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Late Quaternary in a South Atlantic estuarine system: Stratigraphic and paleontologic indicators of coastal evolution

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ABSTRACT

The decisive influence of Late Quaternary sea level changes on the geological evolution of the coastal plain and adjacent continental shelf around the world has long been recognized. Coastal environments evolve actively during transgressive–regressive cycles whose development depends on sea level and sediment supply variations. The interaction of these variables was key to the current morphological and sedimentological configuration of coastal regions. Particularly, the estuarine system of Bahía Blanca (Argentina) presents various types of deposits and marine fossil accumulations, such as paleochannels in the subbottom, sand-shell ridges and extensive layers with fossils in life position. These features are important geological indicators, because its analysis allows us to define different paleoenvironmental conditions that prevailed during the coastal evolutionary process.

1. Introduction

The study of coastal sedimentary units, their stratigraphic and paleontological features and their lateral and vertical relationships provide a relatively complete historic geologic record. The decisive influence of Late Quaternary sea level changes on the geological evolution of the coastal plain and adjacent continental shelf around the world has long been recognized. Coastal environments evolve actively during transgressive–regressive cycles whose development depends on sea level and sediment supply variations (Vail et al., 1977; Boyd et al., 1992). The interaction of these processes during the Late Quaternary was key to the current morphological and sedimentological configuration of coastal regions. Stratigraphic studies on fluvial-marine environments have thoroughly analyzed sea-level rise and fall during the Quaternary (Hori et al., 2002; Wellner and Bartek, 2003; Dalrymple and Choi, 2007; Abrahim et al., 2008).

Particularly, the estuaries are highly sensitive environments to sea level changes. Thus, the estuarine system of Bahia Blanca (Argentina) formed by a dense network of channels, presents various types of deposits and marine fossil accumulations, as well as various landforms and stratigraphic structures that evidence the coastal evolutionary process. Therefore, in this research acoustic seismic methods were applied to study the marine bottom and subbottom, while in the coastal region, sedimentological and paleontological analysis of fossiliferous horizons and sand-shell ridges were carried out. The seismostratigraphic evidence, together with fossiliferous deposits, constitute important geological indicators, because its analysis allows us to define different paleoenvironmental conditions that prevailed during the Late Quaternary coastal evolution.

1.1. Geological setting

The coastal region of Bahía Blanca estuary is formed by a dense net of tidal channels that are separated by low altitude islands and sand shoals (Fig. 1). This mesotidal system has a major channel called Principal, which is the entrance site to the main international harbor complex located in this region. The estuary is also characterized by the presence of large tidal sandy clayey silt flats which were formed during the last postglacial regression (Aliotta et al., 1996, 2004).

Geological units formed during the Late Tertiary–Quaternary are currently part of the surface context in Bahía Blanca region. The Pampean Formation (Darwin, 1846), of Pliocene–Pleistocene

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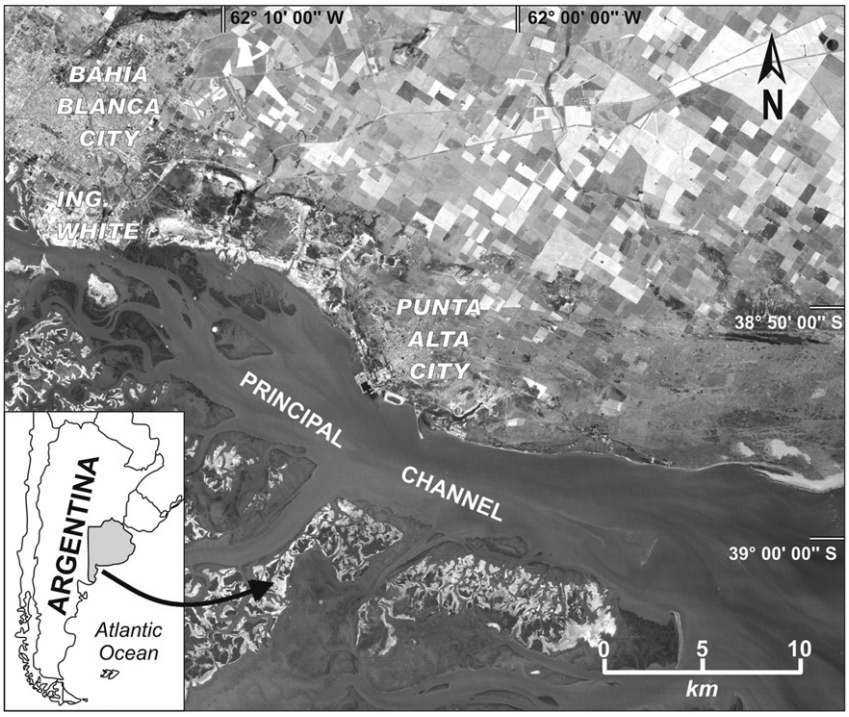

Fig. 1. Location of the Bahía Blanca estuary.

age, is one of the most characteristic sequences in this area. This unit, called by Fidalgo et al. (1975) Pampiano Formation, corresponds to deposits which are widely extended in the Pampean area of Argentina and are formed by fluvial and aeolian agents (Fidalgo et al., 1975). In the coastal zone of Bahía Blanca, this unit is formed by silty sands and sandy silts cemented with calcium carbonate (Fidalgo, 1983). Recent geophysical studies conducted in Bahía Blanca estuary facilitated the seismic identification of the continuation of the Pampean Formation at the subbottom (Aliotta et al., 2004, 2009; Spagnuolo, 2005; Ginsberg et al., 2009; Giagante, 2009). The Pampean sediments within the marine environment form part of the acoustic–stratigraphic basement on which Late Pleistocene–Holocene materials were deposited.

Before the last postglacial marine transgression, the paleoenvironmental conditions of the area in which Bahía Blanca is located were significantly influenced by the drainage systems converging into this region. Palinological and sedimentological studies were carried out along the emerging north coast of the estuary in order to interpret the paleoenvironmental characteristics of river terraces that were produced by old drainage systems (Zavala and Quattrocchio, 2001; Quattrocchio et al., 2008). The evolutionary features of a deltaic environment which affected the Bahía Blanca area, particularly in the south-western of estuary, were also analyzed (Aliotta et al., 1999, 2009; Spalletti and Isla, 2003; Giagante et al., 2008). In addition, fluvial events as well as paleochannel structures were identified in the estuary (Aliotta et al., 2004; Spagnuolo, 2005; Giagante et al., 2008, 2011) and in the continental shelf (Aliotta et al., 1999, 2011). The formation of these deposits of fluvial origin is related to the old runoff network acting in this coastal region prior to the Holocene marine transgression.

Numerous geological studies indicate that the Holocene marine transgressive–regressive cycle has imprinted its particular featuresin the Bahía Blanca area. The main morphosedimentary characteristic of this cycle is the presence of sand ridges containing abundant remains of biogenic material, which are located 5–7 m above mean sea level (MSL) and are relatively continuous and parallel to the current littoral zone (Aliotta and Farinati, 1990; Farinati and Aliotta, 1997; Aliotta et al., 2003, 2006, 2008; Spagnuolo et al., 2006).

The fine grained sediments, typical of Holocene marine sedimentation, are located in the partially emerged coastal areas of Bahía Blanca estuary, forming large muddy flats occasionally interrupted by tidal channels of different sizes. These flats, with abundant marine fossils are found in the subsurface in places near the coastline, resulting from the progradation of clayey silt sediments during the last marine postglacial regressive event (Aliotta et al., 2004).

The sedimentological, paleontological and stratigraphic analysis of Late Pleistocene–Holocene deposits (as paleochannels, sand-shell ridges and levels with fossils in life position) constitutes a key tool to infer ancient environmental conditions and evolutionary processes. This paper includes an analytical expansion in the treatment of these topics.

2. Material and methods

To obtain the different types of data considered in this study various methods were applied. Seismic stratigraphic data were collected during different marine surveys conducted on board the ship Buen Día Señor, which belongs to the Instituto Argentino de Oceanografía (IADO). This information was obtained from high resolution seismic profiles (3.5 kHz), with a Geopulse Transmitter 5430A. Four GeoAcoustics 137D transducers were arranged with this equipment. This made it possible to work with a maximum power of 10 kW, thus optimizing the seismic penetration and allowing to reach several meters of depth at the subbottom. The records were interpreted following the seismostratigraphic principles of Mitchum et al. (1977). Data position during the acoustic surveys was obtained in real time with a DGPS.

