Marine Geology 240 (2007) 43 – 56
MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS
www.elsevier.com/locate/margeo

Mid-Holocene evolution and paleoenvironments of the shoreface–offshore transition, north-eastern Argentina: New evidence based on benthic microfauna

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Received 23 September 2006; received in revised form 17 January 2007; accepted 1 February 2007

Abstract

A sedimentary record spanning 5792–5511 cal yr BP and 3188–2854 cal yr BP was recovered at 36° 45′ 43″ S–56 ° 37′ 13″ W, south-west South Atlantic. The sedimentological features and micropaleontological (benthic foraminifera and ostracoda) content were analyzed in order to reconstruct paleoenvironmental conditions. Considerable environmental fluctuations are indicated by all these proxies. Five different stages were distinguished: Stage 1 (ca. 5800–5000 cal yr BP) consists of muddy sand with abundant microfossils. In this interval, species typical for inner marine shelf environments maintained a high abundance. Stage 2 consists of plastic light greenish grey clays barren of microfossils, and probably represents fluvial input from the de la Plata River to the shelf contemporaneous of a lowering of sea level. Stage 3 is composed of brownish yellow sandy silts, and represents increasing marine conditions in the area as reflected by higher faunal diversity and typical foraminifera of inner shelf environments. Stage 4 is made of homogeneous mud, barren of microfossil, which represents a new pulse of fluvial input to the shelf in consequence of a new fall in sea level. The final part of the core (Stage 5) is a coarsening upward sequence, grading from greeny brown clayey sandy silts to coarse shelly sands and represents the modern sedimentation in the area. This interpretation strengthens the stepped model of late-Holocene sea-level fall between 5511–5792 cal yr BP and 2854–3188 cal yr BP in Buenos Aires coast, and agrees with the relative sea-level history previously proposed by some authors from western South Atlantic coasts.

Keywords: benthic foraminifera; ostracoda; SW South Atlantic; Argentina; mid-Holocene sea-level changes

1. Introduction

The Argentine continental shelf, southern South America, is part of a stable far field margin in which Holocene sea-level fluctuations reflect mainly eustatic

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doi:10.1016/j.margeo.2007.02.001

(meltwater) signals. The northern part of the Argentine inner shelf —adjacent to Buenos Aires province (Fig. 1)— is characterized by a low gradient and smooth relief covered by Holocene deposits. Holocene sea-level reconstructions exist from many locations in South America, but the timing and the nature of the mid-Holocene highstand (MHHS) and the late-Holocene sea-level fall remain unclear due to problems associated with the correct interpretation of sea-level indicators, and with the quality of age determinations (López et al., 2005; Angulo et al., 2006).

With notable exceptions (Boltovskoy, 1954a,b, 1973; Ferrero, 2005), studies of microfossils and their relationship to Holocene sea-level history in northern Argentine shelf are few. Bernasconi and Cusminsky (in press) described the replacement of early Holocene restricted marginal marine assemblages by open shelf assemblages at around 8900 cal yr BP related with the early Holocene sea-level rise. Gómez et al. (2005, 2006) described shallow water faunas related to salt marsh deposits and tidal flats developed around 2720–2365 cal yr BP, indicating a large-scale late sea-level oscillation. This is an interesting finding because Holocene regressive facies are not well represented in the inner shelf, but the paleoenvironmental interpretation is at least debatable.

As a part of an integrated study, the sedimentological features and micropaleontological contents (benthic foraminifera and ostracoda) of a fine-grained sequence contained in a piston core from north-eastern Buenos

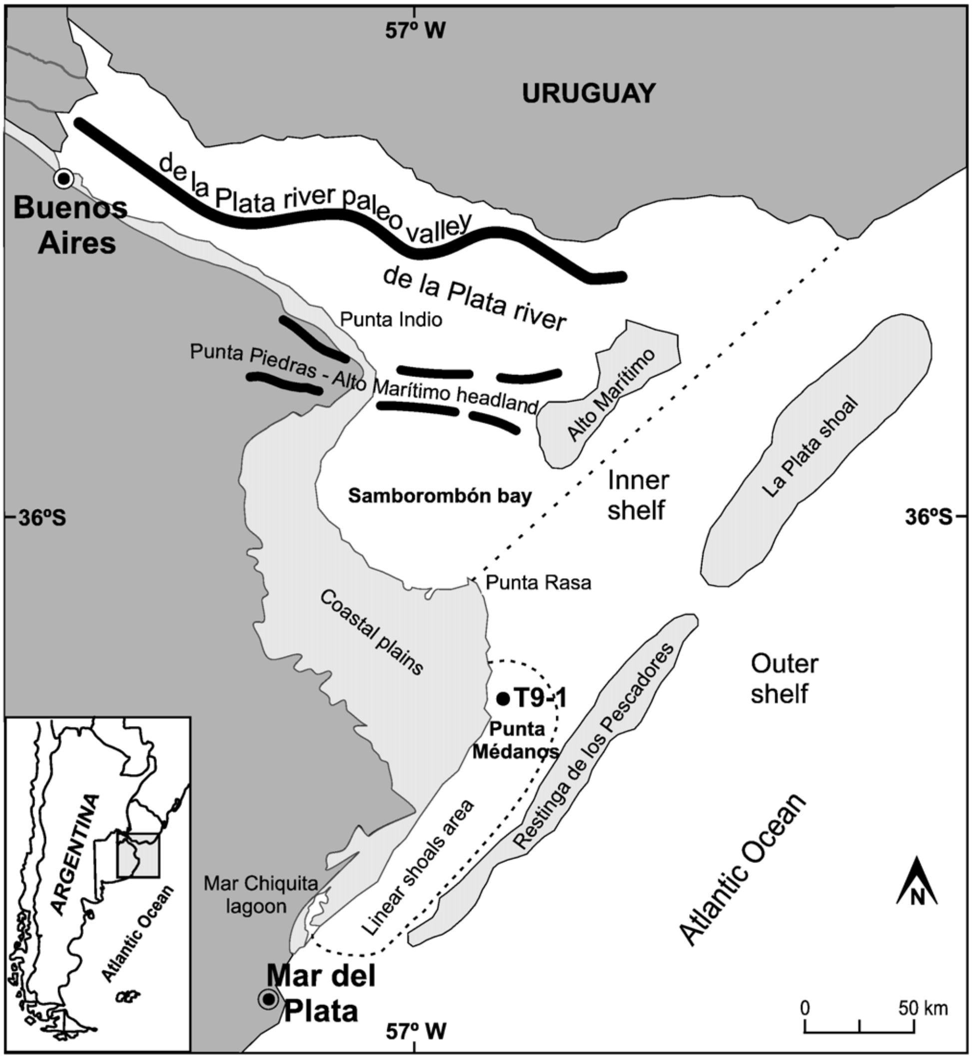

Fig. 1. Location map of the studied area along north-eastern Buenos Aires showing the location of the core T9–1 and predominant physiographic features of the coastal region.

