution satellite images (Pratolongo et al. 2016). A clear relationship was observed between plant associations and their landscape position (Fig. 3). Thickets of *Allenrolfea patagonica* appeared as a continuous fringe at the base of the scarp, at the inland limits of the OMP. *A. patagonica* was the clearly dominant species, commonly in association with less-abundant *Cyclolepis genistoides* and *Atriplex undulata*. Bushes of *Cyclolepis genistoides*, a different woody association, occupied a wide continuous area downslope. *C. genistoides* was the dominant species here, and *A. undulata* was the most common species in the underbrush, completely replacing *A. patagonica*. *Sarcocornia perennis* was also present with lower percent cover. The brushwood of *Geoffroea decorticans* was the last plant association identified in the OMP.

In the RMP, thickets of *A. patagonica* and bushes of *C. genistoides* appeared as discontinuous mosaics occupying supratidal topographic highs, and were jointly mapped as halophytic shrubs. In the supralittoral zone, irregularly inundated by tides, halophytic steppes were the dominant land cover type, characterized by large barren areas between vegetation patches. Barren areas lengthen close to the limits of the HAT, and soils develop bright salt crusts. At some locations, barren areas are large enough to be mapped as salt flats. *S. perennis*, *Heterostachys ritteriana*, and *A. undulata* are common dominant species in halophytic steppes but, as tidal inundation increases, the number of species within vegetation patches decreases, in a gradual downslope transition to *S. perennis* marshes in the PMP. Close to the elevation of the MHT in the upper intertidal zone, marshes of *S. perennis* maintain the same patchy structure, sometimes in association with *H. ritteriana* and *Spartina densiflora*. Salt marshes of *Spartina alterniflora* appear at lower elevations in protected environments subjected to high sedimentation rates, but most of the intertidal zone is covered by non-vegetated mudflats (Pratolongo et al. 2016).