Owing to the effects of significant urban development in the Bahía Blanca coastal area, marine deposits occur discontinuously

and therefore most of the surveying was carried out along a profile almost perpendicular to the coast where the natural conditions are still intact. Over 20 perforations were made with a screw bit to a maximum depth of 5 m and test pits up to 4 m deep were dug. In all sediment samples biogenic material were extracted. Leveling for exact altimetric correlation was carried out continuously. The fossiliferous material contained in some samples was separated from the sediment and ^{14}C ages were obtained at the LATYR laboratory of La Plata University (Argentina). The sedimentological samples were analyzed in the laboratory according to Folk (1974). Data were analyzed statistically following Folk and Ward (1957) and sediments were characterized according to Shepard (1954). Identification and counting of the mineralogical species in the fine sand fraction (retained in a 125 μm sieve) was carried out in accordance with the technique used by Parfenoff et al. (1970).

The taphonomic analysis carried out on mollusk valves included the following parameters: disarticulation, fragmentation, abrasion, bioerosion and dissolution. These evaluations were carried out on the basis of the absence or presence of these parameters and on the qualifying parameters already used by other authors (Russell Callender and Powell, 1992; Meldahl, 1994). Therefore, were measured a scale of "high", "medium", "low" and "none" (Parsons and Brett, 1991), referred to the relative quantity of the taphonomical attributes. Also, a quantitative analysis of the taphonomic attributes, particularly fragmentation, abrasion, bioerosion and dissolution, was carried out through of ternary taphograms (Kowalewski et al., 1995).

An undisturbed sample (30 × 20 × 8 cm) containing *Tagelus plebeius* was taken from the horizon in order to determine the biogenic structures, which were then analyzed by means of X-ray radiography (Siemens equipment) and computer tomography (General Electric 9000 equipment).

3. Results and discussion

3.1. Fluvial seismic stratigraphic sequence

During most of the Quaternary, global sea level was found to be below current sea level (Shackleton, 1987), thus indicating that river base level could have extended further than the current coastline. The sea-level rise associated with the last postglacial phase induced changes in coastal regions, thus generating a transition from fluvial to estuarine–marine environments, which were influenced by the combined action of erosive and depositional processes. This is the reason why, according to the seismic stratigraphic reconstruction of sequences on continental shelves around the world, systems of buried incised valleys could be identified. Several studies which have focused on seismic data, boreholes and drill cores, have contributed to identifying buried channel structures (Karisiddaiah et al., 2002; Weber et al., 2004; Nordfjord et al., 2005; Weschenfelder et al., 2008), and have therefore become useful tools for the interpretation of evolutionary processes that occurred in coastal margins.

Argentinean coasts were greatly affected by sea-level variations after the last glacial maximum (Cavallotto et al., 2004). This, in turn, produced changes in old drainage systems. The transgressive–regressive event, in fact, characterized the evolutionary process of the fluvial paleovalley of de la Plata River (Violante and Parker, 2004).

At higher latitudes, particularly in the Bahía Blanca estuary, sea-level oscillations affected the hydrological, morphological and sedimentary conditions of the old fluvial environments. The latter have been reported in seismostratigraphic investigations showing evidence of fluvial paleochannels prior to the Holocene transgression (Aliotta et al., 1999, 2004; Spagnuolo, 2005; Giagante et al., 2008). Thus, the fluvial facies and paleochannels constitute important geological indicators that allow to know ancient sedimentary processes. In view of the above, we present a regional characterization of an ancient fluvial deposit taking into account the seismostratigraphic facies of which this deposit is composed. The integrated analysis of the sequences and sedimentary structures at the subbottom of this deposit will allow us not only to establish the prevailing Quaternary paleoenvironmental characteristics but also to evaluate the changes in the continental drainage system and the coastal modifications occurring in response to Late Quaternary sea-level rise.

At the entrance to the Bahía Blanca estuary (Fig. 2) the sedimentary deposit at the subbottom forms a sequence (FS) which has particular seismostratigraphic characteristics that are clearly different from those of the upper and lower sequences (Fig. 2). The materials below FS constitute the acoustic basement (AB). Horizontal and slightly inclined reflectors, usually subparallel, having a better defined stratification at the top of the unit were identified in the AB sediments. Seismograms indicated that the AB upper boundary (FS floor) was characterized by an unconformity of a strong acoustic signal and high lateral continuity (Fig. 2, AA'). Similar seismostratigraphic characteristics have been recorded in other marine sectors of Bahía Blanca estuary (Aliotta et al., 2004; Giagante, 2009), thus allowing us to correlate AB with cemented sedimentary deposits regionally associated to the Pampean Formation. This sequence, which belongs to a continental paleoenvironment, is widely distributed in the coastal-marine region of the estuary.

The basal boundary of FS is an erosive discontinuity surface evidenced by its high reflectivity and the presence of paleochannels (Fig. 2, BB'). The incisions identified are located from 15 m below sea level, the largest of which has an apparent width of 270 m and an estimated depth of 10 m. In general, these erosive structures were found to have a concave configuration limited by v-shaped cuts, adopting an irregular configuration in the sectors where they reach larger depths. The areas where the basal erosive boundary was located at shallower depths were frequently found between depressions forming these incisions, thus forming topographic heights (Fig. 2, FR), giving rise to a flat relief between paleochannel deposits. The analysis of the seismic profiles perpendicular to the coast indicated that these planes could have formed part of a large regional surface with a smooth slope towards the south.

Paleochannels were also identified at the eastern end of the area (Fig. 2, DD'), although they were found to be located at a shallower depth (from 12 m) with respect to those at the western end. The slopes of the channels were found to be formed by erosive surfaces having a smoother aspect with respect to those in the western sector. These ancient cuts were found to have, on average, a width of ~110 m and a depth of ~2.5 m. Reflectors indicative of sedimentation processes acting on this erosive surface were determined in the filling of paleochannels. Aggradation–progradation sedimentary structures and slightly oblique reflectors, both indicative of river bed silting, were found. These structures resulted from the irregularities of the erosive surface forming the paleochannels, the depositional energy conditions and the sediment grain size (Schwarzer et al., 2006; Green, 2009). Particularly, the seismostratigraphic configuration of the filling material of paleochannels found in the Bahía Blanca estuary indicates that this material corresponds to sand and gravel facies deposited under high-energy conditions. The materials deposited in the incisions located in the eastern sector exhibited not only acoustically transparent sediments but also poor and slightly wavy reflectors (Fig. 2, DD'). These seismostratigraphic characteristics are indicative of the finer sediments homogeneity and a decrease in depositional energy conditions with respect to the filling material in the western zone.