Aires nearshore–offshore transition were analyzed, in order to reconstruct local paleoenvironmental conditions through time, and enabling sea-level reconstructions during the mid–late-Holocene. This research allows to address specific questions:

1. What do benthic foraminifer and ostracod assemblages indicate about the paleoenvironmental conditions of north-eastern Buenos Aires nearshore–offshore transition in the mid Holocene?
2. What depositional environment do the sediments recovered in the core represent? Do they represent transgressive or regressive facies? Were they deposited in back-barrier or in open-marine environment?
3. What, if any, is the pattern of change of the mid–late-Holocene sea-level curve? Was this pattern smooth, stepped or oscillating?

2. Physiographic features and late-Holocene deposits in Buenos Aires north-eastern shelf

The studied area (Fig. 1) is located in the north-eastern Argentine continental shelf (34°–38°S, 54°–59°W), south of the de la Plata River, a large funnel-like water body which flows into the Atlantic Ocean through a very wide mouth. The de la Plata River has played a major role in coastal evolution for its geomorphologic significance and sediment discharge. South of the river mouth extends the inner shelf, which has a very gentle surface.

The coastal region is divided into three predominant physiographic features (Parker and Violante, 1982): (1) the flat, low lying coastal plain constituted by a sea-side sandy-barrier coast that includes beaches and dunes;(2) the shoreface, 2–4 km wide, extended from the shoreline down to 7–10 m water depth (mwd), with a slope gradient of 1%; (3) the inner shelf, extended down to around 30 mwd. In its outer edge, two main submerged features are present: the Restinga de los Pescadores (a Plio-Pleistocene relict bank representing an ancient shoreline); and the La Plata shoal, an offshore sandy ridge formed as a barrier during the coastline retreat in early stages of the post-LGM transgression (Violante et al., 2001). Between Punta Médanos and Mar Chiquita, a field of linear shoals attached to the coast is present (Parker et al., 1978).

Holocene sea-level reconstructions exist from many locations in the Atlantic coast of South America. The Holocene relative sea-level signal is characterised by a mid-Holocene sea-level maximum, or highstand (MHHS). Even when the nature of Holocene sea-level change is broadly similar in all locations, differences exist in the timing and magnitude of the MHHS, and the nature of the late Holocene sea-level fall, i.e., the presence or absence of late-Holocene high-frequency sea-level oscillations. In South America, there are serious problems associated with the correct interpretation of sea-level indicators and their relationship to mean sea level, with the quality of age determinations and also the interpretation of the paleoenvironments from which indicators derived (López et al., 2005; Milne et al., 2005; Angulo et al., 2006).

The late-Holocene deposits of Buenos Aires have been described as constituted by two lithostratigraphic units (Parker, 1979; Parker and Violante, 1982; Violante et al., 2001):

- yellowish brown muddy fine sands (barrier spit facies) and light greenish grey mud (marshes and tidal flats facies) which represent the regressive Holocene phase encompassing the last 6000 yr. This regressive facies was thought to have been formed exclusively in the coastal plain but in south-eastern Buenos Aires, equivalent facies were described in a few places in the shoreface–inner shelf transition (Gómez et al., 2005, 2006).
- medium to fine-grained shelly sands extended on the inner shelf and formed by reworking processes (waves and tidal currents). This unit constitutes an almost continuous sandy sheet that locally forms mantles, bars and linear shoals attached to the coast. It lacks in a few places where Plio-Pleistocene sediments outcrop (Fig. 1), and in topographic depressions between shoals in the lineal shoals area (Parker et al., 1999; Violante and Parker, 2004).

3. Materials and methods

The core T9–1 is a piston core 499 cm long obtained at 36°45′43″S–56°37′13″W, 4 km offshore at a water depth of 12.8 m (Fig. 1) during the "Goyena-Sobral 77" scientific cruise in January, 1977. The core contains silty sand and sandy–silty clay sediments which are poorly represented in the shelf. It was originally interpreted as coastal lagoons and restricted marginal marine sediments deposited prior to the MHHS (Parker and Violante, 1982). Recent research performed by Vilanova et al. (2006) determined that they are actually younger than 6000 yr BP, which implies that sediments have been deposited during the mid–late-Holocene regression. As significant differences existed between these two interpretations, it was considered the convenience of performing detailed micropaleontological and sedimentological analysis in order to solve these questions and to reconstruct local paleoenvironmental changes.

A total of thirty three sediment samples about 2 cm thick were taken from the core for micropaleontological studies. Position of samples in the core is shown in Fig. 2. Each sample was wet sieved through a 75 μm mesh and dried in an oven at about 40 °C. A microsplitter was used to ensure consistency in splitting. Foraminiferal tests were picked until a representative amount of 300 individuals was obtained. Otherwise, all the available tests were picked. Ostracoda were scarce, but they were identified and counted indeed in order to provide additional paleoenvironmental data. Foraminifera and ostracoda were identified to the species level and their abundance was calculated. Identification of species relied mainly upon works by (Boltovskoy, 1954a,b, 1957, 1959; Closs and Barberena, 1960, 1962a,b; Closs, 1962; Boltovskoy and Boltovskoy, 1968; Boltovskoy, 1976; Boltovskoy et al., 1980; Whatley et al., 1987, 1988; Feijó Ramos, 1996; Whatley et al., 1998; Bertels-Psotka and Laprida 1998a,b; Laprida, 1999). The Shannon diversity index $H'(S)$ has been used as a measure of the diversity. Paleoenvironmental interpretation of fossil assemblages was based upon comparison with recent foraminifera and ostracoda distribution described in several studies from the southern South America (Closs and Madeira, 1962; Boltovskoy and Lena, 1966, 1974; Madeira Falcetta, 1974; Boltovskoy, 1976; Madeira Falcetta, 1977; Boltovskoy and Totah, 1985; Whatley et al., 1987, 1988; Boltovskoy and Totah, 1988; Scott et al., 1990; Whatley et al., 1997; Bertels and Martínez, 1997; Whatley et al., 1998; Martínez, in press, 2005).