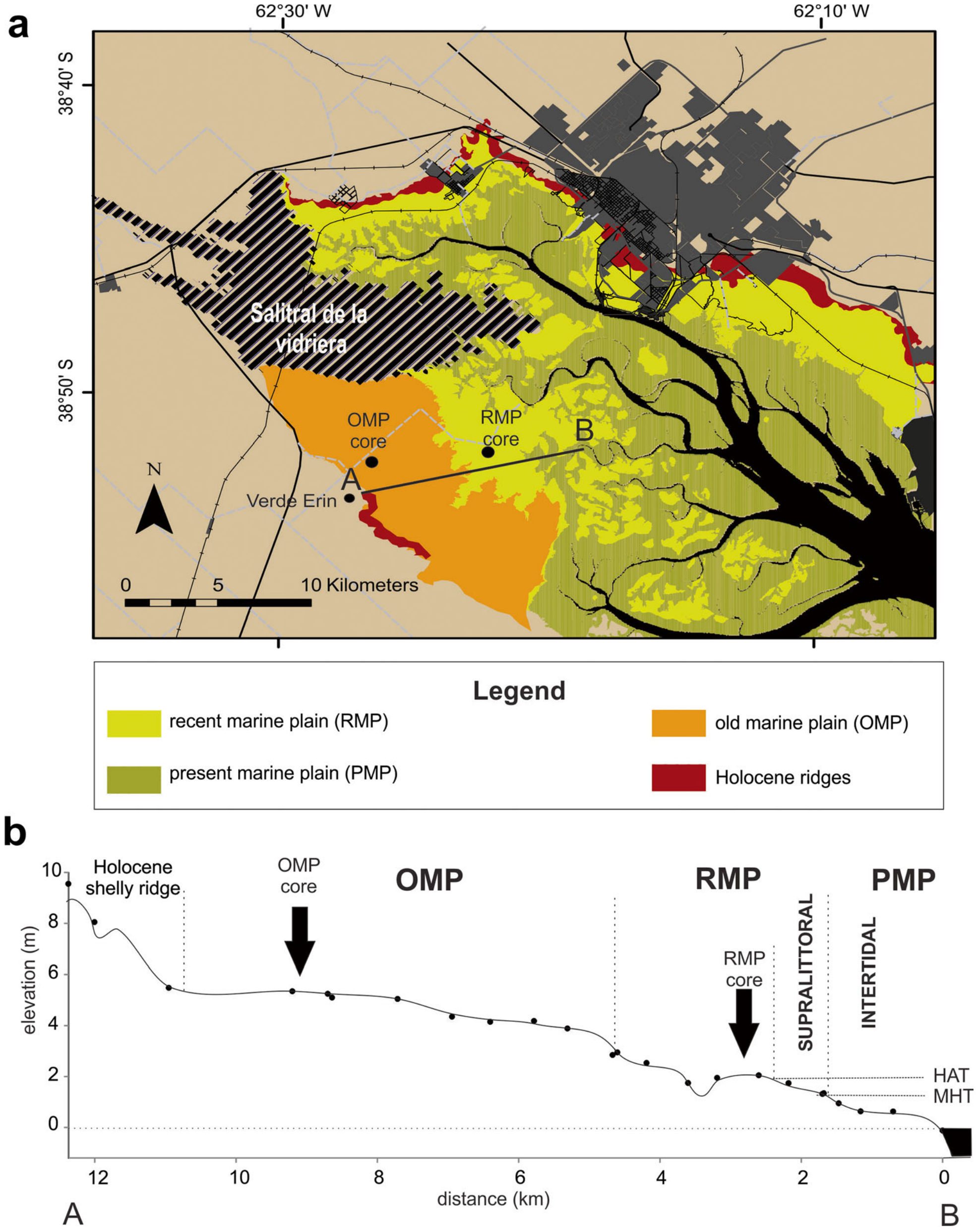


Fig. 2 **a** Landscape units identified in the study area. **b** Schematic profile showing the relative vertical positions of the old marine plain (OMP), Recent marine plain (RMP), and present marine plain (PMP). Tidal datums are mean high tide (MHT) and highest astronomical tide (HAT). Elevations are referred to the present mean tide level (MTL) at the closest tidal gauge (Ingeniero White Port). Redrawn from Fig. 10.3 in Pratolongo et al. (2016)

Materials and methods

Two sediment cores (530 and 310 cm depth) were recovered in May 2015 using a vibracore (cf. Table 1). Real time kinematic (RTK) GPS units (base and rover) were used to determine site position and surface elevation at both sampling points. Measured GPS elevations were relative to datum WGS84, and values were related afterwards to present mean tide level (MTL) at the closest tidal gauge (Ingeniero White Port). Core depths were corrected according to sediment compaction during collection by multiplying the depth measured along the core by a correction factor (= total borehole depth/total core length). Site stratigraphy was described based on sediment color and textural changes throughout the cores.

Radiocarbon measurements were conducted on mollusk shells and bulk organic matter from varying depths down the cores, using accelerator mass spectrometry (AMS) at Beta Analytic Lab. Regarding the regional difference in Holocene ^{14}C reservoir (ΔR), Gómez et al. (2008) showed that shells collected along the Buenos Aires coast had highly variable ΔR values, caused by the mixture of hard water from rivers and groundwater. Therefore, the present study mainly considers uncalibrated radiocarbon ages corrected for isotopic fractionation using δ^{13}C values. Also reported are calibrated radiocarbon ages (cal BP) converted using INTCAL13. Maximum and minimum values are calibrated ages within 2σ uncertainty before present (1950 C.E.; Table 1).