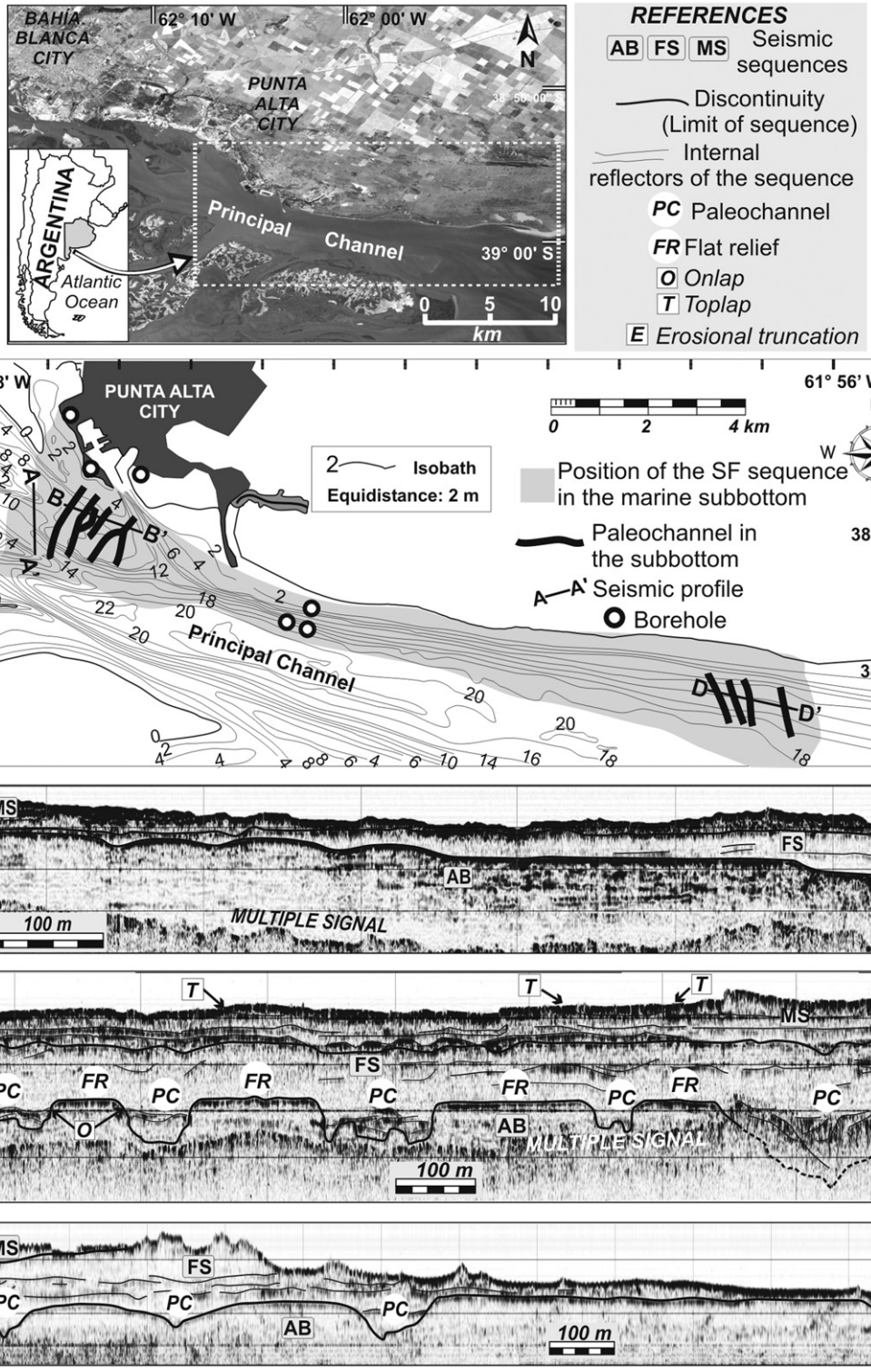

Fig. 2. Location of 3.5 kHz seismic profiles (A–A′, B–B′, D–D′) and identification of seismostratigraphic sequences (AB, FS, MS) with paleochannel structures (PC) (modified after Giagante et al., 2011).

On the other hand, FS thickness was variable. It decreased significantly towards the east and west ends, this being shown in a progressive wedging. It was observed that thickness decreased in both sectors as a result of the shallowing of the materials forming the substratum. In the areas with channel-filling structures, sedimentary thickness increased significantly (more than 7 m) as a result of the presence of these depositional features. The correlation of seismic profiles with borehole data (Oiltanking Ebytem, 2000) showed that this unit is mainly composed of slightly compacted fine sand and silt-enriched layers. Both the semi-transparent configuration of this seismostratigraphic sequence and its low-amplitude reflectors evidence these lithological characteristics. The upper boundary of this sequence was indicated by a strong reflector. One of the irregularities of this

boundary was the presence of v-shaped, ~1–2 m deep cuts, resulting from either small channels or old runoff draining paths. These morphological features show that this boundary is an erosive discontinuity. Furthermore, the overlying materials (MS sequence) were found to exhibit different sedimentation and paleoenvironmental characteristics with respect to FS. In the lower sector of the MS sequence, the reflectors were arranged following the irregularities of the basal boundary and exhibiting a subhorizontal facies which was parallel and/or slightly wavy. This seismic configuration was also present in the materials filling the small channels located at the base of the sequence. A clearly defined horizontal stratification exhibiting continuity was observed towards the shallower sectors in the whole area.

MS thickness was found to be variable all along the area, reaching 5.5 m in some sectors. The upper boundary of this unit usually coincided with the seabed (Fig. 2, AA' and BB'). In certain sectors, this discontinuity surface truncated the wavy-inclined reflectors of the unit, forming toplap configurations (Fig. 2, BB'), whereas the depressions on the seafloor truncated the layers of the sedimentary unit. Some seismic profiles showed small ridges and irregularities in the upper boundary which were indicative of compaction and resistance of the materials of the MS sequence to erosive processes. In contrast, in other sectors, the seismograms showed that the upper boundary of the MS sequence is covered by a layer of sediments that respond to current depositional conditions.

3.1.1. Paleochannels and environmental evolution

The geological processes involved in the formation of the sedimentary units analyzed in Bahía Blanca estuary occurred on cemented clayey silt substrate. The seismic–lithologic correlation with boreholes has allowed us to associate these sediments – herein called AB sequence – with the Pampean Formation. This Plio-Pleistocene sequence, whose origin is related to fluvial and aeolian processes (Fidalgo et al., 1975), is typically found on the subsoil of coastal zone. Within this continental paleoenvironment, erosion led to the formation of a discontinuity surface which is currently the AB upper boundary and the FS lower boundary, the latter having several paleochannels.

The pronounced slope of the paleochannels on the floor of FS as well as their irregular configuration suggest an initial process during which both the incision and erosion of the substrate resulted from strong fluvial influence. In this respect, experimental studies by Wood et al. (1993) showed that vertical incision is the initial response of river systems to base-level fall. In agreement with this, for other fluvial sequences adjacent to our study area, Zavala and Quattrocchio (2001) proposed an evolutionary model with an erosion/non-deposition first stage. In the Bahía Blanca coast the action of old rivers with a dendritic drainage pattern gave rise to paleochannels (Fig. 3, stage I) formed during a high-energy erosive process. Furthermore, the regional morphological observations and the analysis of the distribution of these paleochannels show that they are related to the coastal–continental sector (Fig. 3).

On the other hand, the topographic position of the v-shaped incisions observed seems to indicate that the lower section of FS was formed during a period in which the sea level was below the current sea-level position and developed within a continental environment. These paleoenvironmental characteristics are consistent with those observed by Rabassa et al. (2005), who correlated Patagonian glaciations with units belonging to the Pampeana region within which the Bahía Blanca area is included.

The pioneer work of Fray and Ewing (1963) in Argentine Shelf determined that during the Late Pleistocene (20–18 kyr) the sea-level position was 110–120 m below the present. Rabassa et al. (2005) claimed that during the Late Pliocene–Pleistocene the emerged continental areas were duplicated and that the sea level decreased to 140 m. In this respect, seismic discontinuities in coastal environments could be indicative of a significant sea-level fall (Weschenfelder et al., 2008). Furthermore, Vital and Stattegger (2000) defined stages of evolution for the Late Quaternary and categorized a relative sea-level fall, related to the last glacial maximum, 20,000–18,000 years ago, as state 1. They also identified channel incisions in an old substrate similar to the structures located at the base of FS. The paleochannel structures recorded in the Bahía Blanca coastal region, which are indicative of a marked sea-level fall that significantly affected the southern Atlantic coast, are temporally related to a paleodrainage system which was explored on the coastal area (the Patos Lagoon) in the southern sector of Brazil (Weschenfelder et al., 2008), where large paleochannels were formed at the end of the Late Pleistocene, when sea level fell to 120 m below the current sea level (Corrêa et al., 2004). The prevailing paleoenvironmental conditions in the Bahía Blanca region towards the end of the Pleistocene, which were characterized by periods of extreme aridity and strong aeolic activity (Quattrocchio et al., 2008), modified the fluvial system pattern. The seismic arrangement of the reflectors present in the paleochannel filling sediment showed their gradual silting up. Furthermore, the burial of ancient channels is indicative of the relative base-level change in the fluvial system with the consequent migration of river tributaries. This geological event, which involves the displacement of old river beds, is a common feature among the different fluvial courses that acted and still persist along the studied coastal region (Spalletti and Isla, 2003; Giagante et al., 2008). Thus, both the advancement of aeolian deposits, probably as a result of the high influence of prevailing winds from the northwest, and the changes in the hydrological conditions (aridity, decreasing flow), produced the gradual migration of fluvial channels towards the east, thus giving rise to new runoff paths and fluvial mouths (Fig. 3, stage II). Also, the configuration of the channels in this sector and the seismostratigraphic characteristics (Fig. 2, DD') of the filling materials are indicative of an energy decrease in the hydric system.

On the other hand, the mid-upper seismic facies of FS is characterized by the presence of horizontal reflectors although some slightly curved ones forming concavities were occasionally identified. This seismic configuration evidences a change in the deposition conditions which could be probably due to different deposition pulses of the sedimentary material derived from sporadic reactivations of small streams. From a paleoenvironmental point of view, the upper section of the unit corresponds to deposits close to the river base level. In this respect, observations from Catuneanu et al. (2009) indicate that the concept of base-level change is equivalent to the concept of relative change at sea level. If there is agreement in that the base level is associated with the sea level (Posamentier and Allen, 1999), it could then be concluded that this section of FS is influenced by the sea-level rise process that took place during the Pleistocene–Holocene (Fig. 3, a and b).