Four AMS radiocarbon datings were performed by Vilanova et al. (2006) and calibrated in this work to 2 σ using the calibration curve method in the program CALIB 5.0.2 (http://calib.qub.ac.uk/calib/) considering the South Hemisphere calibration dataset (SHcal04, McCormac et al., 2004). Marine reservoir effect was calculated considering the Marine Reservoir Correction Database. The samples consist of well-preserved bivalve shells belonging to *Mactra isabelleana* d'Orbigny. This species inhabits infralitoral environments up to 20 mwd. Shells were theoretically in situ and well preserved. An AMS radiocarbon dating for the base of the core (~439 cm) is 5360±40 ^{14}C BP (Vilanova et al., 2006). When this radiocarbon age is calibrated becomes 5792–5511 cal yr BP. Another AMS radiocarbon dating at ~45 cm is 3287±39 ^{14}C BP (Vilanova et al., 2006). When this radiocarbon age is calibrated becomes 3188–2854 cal yr BP. All these ages must be considered as maximum ages and provide a time control, even when shells had been reworked (Angulo et al., 2006).

4. Results

A total of 71 species belonging to 26 genera of benthic foraminifera and 51 species belonging to ostracoda were identified. Foraminifera included 70 calcareous taxa and only one arenaceous represented by *Textulariella* sp. aff. *T. gramen*. In several samples, over 2000 specimens/100 g of sediment were present (Fig. 2). *Buccella peruviana* is the most abundant and widespread species in the core (59% of the total assemblage; more than 50% of the total population in 19/33 samples; >1000 specimens/100 g in some single samples). *Quinqueloculina seminulum* (more than 15% of the total population in 7/33 samples; 13% of the total assemblage), and *Elphidium discoidale* (more than 10% of the total population in 9/33 samples; 8% of the total assemblage) are well represented as well. *Ammonia beccarii* is a minor component of foraminiferal faunas (<100 individuals/ g in most cases). Other taxa which exceeded 100 specimens/100 g in a single sample are *Discorbis williamsoni*, *Pyrgo ringens*, *Miliolinella subrotunda*, and *Quinqueloculina patagonica*.

Ostracoda are actually scarce, reaching at most 900 individuals/100 g; assemblages are moderately diverse (Fig. 2). Only marine species are present. Dominant taxa are *Papillosacythere parallela*, *Callistocythere litoralensis*, *Hemicytherura escobasensis*, and *Oculocytheropteron macropunctatum*. Some concerns regarding environmental distribution of principal species of foraminifera and ostracoda are made in Table 1.

On the basis of foraminiferal assemblages (defined in terms of presence, species abundance, diversity and dominance) and lithological features, the core was divided into five units (Fig. 2, Table 2).

Unit I (−499 to −449 cm) represents the base of the core and is composed of dark brownish green sandy–silty clays. Foraminifera are well represented and assemblages are moderately diverse. Abundance and diversity tend to decrease upward. Ostracoda are scarce. Macrofauna is dominated by marine bivalves.

Unit II (−449 to −420 cm) is composed of plastic light greenish grey clay. Sand content tends to decrease upward. A sharp lithological boundary separates this unit from Unit I. Foraminifera are very scarce and assemblages show very low density and diversity. Ostracoda and macrofauna are virtually absent.

Unit III (−420 to −219 cm) is composed of brownish yellow sandy silt. A sharp lithological boundary separates this unit from Unit II. Foraminifera are abundant and diverse. Although normal marine species dominate the assemblages, this unit exhibits