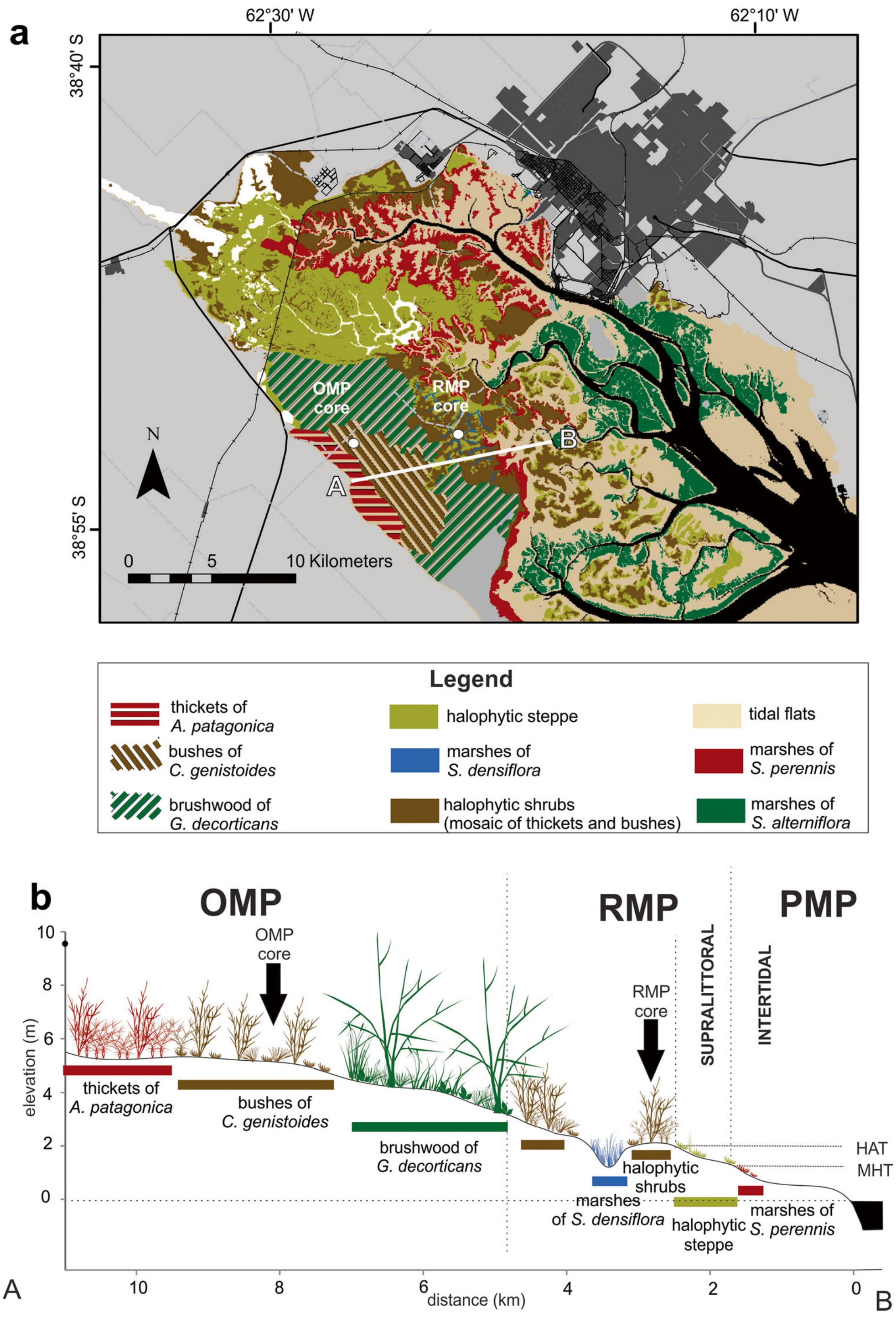


Fig. 3 **a** Map showing the major plant associations identified by Piovan (2016). **b** Schematic profile showing the relative vertical positions of the different vegetation types. *Black arrows* Positions at which the sediment cores were extracted. Tidal datums are mean high tide (MHT) and highest astronomical tide (HAT). Elevations are referred to the present mean tide level (MTL) at the closest tidal gauge (Ingeniero White Port). Based on Fig. 10.4 in Pratolongo et al. (2016)

Results

The OMP core (Fig. 4) was collected in an area covered by bushes of *Cyclolepis genistoides*. Here, surface elevation was 5.09 m above MTL, and the core extended to a depth of 530 cm (base of core at 0.21 m below MTL). The base of the core was dominated by fine sands and silts, fining upward to thinly laminated deposits up to a depth of 288 cm (2.21 m above MTL).

Specimens of *Olivella tehuelcha* and *Nucula nucleus* (marine subtidal to intertidal gastropods) were dated 5,660 ± 30 and 5,470 ± 30 years BP (cal 6,165–5,980 and cal 5,905–5,760 years BP, respectively) at elevations of 0.12 and 0.26 m above MTL, respectively. The top of the laminated section, from 288 to 330 cm below surface (elevations between 1.79 and 2.21 m above MTL), is composed of a tight sequence of dark laminated muds. This fossiliferous layer

Table 1 Sample characteristics and radiocarbon dates for material extracted from cores OMP and RMP