Based on the above-mentioned seismostratigraphic and geological characteristics, and taking into account the geographical positions of the paleobeds, FS could be related to the sedimentary deposits of an ancient mouth of Napostá Chico River (Fig. 3). During the Middle–Late Pleistocene and under semiarid to arid paleoclimatic conditions that prevailed in our study area (Quattrocchio et al., 2008), an ample alluvial cone or fan-like plain could have formed. According to Nichols and Fisher (2007), the seismostratigraphic configuration of the unit at the subbottom as well as its areal distribution pattern can be correlated with the distal area of fluvial deposits. Based on the seismic data collected in the Bahía Blanca estuary it was possible to determine the east and west boundaries of FS, thus showing a lobe-shaped configuration. The

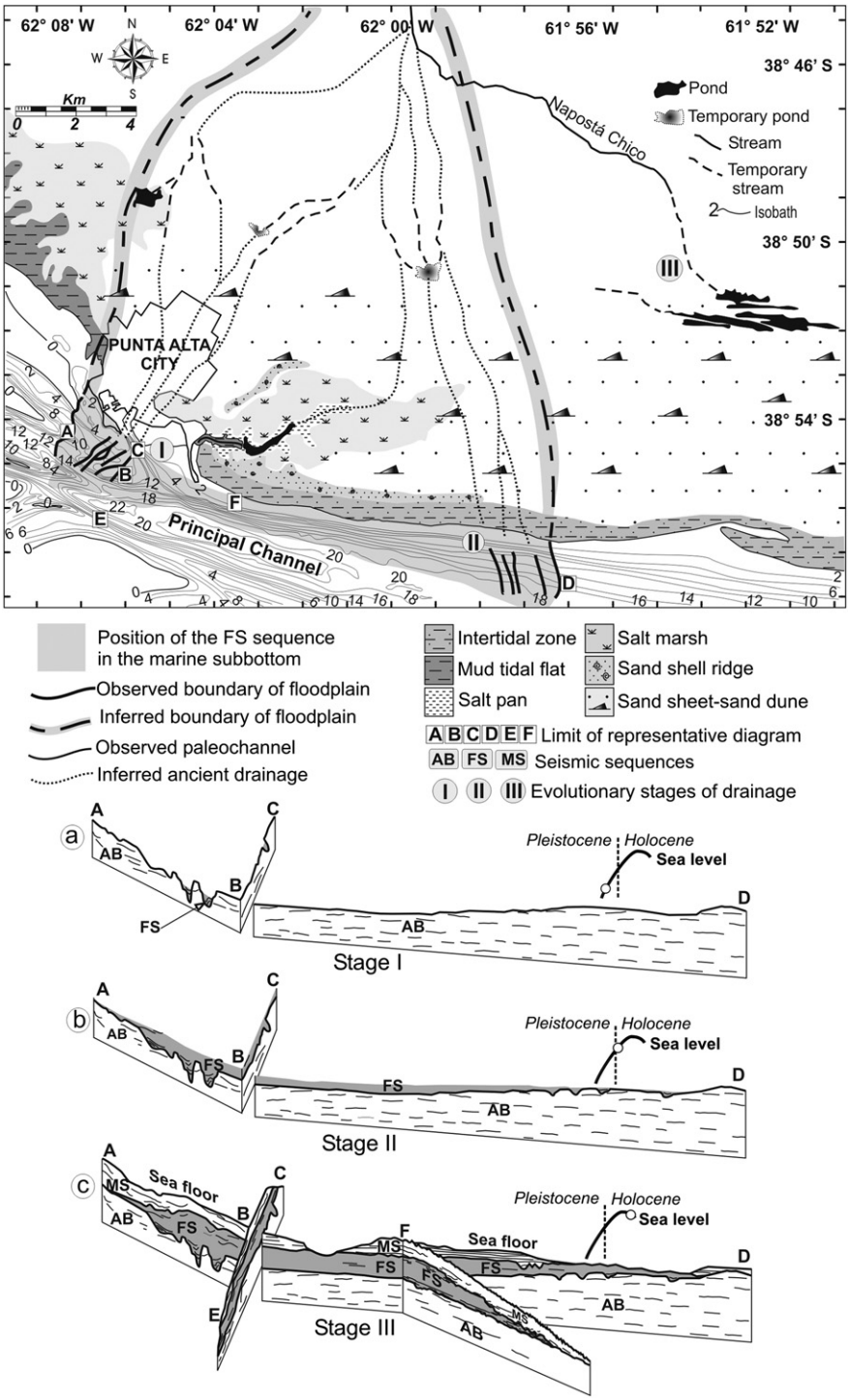

Fig. 3. Evolutionary stages of the ancient drainage system associated with seismic sequences. 3D interpretive scheme showing the evolution of FS sequence (a, b, c) in response to the last marine transgression (modified after Giagante et al., 2011).

presence of fine sand and silt fractions in FS was clearly correlated with its acoustic response, which was found to be transparent and homogeneous (Fig. 2, DD'). This is, in general, associated with relatively uniform sedimentation processes in which deposited materials have high lithological similarity and well sorted.

At the beginning of sea-level rise during the Late Pleistocene–Holocene, the coastline retracted towards the continent, thus changing the mouth of fluvial courses. The action of this marine transgressive process is evidenced by the presence of a discontinuity surface derived from the erosion of FS. Thus, in response to the sea level rise, the coastal front migrated to the continent partially burying FS with sandy marine sediments in the deep areas and with silt materials (tidal plain) in the shallow sectors. Based on previous studies (Posamentier et al., 1988; Catuneanu et al., 2009), it has been concluded that the Holocene transgressive process which affected the South Atlantic was key to the change occurring at the base level of coastal drainage systems. The presence of a large field of sand dunes in the coastal sector of

our study area together with the change at the base level of the ancient fluvial basin of the Napostá Chico River, lead us to infer that this fluvial drainage system became endorheic. In this sense, the current geomorphological setting of the Napostá Chico River mouth is, in fact, a clear evidence (Fig. 3, stage III).

The upper boundary of FS was found to exhibit several v-shaped incisions which were not only indicative of its erosive nature but also reminiscent of the old temporary coastal drainage courses. As a result of Holocene sea-level rise, these drainage courses began to form primitive tidal channels which, due to marine sediment supply and reworking of FS eroded material, were filled with clayey silty sand sediments having shell fragments. The upper sector of the seismic profiles revealed the presence of a unit, hereinafter called MS, with horizontal and slightly curved reflectors, subparallel to each other. This seemed to be indicative of an alternation between clayey sediments with sandy silt sediments. In view of this, MS could be interpreted as a paleoenvironment associated with tidal flat facies, which developed gradually during the Holocene marine event (Fig. 3, C).

Maximum transgression then produced a series of sand-shell ridges in the Bahía Blanca coast. These deposits which, in general, contain a high percentage of biogenic material, are typical morphosedimentary features of the coastal region (Farinati and Aliotta, 1997). Cavallotto et al. (2004) claimed that in the Holocene, coastal progradation was the most important process in the northern coast of Argentina during sea level fall when these protected areas behind littoral ridges became tidal flats and marshes. The regressive process, particularly in Bahía Blanca region, produced the shallowing of the coast and the formation of large tidal flats containing sandy clayey silt sediments with layers with a high concentration of fossils in life position. Both the sand ridge and layers with fossils in life position constitute important geological and paleoenvironmental indicators linked to sea-level changes in the Holocene therefore its analysis is included below.

3.2. Sand-shell ridges

Sandy ridges with a high shell concentration along the coastal sector defined up to 5–7 m mean sea level (MSL) represent the Holocene transgressive maximum. A large number of ^{14}C ages (Farinati, 1985; González, 1989; Farinati et al., 1992; Spagnuolo, 2005) indicate that the last transgressive episode affected the Bahía Blanca area during Middle–Late Holocene occurred between 4600 and 6700 yrs B.P.

3.2.1. Stratigraphy and paleontology

In the continental coastal area the Holocene transgressive marine sediments stand uncomformably on a Pleistocene lithified sandy silt, which is rich in calcium carbonate (calcrete). Silt, sand and clay are the Holocene sediments that form the vast coastal flats which surround the Bahía Blanca estuary, while sand ridges, more or less continuous and approximately parallel to the isohypses, constitute a remarkable morphological feature in the coastal plain (Fig. 4). These forms can reach 100 m in width and 2 m in height.

The sand-shell ridges are composed of a medium to fine sand with a high percentage of shells and their fragments (about 30%) and a smaller proportion of pebbles of quartzite, calcrete, siltstone and pumice (long axes reaching 3 cm). The sand grain size varies between 1.5 and 0.40 phi and the sorting of the sediments is poor (1.5–3.0 phi).

Generally, the ridges have a parallel stratification with beds ranging from 2 to 5 cm in thickness and a slight inclination (about 3°) towards the sea. The beds can be identified by their different concentrations of shells (Fig. 4).

Mineralogically the sand in the Bahía Blanca ridges has similar characteristics. The commonest light minerals are quartz, plagioclase, volcanic glass and orthoclase, whereas the heavy minerals are augite, hypersthene, hornblende, epidote and garnet.