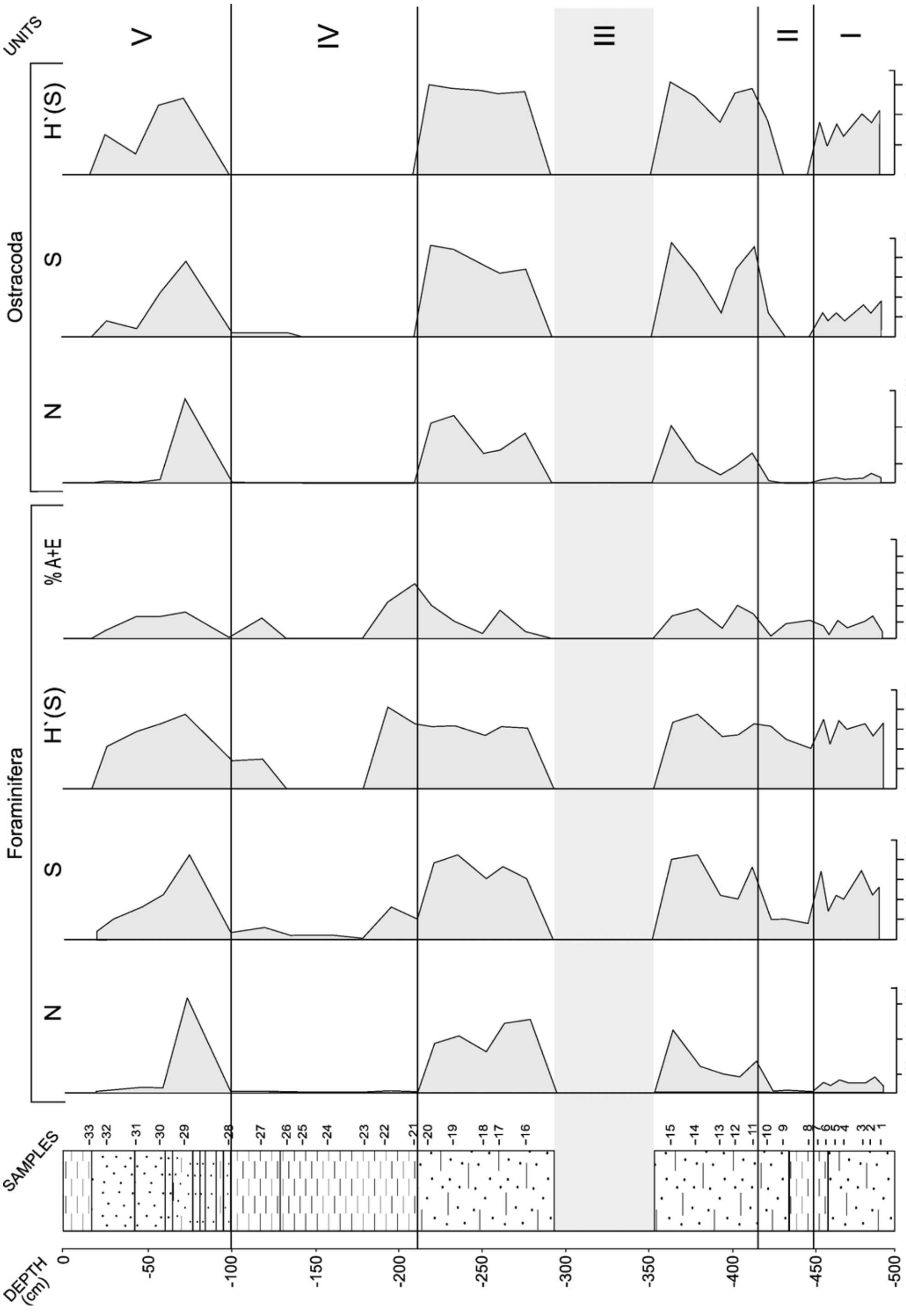

Fig. 2. Sedimentological column, absolute abundance *N* (individuals/100 g), number of species *S*, and Shannon Diversity Index $H'(S)$ of foraminifera and ostracoda. Relative abundance of *Ammonia beccarii* and *Elphidium* spp (% $A+E$) and the lithological and foraminiferal based-units are also indicated. The light grey bar, in the middle of Unit III, represents an empty section on the original sampled core.

the highest content of brackish-water species in the core, representing an average of 13% of the total fauna, and reaching more than 20% in some samples (Fig. 3). Ostracoda are moderately well represented. They are not actually abundant, but they are diverse. To the top, some high-energy-related species occur.

Table 1
Predominant foraminifera and ostracod species in core T9- and their environmental association

Species		Environmental association
Foraminifera	*Buccella peruviana*	The most common and abundant benthic foraminifer in the Argentine inner shelf south of 32–33°S. Small specimens occur in brackish environments. Lowest salinity observed: 30–31‰.
	Ammonia beccarii	Ubiquitous in marginal marine environments. Shallow waters (<30 m) along coasts of the Western Atlantic between 47°N–55°S. It occurs in fine and coarse sediments and tolerates salinities between 1–90‰. In South America, reported along the coasts of Brazil, Uruguay and Argentina, especially in mid-latitude protected bays and inland waters north to 38°S.
	Elphidium discoidale	Inner shelf of the Atlantic coasts of South America north to 41°S. The most common foraminifera for the South Brazilian Subprovince (23°S–33°S), delimiting the North Patagonian Subprovince from the South Patagonian Subprovince. In southern Brazil, it can be also abundant in seaward areas of brackish waters of estuaries and lagoons.
	Elphidium galvestonense, Elphidium gunteri	Marsh environments, together indicate brackish conditions. Dominate in low-salinity lagoons and salt marshes, sharing this dominance with *A. beccarii* which constitutes 30–60% of the total benthic foraminiferal populations.
	Discorbis williamsoni	Inner shelf and brackish waters. Specimens from subantarctic waters rather large and well developed.
	Quinqueloculina seminulum	Cosmopolitan inhabiting the inner shelf, although found in the outer shelf as well. One of the most common species of the Coastal Argentine Waters. In southern South America, also occurs in estuaries and marshes (salinities between 11–30‰). Abundant on the littoral and open beaches.
Ostracoda	*Callistocythere litoralensis, Hemicytherura escobasensis*	Euhaline tidal flats, sometimes associated with *Spartina*.
	Hemicytherura chuiensis, Oculocytheropteron micropunctatum, Oculocytheropteron macropunctatum	Typical nearshore and inner shelf environments; marine and brackish conditions.
	Cytheretta punctata, Cornucoquimba lutziana, Semicytherura rugosoreticulata, Munseyella undulata	Subtidal species indicative of high-energy, wave-dominated marine environments (barriers and open beaches) and high-energy marine estuarine subtidal channels. Empty carapaces and valves usually found in estuary facies.
	Papillosacythere parallela, Neocytherideis ruidis, Frenguellicythere argentinensis	Exclusively tidal flats species in subtidal settings 2–4 mwd.
	Perissocytheridea whitensis, Leptocythere rioplatensis	Brackish-water, restricted-environments species indicating marginal marine, mesohaline environments.

All information from Closs and Madeira, 1962; Boltovskoy and Lena, 1966, 1974; Madeira Falcetta, 1974; Boltovskoy, 1976; Madeira Falcetta, 1977; Boltovskoy and Totah, 1985; Whatley et al., 1987, 1988, 1997, 1998; Boltovskoy and Totah, 1988; Scott et al., 1990; Bertels and Martínez, 1997; Bertels-Psotka and Laprida, 1998b; Martínez, 2005, 2006).

Unit IV (−219 to −99 cm) is lithologically and faunistically similar to Unit 2. Foraminifera are extremely scarce and diversity is low. Several samples are barren of foraminifera. Ostracoda and macrofauna are virtually absent indeed. Foraminiferal tests are usually broken and abraded, and some elphidiids and charophytes typical of brackish environments have been found at the base.