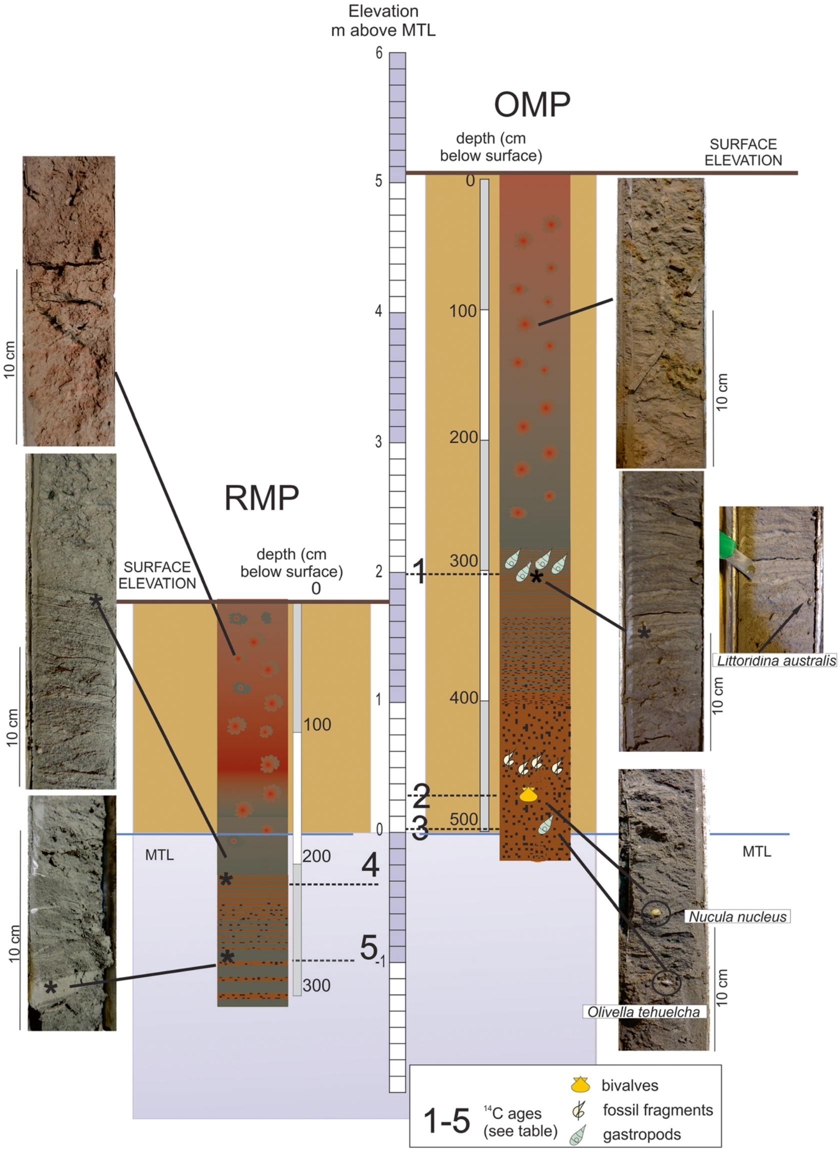
Sample number	Depth (cm)	Elevation (m above MTL)	Number (Beta)	Material–pretreatment	Measured age (years BP)	δ^{13}C (‰)	Conventional age (years BP)	2σ calibration (cal BP)
OMP core: 38°52′12.61″S, 62°26′55.17″; site elevation: 5.09 m above MTL								
1	310	1.99	415058	Organic-rich sediment (reworked)–acid washes	7,530 ± 30	–21.1	7,590 ± 30	8,405 to 8340
2	483	0.26	415057	Gastropod–acid etch	5,030 ± 30	+2.0	5,470 ± 30	5,905 to 5,760
3	497	0.12	415056	Gastropod–acid etch	5,230 ± 30	+1.4	5,660 ± 30	6,165 to 5,980
RMP core: 38°51′38.71″, 62°22′30.46″; site elevation: 1.80 m above MTL								
4	214	–0.34	415055	Organic-rich sediment–acid washes	4,640 ± 30	–20.5	4,710 ± 30	5,570 to 5,560; 5,470 to 5315
5	271	–1.09	415054	Organic-rich sediment–acid washes	6,090 ± 30	–20.1	6,170 ± 30	7,155 to 6,935

Sample numbers correspond to sample positions 1 to 5 in Fig. 4

contains abundant shells of *Littoridina australis* (brackish subtidal to supratidal gastropod), and bulk organic matter was dated 7,590 ± 30 years BP (cal 8,405–8,340 years BP).

This layer is topped by a 3 m thick layer of massive gray muds, rich in large clumps of reddish-brown organic detritus.

Fig. 4 Characteristics and vertical position of cores RMP and OMP relative to current mean tidal level (m above MTL). Depth related to the ground surface (cm) is also shown for each core. Positions of dated material and photographs representative of the different sections of the cores are included



The RMP core was retrieved on a bare salt flat between patches of halophytic steppe vegetation. Surface elevation was 1.80 m above MTL, and the core extended to a depth of 310 cm (base of core at 1.30 m below MTL). The sedimentary sequence of the RMP core is similar to that of the OMP core, with laminated sediments topped by massive grayish muds, but the unconformities occur at lower elevations (Fig. 5). Fine sands at the base intergrade with silty-clay layers up to 1 cm thick. Bulk organic matter from a thick cohesive layer at the base of the core (271 cm depth) was dated 6,170 ± 30 years BP (cal 7,155–6,935 years BP).