The sand-shell ridges stand unconformably on clayey sandy silt (Fig. 4). The upper part of this horizon has a somewhat undulatory laminated structure. These laminae are thin (about 0.2 cm) and composed of silt-clay and fine sand with flaser structures. The mean grain size varies between 4.08 and 5.67 phi (average 4.90 phi), and the sorting is very poor (3.23 phi). Between 80 cm and 1 m below the base of the ridges the sediment changes transitionally to clay-silt, with a small quantity of sand (less than 5%). The main characteristic of this material is its great plasticity. The clay fraction comprises mainly montmorillonite and illite, with a smaller proportion of kaolinite. Between the level described above and the calcrete substratum there is a silty sand (Fig. 4). The paleontological content of the ridges comprises 106 species of molluscs, in addition to other organisms (bryozoarians, annelids, cirripedia and decapods). The quantitative analyses of fossil malacofauna revealed a high diversity of molluscs during the Late Quaternary, where 58 species of gastropods and 48 species of bivalves have been recorded. All the species found inhabit the littoral zone and there are no taxa from deep waters. Most of the species are marine and euryhaline marine. Most of the bivalves (80%) are shallow infaunal, suspension feeders of soft substrates, while the gastropods are epifaunal, free-living, carnivores of hard substrates.

In the ridges, there are dense fossiliferous levels formed by skeletal concentrations. The orientation of the shells usually coincides with the bedding. In the case of *Brachidontes rodriguezi* d'Orbigny, one of the most abundant species, most of the shells have been laid down with their convex sides up. The tubular bryozoans (*Membranipora*) are laid horizontally and follow the bedding. In addition, *Littoridina australis* d'Orbigny shows a random orientation and sometimes occurs in levels made up only of this species. Some specimens of *B. rodriguezi* were found with both shells together, even though they have a dysodont dentition of feeble articulation. The shells show a large variety of sizes, ranging between 3 and 40 mm. The most abundant gastropods includes the following species: *Tegula patagonica* (d'Orbigny), *Diodora patagonica* (d'Orbigny), *Calliostorna coppingeri* (Smith), *L. australis* (d'Orbigny), *Teinostoma maldonadoensis* Farinati, *Ataxocerithium pullum* (Philippi), *Epitonium georgettina* (Kiener), *Crepidula protea* (d'Orbigny), *Crepidula aculeata* (Gmelin), *Natica isahelleana* (d'Orbigny), *Tritonalia cala* (Pilsbry), *Anachis moleculina* (Duclos), *Anachis isabellei* (d'Orbigny), *Anachis paessleri* (Strebel), *Buccinanops deformis* (King), *Buccinanops globulosum* (Kiener), *Olivancillaria carcellesi* Klappebach, *Olivella tehuelchana* (d'Orbigny), *Olivella plata* (Ihering), *Eulimella bermudensis* (Dall-Bartsch), *Turhonilla smithi* Pfeffer, *Turbonilla fasciata* (d'Oorbigny), *Turhonilla madrynensis* Lamy. The following bivalves are the most abundants: *Nucula semiornata* (d'Orbigny), *Nucula puelcha* d'Orbigny, *Adrana electa* (Adams), *Nuculana whitensis* Farinati, *B. rodriguezi* (d'Orbigny), *Ostrea equestris (*Say), *Phlyctiderma semiaspera* (Philippi), *Carditamera plata* (Ihering), *Raeta plicatella* (Lamarck), *Darina solenoides* (King), *T. plebeius* (Lightfoot), *Semele proficua* (Pulteney), *Tellina gibber* (Ihering), *Pitar rostratus* (Koch), *Gouldia camachoi* (Farinati), *Amiantis purpurata* (Lamarck), *Petricola lapicida* (Gmelin), *Sphenia hatcheri (*Pilsbry), *Corbula patagonica* (d'Orbigny), *Corbula lyoni* (Pilsbry, *Erodona mactroides* Daudin, *Cyrtopleurala lanceolata* (d'Orbigny), *Entodesma patagonica* (d'Orbigny), *Periploma ovatum* d'Orbigny.

Generally, the ridges material is bioclast-supported (Fig. 5, a), with a shell-sediment radio of 3:1. According to the concept of Kidwell et al. (1986), these skeletal accumulations are parautochthonous, though there are obviously differences in the biofabric. The taphonomic evaluation carried out on mollusk valves indicates high disarticulation, medium fragmentation and abrasion

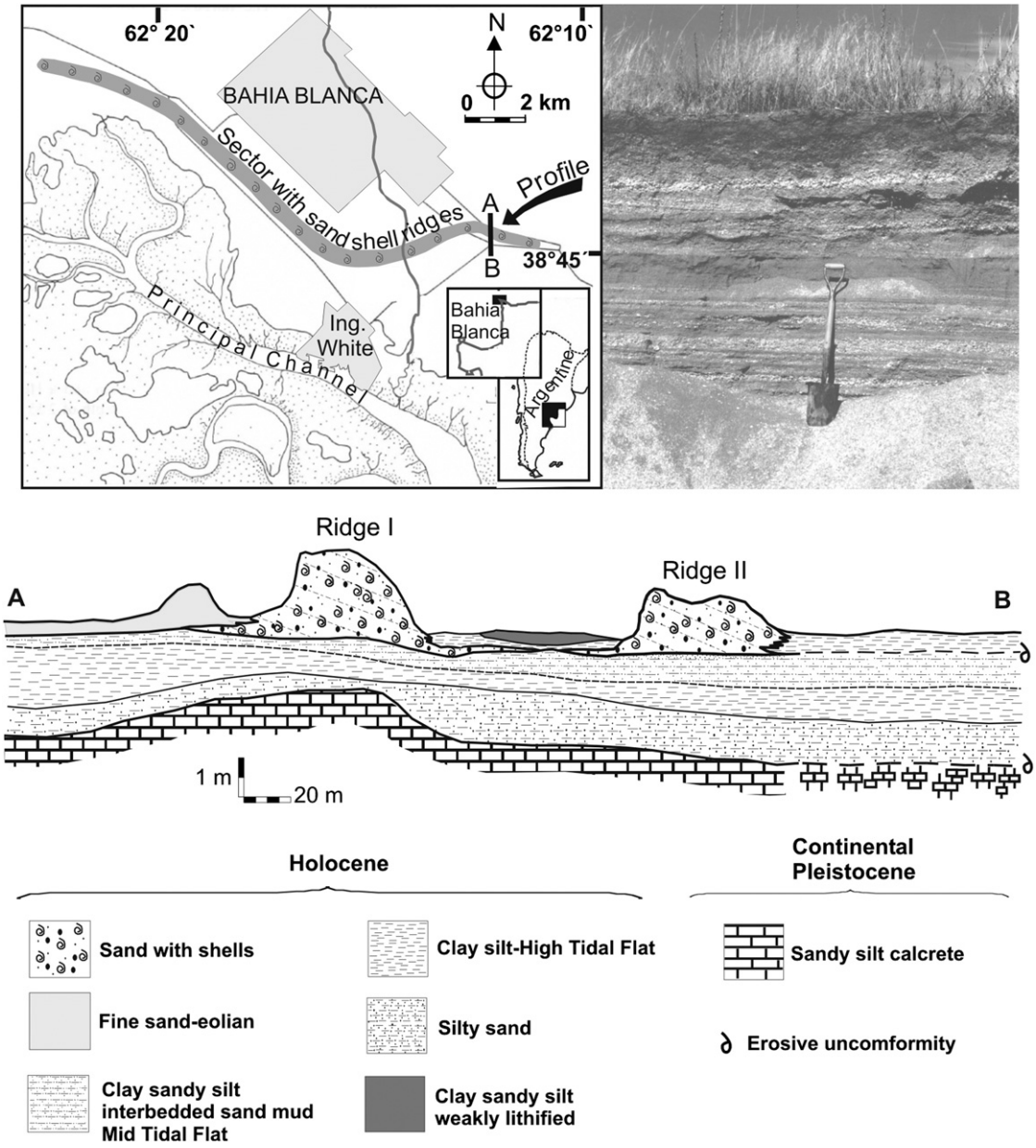

Fig. 4. Stratigraphical cross-section of the sand-shell ridges along the coast of Bahía Blanca estuary (modified after Aliotta and Farinati, 1990).

and medium–high dissolution. Fragmentation can vary at different levels of the ridge (Fig. 5, b–d). Several valves show bioerosion marks (Fig. 5, e, f). There are strong signs of abrasion on the outer surface of the shells indicates by the loss of surface ornamentation (Fig. 5, g, h). The most common signs of dissolution include chalky appearance and loss of luster (Fig. 5, i).

3.2.2. Paleoenvironmental conditions of the sand-shell ridges formation

The stratigraphic configuration of the Holocene ridges corroborates wave activity as an important variable in the depositional mechanism. The very well-defined discontinuities between strata and the high concentrations of biogenic remains in their composition indicate episodic energy conditions (Aliotta et al., 2002). In addition, the presence of the quartzite and calcrete pebbles proves some indirect fluvial contribution to the material of the ridges. The stream power of the Holocene rivers related to the Bahía Blanca estuary may have been greater than at present; today there is no pebble input.