Unit V (0 to −99 cm). A sharp lithological boundary separates this unit from Unit IV. The lower part (99–16 cm) is represented by a coarsening upward sequence, grading from greeny brown clayey sandy silts to coarse shelly sands. The upper 16 cm consists of a massive layer of dark greyish green sandy–silty clays. Foraminifera are abundant only in the base where the density and diversity are very high. Although 22 ostracod species were recognized in this unit, ostracoda are actually scarce in comparison with foraminifera. Some estuarine species were found at the top.

The sedimentological and micropaleontological differences observed along the core (Units I to V) seem to reflect the long-term forces and changes that have affected the coast between 6000 and 3000 yr BP, as we will discuss later in this paper.

5. Discussion

5.1. Depositional environment

Based on stratigraphical and sedimentological evidences, T9–1 sediments were previously interpreted as deposited in low-energy lagoons and marshes partially isolated from the open sea by a coastal barrier (Parker, 1979; Parker and Violante, 1982; Violante et al., 2001). However, the consistent dominance of the shelf *B. frigida*/ *Q. seminulum* group over the marginal marine, brackish-water *Elphidium* spp./*A. beccarii* group in all samples indicates normal marine to polyhaline conditions. Foraminifers of core T9–1 form a typical North Patagonian inner shelf assemblage (Boltovskoy et al., 1980). They can be found in a variety of littoral environments in southern South America, including beaches (Closs and Barberena, 1960, 1962a,b; Madeira Falcetta, 1977) and low-energy environments such as lagoons, bays and estuaries (Table 1). Dominant taxa also occur in meso-polyhaline waters (Boltovskoy, 1954a, 1957; Boltovskoy and Lena, 1974; Closs and Madeira, 1962). These findings are consistent with those obtained by analyzing ostracod assemblages, which constitute a mixed of open shelf and tidal flats species. The majority of the species are indicating subtidal settings and euhaline to polyhaline conditions (Whatley et al., 1987, 1988, 1997, 1998). Other ostracods are subtidal species indicative of high-energy, wave-dominated marine environments such as barriers and open beaches (Bertels-Psotka and Laprida, 1998a). Estuarine genera are represented only in the topmost samples.

T9–1 foraminiferal assemblages actually differ from those obtained by Boltovskoy and Totah (1985) from the modern adjacent shelf at depth greater than 40 mwd. For instance, at 40 mwd in the Buenos Aires shelf, total fauna is dominated by *B. peruviana* and *D. williamsoni*; at depths greater than 40 mwd, dominant taxa is *Epistominella exigua*. Although *B. peruviana* dominates T9–1 core assemblages and *D. williamsoni* is well represented in the base of the core (between 3–12% of the total fauna), no specimens of *E. exigua* were found. Thus, we consider that this succession represents the nearshore–offshore transition ∼20–30 mwd.

Reworking of shelf sediments has been particularly intense during the late Holocene in Buenos Aires. Thus, taphonomic processes affecting composition of fossil shelf assemblages must not be discarded. The recognition of autochthonous fauna is essential because paleoenvironmental interpretation must be based on the material being in situ. In core T9–1, autochthonous shells show high taphonomic grade, in which no major physical alterations were observed (preservational group A of Laprida and Bertels-Psotka, 2003). First 1–2 chambers are used to be broken or event absent, but this though to be due to reworking and/or low-distance (intra-habitat) transport. They roughly represent the

Table 2
Sedimentary units, sedimentology, abundance and diversity (number of species and Shannon Diversity Index $H'(S)$) of foraminifera and main foraminifer and ostracod species for T9–1 core, south-west South Atlantic

Unit	Description	Foraminifera abundance	Foraminifera diversity	Foraminifera main species	Ostracoda
I	Dark brownish green sandy–silty clays, up to 25% of medium to coarse sand and shell fragments	Abundant 854–301 ind/100 g	7–17 species, $H'=1.11–1.73$	*B. peruviana, Q. seminulum, E. discoidale, D. williamsoni*	*P. parallela, O. macropunctatum, S. clavata*
II	Plastic light greenish grey clay with minor amounts of silt and sand	Less than 115 ind/100 g	4–6 species; $H'=1.00–1.55$	Only *B.* peruviana moderately well represented	Almost absent
III	Brownish yellow sandy silt	More than 860 ind/100 g in all samples	11–22 species, $H'=1.30–1.85$	*B. peruviana, Q. seminulum D. williamsoni*. Highest content of brackish-water species: *E. gunteri, E. galvestonense, E. discoidale, A. beccarii*	*P. parallela, O. macropunctatum, C. litoralensis, O. micropunctatum, H. chuiensis*. High-energy-species: *C. lutziana, M. undulata, S. rugosoreticulata*
IV	Plastic light greenish grey clay with minor amounts of silt and sand	Less than 52 ind/100 g	0–7 species $H'=0–2.03$	Only *B. peruviana* is well represented	Almost absent
V	Base: coarsening upward sequence, grading from greeny brown clayey sandy silts to coarse shelly sands	>4900 ind./100 g	22 species $H'=1.85$	*B. peruviana, Q. seminulum, Elphidium spp., A. beccarii*	*H. escobasensis, C. litoralensis, O. macropunctatum, O. micropunctatum*
	Top: massive dark greyish green sandy–silty clays, slightly plastic, with shell fragments	18 ind/100 g	1 species	*B. peruviana*	Estuarine species: *P. whitensis, L. rioplatensis*