Upward, the lamination becomes finer and extends up to a depth of 211 cm (0.31 m below MTL), where a sharp discontinuity separates laminated sediments from the overlying massive muds. Bulk organic matter from the top laminated layers (0.35 m below MTL) was dated 4,710 ± 30 years BP (cal 5,570–5,560 and cal 5,470–5,315 years BP). An overlaying layer, about 2 m thick, extends up to the surface. This top layer is composed of massive gray and reddish muds rich in large clumps of reddish-brown organic detritus, similar to those observed in the top layer of core OMP. Slight variations in matrix shading and texture were observed through the layer, with a highly cohesive and more reddish section around 134 cm depth.

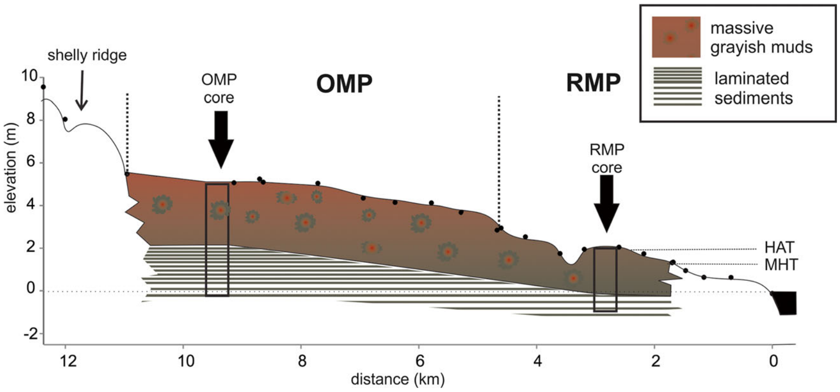
Discussion

In this study, well-preserved mollusks at the base of core OMP (530 cm deep), with ages between 5,660 ± 30 and 5,470 ± 30 years BP, indicate a subtidal elevation close in time to the Holocene transgressive maximum, at a landscape position near the inland limits of the marine ingression. The shelly ridge described by Farinati (1983) in Verde Erin corresponds to storm deposits indicating the inland limit of the marine transgression, and the OMP core was collected about 1,300 m eastward from the base of this shelly ridge. According to the elevation profile, these storm deposits formed at 6–7 m above present MTL and 1–2 m above the core surface, which is in agreement with a subtidal elevation slightly above present MTL by the time of the transgressive peak. The sandy bottom of the core is therefore interpreted as the last stage of the transgressive phase, followed by a lower-energy period during which the estuarine system became progressively infilled, as suggested by the thinner laminated sediments containing abundant shells of a brackish gastropod species. The overlying massive muds would then correspond to rapid sedimentation during a high sea-level stillstand or slow regression.

A similar evolution was described for a series of creeks crossing the southern barrier of Buenos Aires (Isla et al. 1996), which extends in the coastal region west of the Bahía Blanca Estuary from Pehuen Co (out of the Bahía Blanca Estuary) to Punta Hermengo (Miramar). For these inlets, infill estuarine sequences were described with massive, grayish organic-rich muds. Grayish muds of the southern barrier form flat plains in coastal lagoons or estuaries, rapidly filled during the Holocene transgression. In these estuaries, a significant supply of mud became hydrodynamically blocked by the rising sea level, and the massive muds may represent environments with a rapid sedimentation rate: “The massive muds of Arroyo Las Brusquitas, Punta Hermengo, Arroyo La Ballenera and Claromeco represent environments of rapid sedimentation rate, suggesting the turbidity maxima cited for estuarine depositional models” (Isla et al. 1996, p. 839). A more recent paleoenvironmental reconstruction in Arroyo Las Brusquitas, based on foraminifera, ostracod and charophyte assemblages, also suggested a high sedimentation rate in an oligohaline environment until the end of the transgressive phase (Marquez et al. 2016).