The mineralogical analysis throws light on certain peculiarities of Quaternary sedimentation. The compositional results are valuable parameters for determining not only the transport mechanism energy (Ito and Masuda, 1986) but also the source of lithic clasts and sediment origin (Komar, 1976). According to the observations of Teruggi et al. (1964), Holocene sediments with only one type of volcanic glass are associated with present-day beach sands and with sands in the southern tidal channels of the estuary (Gelós and Spagnuolo, 1989). The augite, hypersthene and plagioclase characteristics are all in agreement with the above-mentioned sedimentary sources. The absence of titaniferous augite, euhedral hypersthene, for the most part limpid plagioclase and the absence of biotite are linked with characteristic beach sediments toward the west of Bahía Blanca and outside the estuary (Teruggi et al., 1959; Gelós and Spagnuolo, 1989).

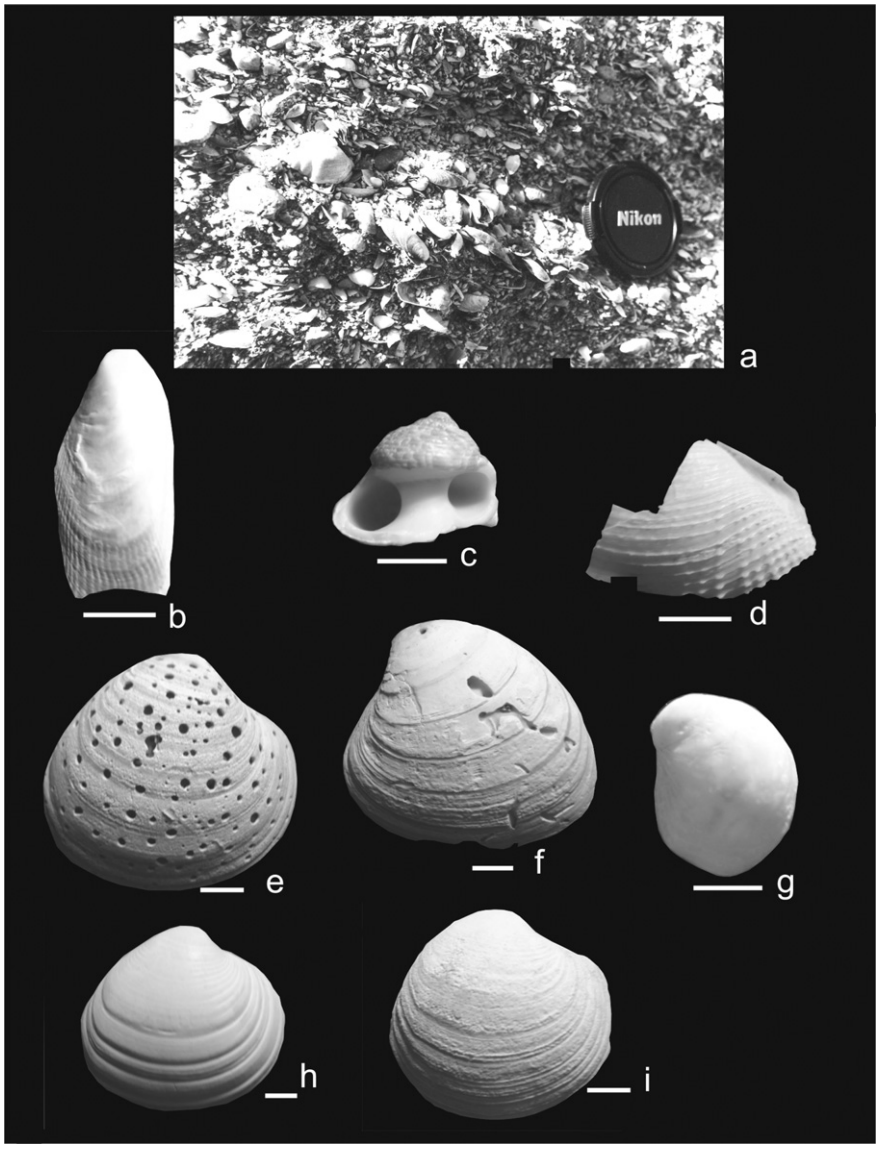

Fig. 5. Taphonomic features representative of sand-shell ridges. a. Characteristic biofabric: bioclast-supported. Fragmentation of molluscs: b. *Brachidontes rodriguezi,* c. *Tegula patagonica,* d. *Cyrtopleura lanceolata*. Bioerosion on bivalves: e. *Amiantis purpurata* with *Entobia* borings, f. *Pitar rostratus* with *Maeandropolydora* borings. Signs of abrasion: g. *Crepidula aculeate,* h. *Pitar rostratus*. i. Effects of dissolution in *Amiantis purpurata*. Graph scales: white bars correspond to 1 cm.

Based on the vertical sequence of sedimentary lithofacies in the Principal Channel, Aliotta et al. (1996) defined the Holocene estuary as an inverse filled basin. That is to say, in agreement with the sedimentological results, the sedimentation of the last transgressive phase is produced fundamentally by materials that enter the system from the sea. At maximum sea level the coastal paleogeography would have been characterized by a wide shallow bay fed by sand drifting in from the south and east. The strong south-southeast winds had sufficient fetch to generate the waves responsible for the formation of the sand-shell ridges distributed along the north coast of the estuary.

The assessment of the taphonomic characteristics of mollusk valves has become an established tool for paleoenvironmental reconstruction and for the determination of sedimentation conditions. Such studies have been conducted in environments as diverse as reefs (Parsons, 1989), intertidal to shallow shelves (Meldahl and Flessa, 1990) and inner continental shelves (Staff and Powell, 1990a,b). Disarticulation and fragmentation, the first stages of the taphonomic pathway, are clear indicators of the level of energy regulating the sedimentary environment. The degree of fragmentation is a helpful parameter for differentiating regressive-transgressive deposits of the same epoch but with different wave surf conditions (Meldahl, 1995).

In the sand ridges of Bahía Blanca, both the disposition of the layers as the observations carried out on Holocene bioclasts suggest relatively moderate high-energy levels. originated by the combined action of waves and littoral currents.

According to Brett (1990), this characteristic suggests intervention of depositional events in which wave energy is sufficient to play an important role in the sediment transport mechanism. Through a ternary taphogram (Kowalewski et al., 1995) the semi-quantitative evaluation of the distribution of taphonomic attributes (Fig. 6) is summarized. This analysis, indicative of paleoenvironmental conditions, was performed on two differents taxa of molluscs considered the most abundant (*B. rodriguezi* among the bivalves and *T. patagonica* among the gastropods). The relative position of the attributes within the triangle is average values

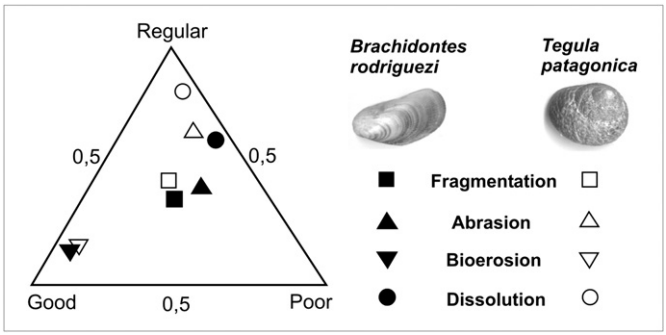

Fig. 6. Ternary taphogram showing the distribution of taphonomic attributes.

obtained from several taphonomic studies (Farinati et al., 2006, 2008; Spagnuolo et al., 2001).

The erosion or smoothness of shells as a consequence of their differential movement with respect to sediments is an indicator of the degree of abrasion (Driscoll and Weltin, 1973). Both abrasion and bioerosion, as a result of the action of boring organisms, are significant taphonomic parameters. The bioerosion in the Holocene material is associated with the time of exposure to grazing and boring organisms. The bioeroded valves of littoral–sublittoral sectors of calm waters are captured and transported to the supratidal zone by episodic storm events.

Although dissolution of shell is a complex process occurring both before and after burial, the ridges of Bahía Blanca estuary underwent dissolution mainly during the fossil diagenetic stage. This mechanism continues until now as a subaereal weathering process derived from pluvial precipitations, rise of the phreatic level, daily temperature fluctuations, presence of vegetation and exposure to the sun.

3.3. Fossiliferous strata with valves in life position

Study of organisms and their relationship with the surrounding sediments helps us to determine the geological processes which took place in the areas where they lived. Much research has been carried out on benthic communities in estuaries throughout the world. In the Bahía Blanca coastal zone, between the sand ridges described and sea level, an important fossiliferous strata occurs on the banks of the Naposta River (Fig. 6), which extends for 800 m along both banks (González et al., 1983). In this case, sedimentological and paleontological analysis is essential to define geological history of the area and the mechanism responsible for the mass mortality seen in the fossiliferous layer.