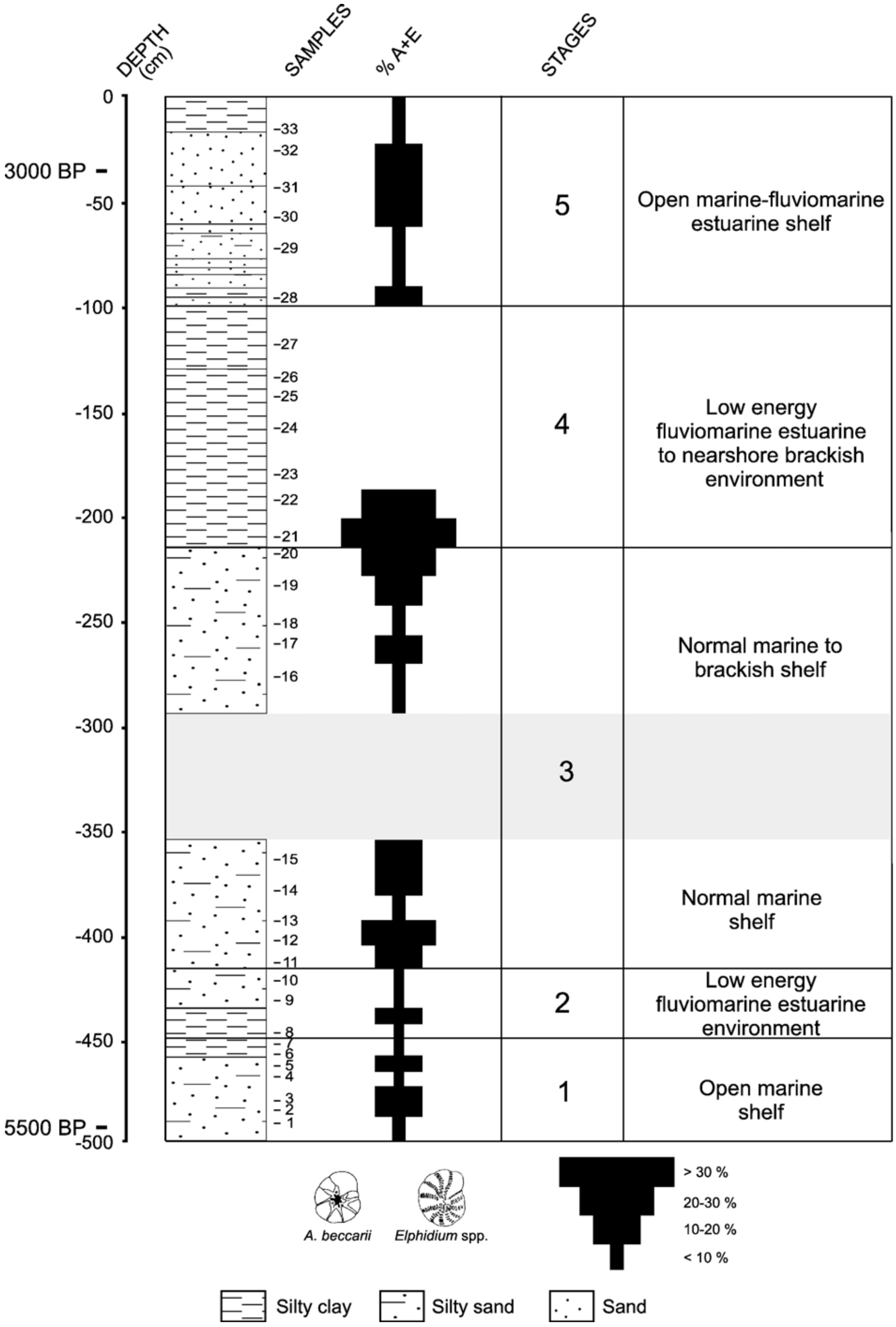

Fig. 3. Sedimentological column and distribution and relative abundance of the main brackish-water foraminiferal taxa *Ammonia beccarii* and *Elphidium* spp. (% A+E) in the T9–1 core. The paleoenvironmental stages and calibrated radiocarbon dates based on Vilanova et al. (2006) are also indicated.

paleobiocoenosis, although destruction of fragile and/or preferential preservation of robust tests could have modified the thanatocoenosis. Some few specimens with lower taphonomic grade (preservational group C of Laprida and Bertels-Psotka, 2003) were probably reworked from “older” deposits. They are especially abundant in Unit IV, where some inverted datings were found. However, the vast majority of the specimens are in situ in all the units, being the relict forms always subordinated.

5.2. Sea-level history and coastal dynamic in north-eastern Buenos Aires

For the Holocene, a number of studies have been made in Buenos Aires coast suggesting a chronology of regressive phases based mainly on regional geology, stratigraphy and paleoenvironmental reconstruction partially supported by radiocarbon datings (Parker and Violante, 1982; Codignotto et al., 1992; Codignotto and Aguirre, 1993; Cavallotto et al., 1995; Violante et al., 2001; Gómez et al., 2005). Sea-level history is subjectively divided in three main phases (Fig. 4):

1) An early Holocene transgression, when extensive landward barrier translation commenced and alongshore northward drift was essentially unimpeded. As sea level rose, older barriers became flooded and were partially reworked, remained as relictic submerged shoals in the inner shelf.
2) Between 7000 and 5000 yr BP, when the MHHS was attained reaching 5–6.5 m asl (above sea level), and the rising sea flooded the Punta Piedras–Alto Marítimo headland that separated the de la Plata River paleovalley from the open sea (Fig. 1). As a consequence, fluvial sediments begun to arrive to the Samborombón paleobay, where an extensive coastal barrier system was formed.
3) After the MHHS, the late-Holocene regression begun around 5000 yr BP. Regressive beach ridges and prograding barrier/back-barrier systems including lagoons, marshes, and tidal flats were developed in Samborombón paleobay. Rapid progradation of the coastal plains occurred specially after 3000 yr BP. According to the model proposed by Milne et al. (2005), the MHHS in Southern South America (Santa Catarina Curve) has reached 2.5 m asl and late-Holocene sea-level fall occurred gradually and monotonocally after 5000 yr BP (Fig. 4).

Sea-level data on which this chronology is based have large age or altitude uncertainties, but in the context of this large-scale coastal behaviour, the late-Holocene sea-level fall had apparently occurred gradually and, while uneven rates of falling or steps were recognized (Cavallotto et al., 1995, 2004), up-and-down fluctuations have not been reported between 6000 and 3000 yr BP.

Data collected in the present study confirm that during the late Holocene the area evolved in response to the interaction between sea-level fluctuations and littoral dynamic factors such as northward alongshore currents and southward fluvial input from the de la Plata River. According to our results, the five units previously defined correspond to five distinct paleoenvironmental stages which reflect the environmental evolution between 5792–5544 cal yr BP and 3188–2854 cal yr BP.