In the OMP core, the bulk organic matter in the laminated sediments was dated 7,590 ± 30 years BP, which is inconsistent with the younger ages observed in mollusks from the deeper layers. For the study area, previously observed discrepancies in radiocarbon ages between gastropod shells and organic matter have been interpreted as a regional reservoir effect (Borel and Gómez 2006). Marine organisms that assimilate carbon from seawater may have an older apparent

Fig. 5 Schematic cross-section of the study area showing the landscape position of cores OMP and RMP relative to the shelly ridge that indicates the inland limit of the marine ingression. In both units, a layer of massive grayish muds overlies laminated sediments



radiocarbon age than contemporaneous organisms that assimilate carbon from the atmosphere. The effect varies among regions, and aging in mollusk shells may be incremented by the presence of dissolved carbonates of terrestrial origin (Gómez et al. 2008). In the present work, however, dating of mollusk shells yielded an age younger than the overlaying organic matter, which is the opposite of the bias expected from reservoir effects. A similar pattern was found in a sediment core from the Bahia San Blas estuarine complex 200 km south of the study area (Espinosa and Isla 2011), and the older organic matter in that sequence was interpreted as "reworked (organic matter) from the marshes surrounding the estuarine complex. Lateral migration of the channel and consequent erosion of levees may produce concentrations of peat (*gyttja*) in the sequence" (Espinosa and Isla 2011, p. 418).

In the Bahía Blanca Estuary, González-Uriarte (1984) described a paleodrainage that occupied the aligned depressions Salitral de la Vidriera–Canal Principal, which brought sediments to the region within a deltaic environment. Based on geomorphic evidence, Melo (2004) also suggested that rivers introduced large amounts of fine sediments (mostly loessic pampean silts) to the estuarine area during the early Holocene, via older topographic depressions like the Salitral de la Vidriera–Canal Principal. According to Aguirre (1995), a sharp change in climate occurred in the study area around 7,000 years BP, establishing a period of warmer and more humid conditions before the transgressive maximum. Additional evidence of a humid climate during the transgressive phase was found in the coastal zone extending up to 100 km west of Bahía Blanca. In this area, continental lakes recorded a rise in water levels and higher abundances of freshwater diatoms, fishes, and vascular plants about 7,100 years BP (Gutiérrez-Téllez and Schillizzi 2002; Aramayo et al. 2002). Moreover, palynological assemblages dated at 7,125 ± 75 and 7,030 ± 100 years BP reflect locally humid conditions, and a RSL still lower than present (Quattrocchio et al. 2008). Similar descriptions were given by Pardiñas (2014) based on micromammal records. Humid environmental conditions may have continued until about 5,000 years BP when the establishment of psammophytic and halophytic communities indicates a climatic change toward subhumid–dry conditions (Prieto 1996).

Combining the available paleoclimatic information with results presented in this work, it is proposed that a significant amount of mud supplied by continental runoff via the paleodrainage aligned with the Salitral de la Vidriera–Canal Principal was reworked at the end of the transgressive phase. Enhanced sedimentation under low-energy conditions may have filled the estuarine area, and deposited the top massive mud layer observed in both cores. This model is in agreement with fluvial paleochannel structures described along the Canal Principal (Spagnuolo 2005; Giagante et al. 2008, 2011), and particularly with the fluvial–deltaic environment described by Aliotta et al. (2014) just in front of the study area, which would represent the distal section of a deltaic lobe of the large drainage system occupying the aligned Salitral de la Vidriera–Canal Principal during the late Pleistocene to early Holocene. According to those authors, "… The constructed seismostratigraphic column shows variations in the paleoenvironmental conditions occurring between the late-Pleistocene and the early-Holocene (…) which were consistent with a period of reactivation and redistribution of the drainage system (and) during which paleochannel structures with different seismic configurations formed …" (Aliotta et al. 2014, p. 659).

Sediments in the mud layer in the OMP core were deposited after the Holocene transgressive maximum, as evidenced by radiocarbon ages of mollusks found deeper, but it is proposed that they are enriched in aged organic matter inherited from the fluvial past described for the study area (Melo 2004; Giagante et al. 2008; Aliotta et al. 2014). Fluvial–deltaic paleoenvironments have also been found in other inner and outer areas of the estuary (Aliotta et al. 1999; Spalletti and Isla 2003; Spagnuolo 2005; Giagante et al. 2011), indicating a regional extension of the fluvial influence. The slightly lower (more negative) $\delta^{13}C$ values reported for this aged organic matter are in agreement with a higher degree of continental influence, larger influx of organic matter from terrestrial sources, and lower salinity values (see Yu et al. 2010; Khan et al. 2015, and references therein to values observed worldwide).