3.3.1. Sedimentological and paleontological characterization

To the south of Bahía Blanca city the wide Holocene coastal plain is eroded by the river Napostá, which forms banks as high as 2.0 m. A sedimentary sequence characteristic of the fluvial–coastal area occurs (Fig. 7, a). At the top of the exposure is a 0.15 m thick bed made up of fining-upward sand (medium to fine sand). Between 0.15 and 0.27 m the sand has a low percentage of silt. The bed directly beneath at 0.28 m is made up of medium to fine sand with some levels of wavy bedding. In this bed, as in the beds above, no marine mollusc remains were found, although ostracod taxa of clearly non-marine affinity such as *Heterocypris salina*, *Darwinula* sp. and *Ilyocipris gibba* were present (Bertels and Martinez, 1990). We attribute a fluvial origin to these sediments. Between 0.70 and 0.90 m from the surface, there is a fossiliferous level with a significant concentration of *T. plebeius* with its articulated valves and individuals still in life position (Fig. 7, b). Radiocarbon dating carried out by González et al. (1983) on *T. plebeius* valves indicated ages of 3850 and 3560 yrs B.P. Farinati (1985) established a similar approximate age of 3373 yrs B.P. The following molluscs were identified. Pelecypods: *N. semiornata* d'Orbigny, *B. rodriguezi* (d'Orbigny), *P. semiaspera* (Philippi), *R. plicatella* (Lamarck), *D. solenoides* (King), *Macoma uruguayensis* (Smith), *S. proficua* (Pulteney), *T. plebeius* (Lightfoot), *P. rostratus* (Koch), *S. hatcheri* (Pilsbry), *E. mactroides* Daudin, *C. patagonica* d'Orbigny, Gastropods: *L. australis* (d'Orbigny), *Natica isabelleana* d'Orbigny, *B. deformis* (King), *O. tehuelchana* (d'Orbigny).

At a depth of 1.60–1.70 m from the top of the bank, the sediment changes transitionally to a silty sand, with small subangular pebbles (<0.5 cm in diameter) made up of a well-consolidated siltstone rich in calcium carbonate. At approximately 2.15 m (Fig. 7, a) there is fine sand with some silt and large amounts of fine particulate calcium carbonate. Grain size increases downwards, and at the limit of the borehole the additional presence of bryozoa, cirripedia, calcareous microfossils such as ostracodes and foraminifera, and remains of *Stylatula darwini* (Anthozoa, Pennatulacea) has been determined.

3.3.2. Paleoecological reconstruction and mass mortality

A complete determination and analysis of Holocene biogenic remains is the tool to establish the old conditions of benthonic life. The paleoecological reconstruction of the fossiliferous horizon described in the coastal plain of Bahia Blanca is shown in Fig. 7,b. It has been noted that most of the organisms in the layer are infaunal and are thus highly dependent on the water–sediment interface. Some are deposit feeders (*N. semiornata*, *S. proficua*), but most are suspension feeders. Among the epifaunal organisms are *B. rodriguezi,* which attaches to the substrate by its byssus, and the gastropods *L. australis* and *B. deformis.* Organisms of this type were found at different levels.

In the fossiliferous strata all remains of the fauna are very well preserved. The most outstanding feature in the faunal association is the presence of *T. plebeius* in life position. Also, some loose valves in a horizontal position have been recorded, and none of these showed any sign of wear caused by transport. *T. plebeius* is a bivalve of the family Solecurtidae, whose wide distribution extends from North Carolina (USA), Surinam, Brasil, Uruguay, and down to the San Matias Gulf in Argentina. This bivalve has an elongate shell with rounded ends and its outer surface shows a growth line and a deep pallial sinus. The valves may be up to 90 mm long (Holland and Dean, 1977b). *T. plebeius* is a euryhaline species which lives in the river mouth in a vertical position with its foot downwards and the long exhalant and inhalant siphons stretching upwards to the water–sediment interface (Fig. 7, b). These siphons, which reach 30 cm in length are extendable structures. The foot is perfectly adapted to excavation. According to Coscaron (1959), *T. plebeius* replaces *Mesodesma mactroides* (Deshayes) (yellow clam), which lives in strictly marine environments, because riverine influences are unfavourable for the latter mollusc.

Holland and Dean (1977a,b) established that *T. plebeius* does not live in unstable, mobile sandy areas where it cannot maintain the integrity of its siphon tubes. Instead, the ecological environment of Tagelus is in tidal flat areas between the mean low tide level and 90 cm above this level, where it inhabits sediments composed of more than 2% silt and clay. This explains why, in the Naposta River, the sediment that contains *T. plebeius* is a cohesive sandy silt. This sediment is found on the Holocene tidal flat that developed during the transgressive–regressive process which affected the Bahia Blanca area and which is being eroded by the creek today. Certainly a mass mortality phenomenon affecting an entire living population of the old tidal flat took place and was responsible for the sudden death of the organisms. Brongersma Sanders (1957) defined catastrophes of limited scope that produce mass mortality in the sea

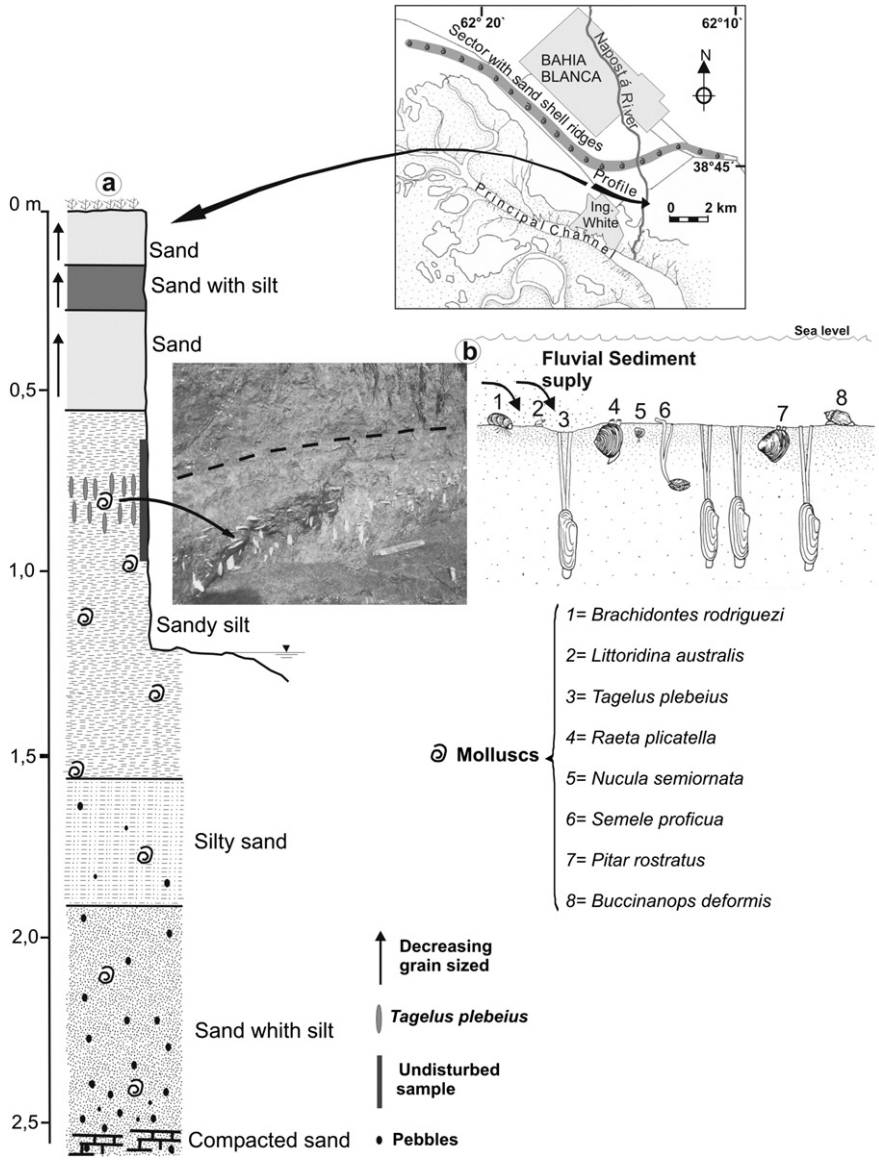

Fig. 7. a. Stratigraphic profile on bank of the Napostá river; b. Horizon of *Tagelus plebeius* in life position and paleoecologic reconstruction with associate fauna (modified after Farinati et al., 1992).

and investigated their cause and significance in paleontology. At the sea bottom, near the water–sediment interface, burial of organisms over small areas is a fairly common occurrence, generally taking place over brief periods. This is the primary cause of mass mortality of resident populations. However, there are relatively few recognized cases of catastrophic burials in the paleontological literature. For animals as small as *T. plebeius*, sudden burial under an influx of sediment several centimeters deep is a major catastrophe that is capable of killing them. Not all bivalves are able to escape burial because such ability is related to life habits, size, and the type of sediment in which the organisms are buried (Kranz, 1974). Using sand and silt Shulenberger (1970) has demonstrated the ability of the bivalve *Gemma gemma* to burrow upwards in response to catastrophic burial.