- Stage 1 is interpreted as a normal marine, open shelf environment ~20–30 mwd. This stage represents the environmental episode with highest marine character in the sequence, and coincides with the lasting phase of the MHHS.
- Stage 2 represents a low-energy, fluviomarine estuarine environment with normal to polyhaline salinity. This interpretation is based mainly on *B. peruviana* dominance, with restricted-environment typical fauna being absent. With all probability these silty clays represent the first extension toward the south of the de la Plata River fluvial driven sedimentation. The fluviomarine estuarine environment was developed probably as a consequence of a sudden sea-level-fall after ca. 5500 cal yr BP. A submerged barrier located eastward in the shelf —

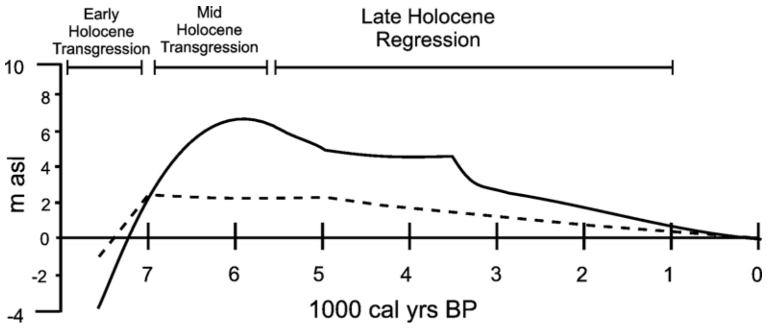

Fig. 4. Paleo-sea-level curve proposed by Cavalloto et al. (1995, 2004) for the de la Plata River region (solid line), and eustatic reference curve (dashed line) predicted by the geophysical simulations made by Milne et al. (2005) at Santa Catarina, Southern Brazil. asl = above sea level.

probably the extension to the south-west of the La Plata shoal (Fig. 1) — would have operated as a big shoal allowing waves to break at considerable distance from the shore, and leading the deposition of fine-grained sediments in the nearshore toe. The base of this stage is characterized by a sharp lithological boundary interpreted as a sequence boundary, a regressive surface of erosion indicative of a fall in sea level after de MHHS.

- Stage 3 represents the restoration of marine conditions in the nearshore–offshore transition. The base contains assemblages representative of normal marine environments, whereas in the middle–upper part, assemblages are made up of a mixture of brackish and marine species, indicating a gradual sea-level fall and/or coastal progradation and a change to more estuarine conditions. In the middle and upper parts, high-energy and tidal flat ostracoda were probably transported by waves and littoral drift from a big barrier spit developed landward and from a prograding barrier island system developed offshore the Samborombón bay. The base of this stage is characterized by a sharp lithological boundary interpreted as a marine flooding surface reflecting a discontinuity in depositional conditions related to changes in sediment supply and source.
- Stage 4 is interpreted as a low-energy fluviomarine estuarine environment established in response to a rapid sea-level drop. These silty clays were in all probability supplied by the de la Plata River which gradually increased it influence on the inner shelf. Extremely low number or complete absence of foraminifera may suggest that sediments have a non marine origin. However, this section is barren of pollen indeed (Vilanova et al., 2006) indicating that taphonomic processes related to very particular geochemical conditions have probably operated, affecting the preservation of microfauna and microflora.
- Stage 5 represents an open-marine, high-energy nearshore environment ~20 mwd. To the top, there is a gradual change towards estuarine conditions. The base of this stage is characterized by a sharp lithological boundary, a marine flooding surface generated by changes in depositional conditions related to sediment supply and source. In summary, core T9–1 represents the final phase of the MHHS and the initial phase of the Holocene regression. Sedimentation was controlled by northward littoral transport, erosive processes acting on coastal and shelf environments and fluvial discharge from the de la Plata River. The presence and/or lack of certain biogenic components (absence of rooting or plant structures in mud layers, abundance of open-marine microfauna as compared to the absence of fauna restricted to lagoons in all the samples) indicate clearly that the core was deposited on an open nearshore and not in a lagoon environment as suggested previously (Parker and Violante, 1982).

5.3. Muddy deposition on the shoreface–inner shelf transition

Under present conditions, mud is not accumulated in north-eastern Buenos Aires nearshore. But in the regime of the mid-Holocene regression, the de la Plata River began to supply large quantities of fine sediments into the coastal embayment, resulting in a rapid progradation of the coastal plain, and in the deposition of estuarine mud in the nearshore–offshore transition. Nowadays, fresh water supplied by the de la Plata River changes to saline waters in the nearest of Punta Rasa. There, a mixing of fresh and saline waters creates a maximum concentration of suspended sediments (the maximum turbidity zone, MTZ). Changes in sea level modify the configuration of the coast, and the position of the MTZ. As such, during the MHHS, estuarine zonation migrated northwards and fluviomarine estuarine conditions prevailed north of Punta Indio (Cavallotto, 2002; Fucks et al., 2005). When sea level fell, the MTZ migrated toward the south and caused the transition from sand- to mud-dominated depositional mode in core T9–1 site.

The occurrence and preservation of this mud layers was favoured by the presence of a relictic SW–NE offshore sandy barrier drowned by the early Holocene transgression (Violante et al., 2001). The relicts of this barrier built up the La Plata shoal (Fig. 1). During the MHHS, deeper water conditions prevailed and onshore currents were unable to deeply enough to remove submerged barrier sediments. When sea level suddenly fell, the top of the submerged barrier spit impeded the waves to reach the shoreface, resulting in a dampening of the wave energy and the ultimate deposition of fluid mud in the nearshore toe (Units II and IV). As fluvial input increased, the fine sediment discharge provoked the deterioration of nearshore benthic communities, and a reduction in the abundance and diversity of the meiofauna. Sediments on the top of the drowned barrier, located now on the exposed sector of the shoreface, started to be eroded by alongshore and crosshore currents allowing in turn the offshore transport of estuarine mud, and the onshore transport of marine sand (Units III and V). The particular evolutive characteristics of this shoreface–offshore transitional zone, where dynamic are mainly dominated by nearshore rather than by shelf processes, allowed exceptionally the preservation of these low-energy, fine-grained outcrops in only a few places in the shelf.