Plant associations in the study area were shown to be reliable indicators of the dominant hydro-geomorphic conditions imposed by landscape position (Pratolongo et al. 2013, 2016). Thus, the distinction between an OMP and a RMP (González-Uriarte 1984; Kruger 1989; Kruger and Peinemann 1996) is further supported by (1) the stepped elevation profile across units, (2) the clearly different landscape patterns, with a continuous and elevated OMP and a lower and contrastingly dissected RMP, in which topographic highs and old tidal channels can be clearly differentiated, and (3) the sharp distinction between plant associations that cover both units. Based on these lines of evidence, it is proposed that the RMP formed at a later stage during the regressive phase, under a lower RSL. The thickness of the grayish mud layer is a major difference between the OMP and RMP cores, but deeper layers had similar ages, suggesting a common origin at the end of the transgressive phase. Deposition of the massive muds is proposed to have occurred in an estuarine environment under high sea-level stillstand conditions, whereby the thickness of the mud deposits decreases through the distal zone (in the direction of the delta lobe limits described by Aliotta et al. 2014). It is also proposed that, at a later stage after a rapid sea-level drop to about 3 m above MTL (the approximate highest elevation of the RMP), a flat and continuous surface corresponding to the OMP emerged, and more recent coastal dynamics shaped the dissected landscape pattern of the RMP. The old tidal channels presently occupied by *Spartina densiflora* marshes formed during this later stage, after tidal working dissected the older surface of mud deposits.

Conversely, there is no well-defined boundary between the RMP and the PMP, but a gradual transition reflecting an increasing tidal influence. Both units share similar landscape patterns and plant associations, suggesting a common formation under similar environmental conditions during the later regressive phase after the OMP emerged. A recent rising trend in relative sea level (rate of 1.6 mm/year) was estimated by Lanfredi et al. (1988) based on tidal records obtained in Puerto Quequén, 290 km northeast of Bahía Blanca. The differentiation between the RMP and PMP is then interpreted as a response to the more recent tidal influence over the RMP environments. This is in agreement with the observed erosion of *Sarcocornia perennis* marshes occupying RMP surfaces, due to increasing tidal inundation (Pratolongo et al. 2013).

For the Bahía Blanca Estuary, the evolution of RSL after the Holocene highstand has been a controversial topic. Smooth regressive trends have been proposed (e.g., Spagnuolo 2005; Aliotta et al. 2013), but also stepped curves characterized by several episodes with exceptionally high tide levels and wave energy, which built beach ridges on the northern shore of the Canal Principal (e.g., González 1989; Aliotta and Farinati 1990). A stillstand or slowly dropping sea level was described around 3,850 ± 100 years BP (González 1989). The development of extensive coastal flats (radiocarbon ages between 3,300 and 3,900 years BP; Farinati et al. 1992), today located above the spring tide level and subjected to erosion (Pratolongo et al. 2013), would correspond to this stillstand. Finally, Gómez et al. (2005) proposed that negative RSL oscillations occurred ca. 7,300, 5,800, and 2,500 cal years BP, in phase with variations in Holocene solar irradiance.

The evidence showed in this work supports the occurrence of a stepped regressive trend that, at least locally, presented two different stages enabling the formation of the OMP and RMP. A non-uniform regressive trend was also proposed by Cavallotto et al. (2004) for the Río de la Plata Estuary, with a first RSL fall of 1 m between 6,000 and 5,000 years BP. A stable period occurred between 5,000 and 3,500 years BP, and a rapid sea-level drop during the following 600 years. The final regressive phase was associated with a continuous and slow RSL fall to the present-day level. Similarly, a stepped regression was described for the Patagonian coast (Schellmann and Radtke 2010), comprising a RSL maximum at about 6,200–6,900 years BP (ca. 6,600–7,400 cal BP) followed by a generally declining trend, with two longer periods of stable RSL about 6,200–6,900 years BP (ca. 6,600–7,400 cal BP) and about 2,600–6,000 years BP (ca. 2,300–6,400 cal BP). During the first period, with a RSL close to its maximum level, beach ridge systems, littoral and valley-mouth terraces were formed. Two sea-level falls at 6,200–6,000 years BP (ca. 6,600–6,400 cal BP) and 2,600–2,400 years BP (ca. 2,300–2,050 cal BP) were inferred from the successively lower elevations of coastal forms that developed during the stable periods afterward.

Evidence for sea-level oscillations during the mid-to-late Holocene has been also presented from the southern sector of the African continent and Australia. Along the southern coast of Namibia, Compton (2006) found that, after a highstand of 3 m above mean sea level (amsl) from 7,300 to 6,500 cal years BP), the "sea level fell to near or 1 m below its present-day position between 6500 and 4900 cal yr BP (after which) sea level rose to 1 m amsl between 4800 and 4600 cal yr BP and then fell briefly between 4600 and 4200 cal yr BP before returning to 1 m amsl. Since 4200 cal yr BP sea level has remained within one meter of the present-day" (Compton 2006, p. 303). Lewis et al. (2008), in a reanalysis of sea-level data from eastern Australia, found that a sea-level highstand of 1 to 1.5 m above present occurred about 7,000 cal years BP and fell to its present position after 2,000 years BP. During this period of high sea level, they described two "short-lived oscillations in sea-level of up to 1 m during two intervals, beginning c. 4800 and 3000 cal yr BP. The rates of sea-level rise and fall (1–2 mm yr) during these centennial-scale oscillations are comparable with current rates of sea-level rise" (Lewis et al. 2008, p. 74). According to those authors, this curve contrasts with the smoothly falling hydro-isostatic sea-level model for the eastern Australian coastline, and they proposed that "the origin of the oscillations is (…) most likely the result of oceanographic and climatic changes, including wind strengths, ice ablation, and melt-water contributions of both Greenland and Antarctic ice sheets" (Lewis et al. 2008, p. 78). Finally, Sloss et al. (2007) combined previously published and new data to provide a revised Holocene sea-level curve for the southeast coast of Australia. In that overview, the late Holocene oscillating or stepped model proposed by Baker et al. (2001) was considered, and radiocarbon dates were calibrated to sidereal years. After calibration, a redrawn oscillating sea-level model was presented, and the authors concluded that "a series of minor negative and positive oscillations in relative sea level during the mid to late Holocene are superimposed over the Holocene sea-level highstand" (Sloss et al. 2007, p. 1012).

Sea-level oscillations during the mid-to-late Holocene are not in agreement with GIA model predictions. Sloss et al. (2007) proposed that minor oscillations would be related to local changes in wave climate and tidal range throughout the Holocene. Schellmann and Radtke (2010), on the other hand, concluded that there is evidence for two or more sea-level oscillations during the mid-to-late Holocene along the Atlantic coast of South America, southern Africa, and Australia, and that the consistent timing of these oscillations suggests that they would be driven by eustatic changes of ocean volume, as well as thermosteric and gravitational changes. Further work on Holocene deposits along the western margin of the Bahía Blanca Estuary, which represent a different depositional environment than the well-studied ridges on the northern shore of the Canal Principal, may contribute valuable information to better understand Holocene sea-level changes in the South Atlantic.

Conclusions

In this work, sedimentological descriptions and radiocarbon dates were presented for two cores obtained on the wide coastal plains along the northwestern margin of the Bahía Blanca Estuary. Based on results from these cores and previous studies carried out in the study area, it is concluded that:

1. In the unit identified as OMP near the inland limits of the area affected by the marine ingression, sandy sediments deposited in a subtidal environment, about 5 m down the present surface elevation at about 5,660 years BP. This is in agreement with a subtidal elevation slightly above the present MTL by the time of the transgressive peak.
2. The sandy bottom of the OMP core was deposited during the last stage of the transgressive phase, followed by a lower-energy period during which the estuarine system became progressively infilled. The area today occupied by the OMP and RMP is interpreted as a Holocene estuarine environment receiving significant amounts of fine sediments of continental origin through the aligned Salitral de la Vidriera–Canal Principal. The overlying layer of massive muds in both cores corresponds to rapid sedimentation during a high sea-level stillstand or slow regression. This is in agreement with other studies in the area describing paleochannels and fluvial–deltaic deposits aligned with the Salitral de la Vidriera–Canal Principal depression, and corresponds to similar infilling sequences described in Holocene estuarine environments of creeks crossing the southern barrier of Buenos Aires.
3. Considering previous studies in the area, the distinction between an OMP and a RMP is further supported by the stepped elevation profile across units, the clearly different landscape patterns, and the sharp distinction between plant associations. It is proposed that the OMP and RMP had a common origin at the end of the transgressive phase. Deposition of the massive muds is proposed to have occurred in an estuarine environment under high sea-level stillstand conditions and, in a later stage after a rapid sea-level drop to about 3 m above MTL, a flat and continuous surface corresponding to the OMP emerged, and more recent coastal dynamics shaped the dissected landscape pattern of the RMP.
4. These conclusions support the occurrence of a stepped sea-level regressive trend after the transgressive maximum. At least two distinct stages can be identified, as suggested by the differentiation between the OMP and the RMP. This is consistent with earlier reports of a non-uniform regressive trend for the Río de la Plata Estuary and the Patagonian coast.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest with third parties.

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