5.4. Holocene sea-level fluctuations in south-eastern South America

To date, mid-to-late-Holocene sea-level history in Buenos Aires is still uncertain. MHHS occurred apparently at 7000–6000 yr BP (Fig. 4) when sea level reached 5 to 6.5 m asl (Codignotto and Aguirre, 1993; Cavallotto et al., 1995), followed by a progressive sea-level fall occurring at different rates (Cavallotto et al., 1995; Violante et al., 2001; Violante and Parker, 2004). Other authors have suggested that the latter stage of Holocene sea-level history must be graphed as a smoothed curve (Farinati, 1985). Smoothed curves have also been used to describe the eustatic history of relative sea level in South America (Fig. 4), based on glacial isostatic models (Milne et al., 2005). Our primary evidence strongly supports that two events of sea-level fall occurred between 5792–5511 cal yr BP and 3188–2854 cal yr BP, strengthens the theory of stepped model of mid–late-Holocene sea-level fall in Buenos Aires coast. It is possible, however, that small-scale (few decimeters) oscillations such those proposed by Baker et al. (2001) could have happened.

Several studies carried out on Brazilian coasts have proposed that the MHHS was reached at ~5500 yr BP, and thereafter, two negative sea-level oscillations occurred between 4100 and 3800 cal yr BP and between 3000 and 2700 cal yr BP (Martin et al., 1979; Martin and Suguío, 1992; Angulo and Lessa, 1997; Martin, 2003; Martin et al., 2003). Recently, Gómez et al. (2005, 2006) analyzed submarine evidence in south Buenos Aires inner shelf and proposed that a negative sea level “several meters below the present one” (sic) occurred at 2720–2385 cal yr BP probably related with a global climatic change. Angulo and Lessa (1997) and Angulo et al. (1999) discussed and criticized all the available information and concluded that the more reliable interpretation suggests a smooth but uneven decline of sea level since the end of the MHHS. Recently, Angulo et al. (2006) have considered that the evidence of high-frequency sea-level oscillations are contradicted by the widespread evidence of higher-than-present sea levels in the last 5000 yr, and much of the evidence of secondary sea-level oscillations actually indicates the opposite, i.e., higher sea levels.

A model performed by Milne et al. (2005) suggests that the MHHS occurred in South America around 7000 cal yr BP at which time the rate of meltwater slows down and is defined to be zero after 5000 cal yr BP. The Antarctic ice sheet is a potential source of this signal. The model suggests a period of relative sea-level stabilization between 7000 and 5000 cal yr BP, falling steady after then due to glacial isostatic adjustment (Fig. 4). They considered that from the mid Holocene to present, there is no strong evidence to suggest that there has been significant net growth/melt of ice reservoirs. The model indicates that the ice-induced signal related with equatorial syphoning is the dominant contributor to mid–late-Holocene sea-level trends in South America. Ocean-induced signal (continental levering effect) also plays a key role but it is less apparent.

In contrast with the progressive declined of relative sea level proposed by Milne et al. (2005), our evidences indicate that between the MHHS and 3188–2854 cal yr BP, the drop in sea level was stepped. Periods of cooling within the mid-to-late Holocene could explain the pulses we see as ice accumulated again after the mid Holocene, during the so-called Neoglaciation. Pulses of sea-level fall recorded in Core T9–1 appear to have been synchronous with climate coolings and/or changes in moisture conditions in various regions of both hemispheres and coincide with some Mid-Holocene Rapid Climatic changes defined by Mayewski et al. (2004) and Neoglacial pulses based on glacier fluctuation record (Denton and Karlén, 1973). Such rapid climatic changes can cause a sharp variation in the rate of sea-level change even in short term events (Scott and Collins, 1996), and coastal geometry is likely to have climatic-promoted variations in tidal range.

6. Conclusions

We used a sediment core to infer changing environments of deposition through time, enabling relative sea-level history reconstruction of south-eastern South America between 5792–5511 cal yr BP and 3188–2854 cal yr BP. Main forcing factors responsible for shoreface evolution during mid to late Holocene were sea-level variations and de la Plata River fluvial input which could have initiated soon after 5000 cal yr BP. Five paleoenvironmental stages have been defined. The initial stage is interpreted as a normal marine, open shelf environment ~20–30 mwd (Stage 1) and represents the final phase of the MHHS occurred in the region between 7000–5000 cal yr BP. Soon after ca. 5000 cal yr BP the sea-level drop and a fluviomarine estuarine environment was established characterized by mud deposition in the shoreface toe (Stage 2). This was followed by a normal marine to brackish shelf environment (Stage 3) characterized by a diverse and abundant foraminiferal assemblage made up mainly of a mixture of brackish and marine species. After this, a new pulse of decrease of the sea level associated to fine-grained fluvial input caused a return to fluviomarine estuarine conditions (Stage 4). Finally, sometime before 3188–2854 cal yr BP, an open marine, high-energy nearshore environment ~20 mwd with large estuarine influences was established (Stage 5). This paleoenvironmental evolution suggests that, during mid to late Holocene, a drowned barrier located eastward in the shelf was present impeding the waves to reach the shoreface. As sea level fell, sediments on the top were eroded and reworked allowing the high-energy S–SE waves to reach the coast.

Even when the reconstruction based on this facies description has wide indicative ranges regarding relative sea levels, the paleoenvironmental interpretation indicates that two pulses of fall in sea level have occurred between 5792–5511 cal yr BP and 3188–2854 cal yr BP. Thus, a stepped model of mid to late-Holocene sea-level fall in north Argentine shelf is confirmed by our data.

Acknowledgements

Funds to carry out this research were provided by the National Agency for the Promotion of Science and Technology (ANPCyT), PICT 03–14417, and by the National Research Council (CONICET), PIP 5006. This is a contribution to the Project IGCP 464 “Continental Shelves during the Last Glacial Cycle, knowledge and applications”.

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