T. plebeius is a deep-burrowing bivalve whose behaviour when faced with sudden burial is changeable. When young, it is a rapid burrower capable of escaping from depths of between 15 and 50 cm. With age, however, it develops a boring behaviour and cannot escape once buried; it therefore survives to maturity only when sedimentation is feeble (Kranz, 1974). Sedimentary processes such as erosion or deposition acting in estuarine environments (tidal flats) may induce imbalance in the ecosystem. The organisms react to the new conditions and try to find their ideal habitat. Thus, where sedimentation is rapid and excessive, they must migrate from their living horizon to new levels near the water–sediment interface, thus producing escape structures (Reineck, 1958).

To study the subsurface behaviour of *T. plebeius* in the Bahía Blanca estuary conventional X-ray equipment supplemented with computer tomography was used (Fig. 8). It was thus possible to analyze the sedimentary structures produced by the organisms and to infer from them the sedimentary processes affecting their habitats. Specimens of *T. plebeius* in life position and the excavation burrows of two of them are shown in Fig. 8, I-a. The absence of sedimentary structures in the material is evident. Transverse slices through the core using computer tomography were carried out to supplement the limited information provided by the X-ray radiography. These slices take the shape of a 10 mm thick plane in which different material shows variations according to its

absorption coefficient: the lightest shades correspond to the most dense material. On the right-hand side of Fig. 8,II, two small semicircular areas (b) correspond to the disturbed material of the excavation trace formed by the organisms. These are the same structures as shown in the radiograph, but in a vertical position. Valves of *T. plebeius* and the inner part of the organisms without sediment (black) are shown in Fig. 8, III-c. Below these specimens (Fig. 8, IV and V) is a darker zone (d) which was not observed in the slice (Fig. 8, VI). The biogenic structure observed in Fig. 8, IV and V demonstrates that in this area the sediment was disturbed by organisms, probably during a period in which the bivalves inhabited a lower level. This level was later abandoned and escape structures were excavated during migration towards the surface. The structures reflect the reaction of the bivalves to the imbalance produced at the water–sediment interface.

The process described above is undoubtedly related to the geological evolution of the estuary, particularly with the last marine regression. Due to the very slight slope of the flooded coastal area the tidal flat was formed slowly in the littoral zone. These sandy silt sediments formed the habitat of *T. plebeius* and other associated marine organisms. The deposition of fluvial sand over the sandy silt (i.e. over the habitat of *T. plebeius*) occurred in the Late Holocene. Simultaneously with the marine regression this process was responsible for the burial and mass mortality of the *T. plebeius* population. The velocity of sedimentation must have been very high, and the bivalves were unable to survive in the new environmental conditions. The sandy burial material came from the old area of the Naposta River mouth. The fluvial sediment must have been deposited during the regressive period, where the influence of marine dynamics was either very reduced or non-existent.

4. Overview and conclusions

Coastal depositional environments evolve actively during transgressive–regressive cycles whose development depends on sea level and sediment supply variations. The interaction of these geological processes during the Late Pleistocene–Holocene gave origin to stratigraphic and paleontological indicators, which are key to understanding the current morphological and sedimentological configuration of coastal regions.

During most of the Quaternary, global sea level was found to be below current sea level (Shackleton, 1987), thus indicating that river base level could have extended further than the current coastline. The sea-level rise associated with the last postglacial period induced changes in coastal regions, thus generating geological indicators that evidence a transition from fluvial to estuarine–marine environments which were influenced by the combined action of erosive and depositional processes. This is the reason why, according to the seismostratigraphic reconstruction of sequences and observations on continental shelves around the world, systems of buried incised valleys were identified.

Particularly in the coastal system of Bahía Blanca, the integrated analysis of the seismostratigraphic sequences at the subbottom and of fossiliferous deposits allowed us to define geological indicators of the prevailing Quaternary paleoenvironmental characteristics, evaluating the changes in the continental drainage system and the coastal modifications occurring in response to Late Quaternary sea-level rise. We have taken the curve of Holocene sea level change given by Spagnuolo (2005), which was modified and enlarged based on the integration of geological indicators considered in this study.

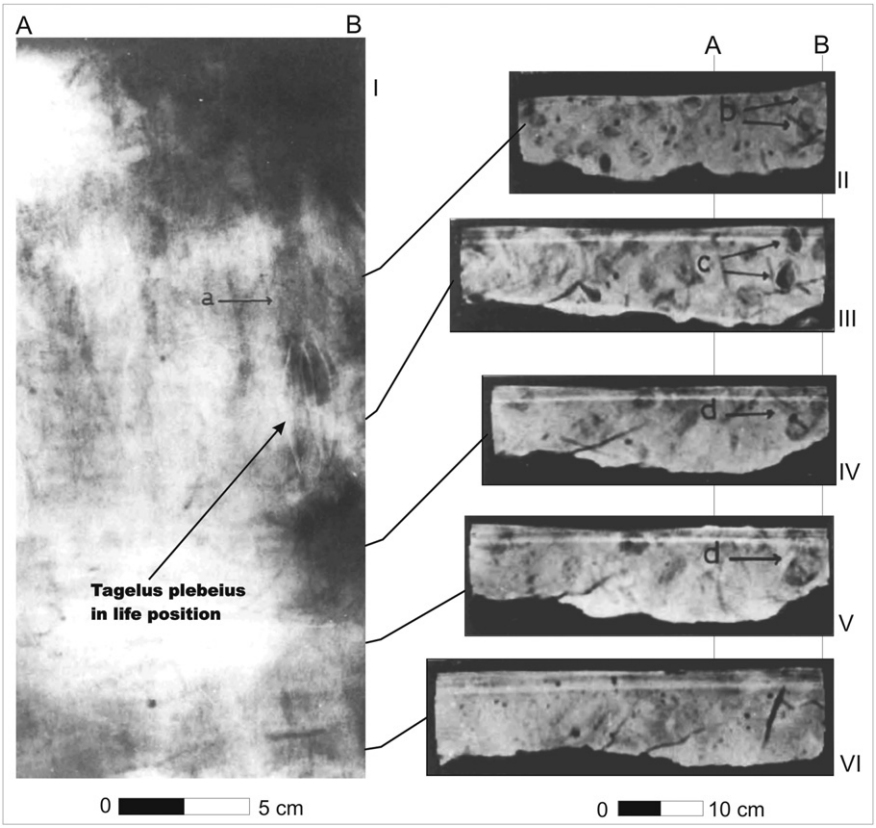

Fig. 8. X-ray radiography (I) and computed tomography images (II–VI). A and B: right and left limits of the X-ray radiography; a, b: excavation burrows of *Tagelus plebeius*; c: the inner part of the organisms (black) without sediment; d: escape structures (modified after Farinati et al., 1992).

Thus, we can conclude that in the Late Pleistocene period and before the marine transgressive process, the sedimentary paleoenvironment corresponding to the current coast of Bahía Blanca estuary was highly influenced by an ancient fluvial drainage system. A large alluvial plain composed of numerous fluvial dendritic courses was formed in this coastal area of the Southwest Atlantic, giving rise to fine to medium sand deposits with silt-enriched levels. These sediments (FS) show evidence of an old fluvial sedimentary environment. The floor of FS with compacted sediments forming the substrate was characterized by the presence of paleochannel structures whose basal erosive surface forms the lower boundary of the sequence.

These fluvial incisions were formed in periods during which the sea level was at least ~35–40 m below the current sea level and during which the environmental conditions were under continental regime (Fig. 9, A). The filling structures of the paleochannels and the marked acoustic transparency of the upper facies are, in general, the main distinguishing seismic features of this unit.

On the other hand, in response to the transgressive event the sea-level rise changed the base level of the hydric system and river flows decreased as a result of the increasing arid conditions typical of the Early Holocene (Fig, 9, B). As a result of this environment, which was accompanied by Holocene sea-level rise, the drainage system became endorheic and therefore FS at the subbottom demonstrates to be a seismostratigraphic indicator of ancient continental conditions. During the middle Holocene, sea erosion in this alluvial sequence formed the upper boundary of FS. Biogenic debris and marine sediments associated with large sandy clayey silt tidal flats formed during the transgresive marine cycle were deposited on this discontinuity surface (Fig. 9, C). With the slow rise in sea level, an extensive tidal flat was developed over the Holocene littoral owing to the very slight slope of the coastal area. An increase in wave energy with storm events, gives rise to transport of the sandy sediment and a large percentage of calcareous shells of the subtidal zone as bedload. Sand-shell ridges deposited on the coastal area to an altitude of approximately 5–7 m above sea level are an important geological indicator of the Holocene transgressive maximum (Fig. 9, D).

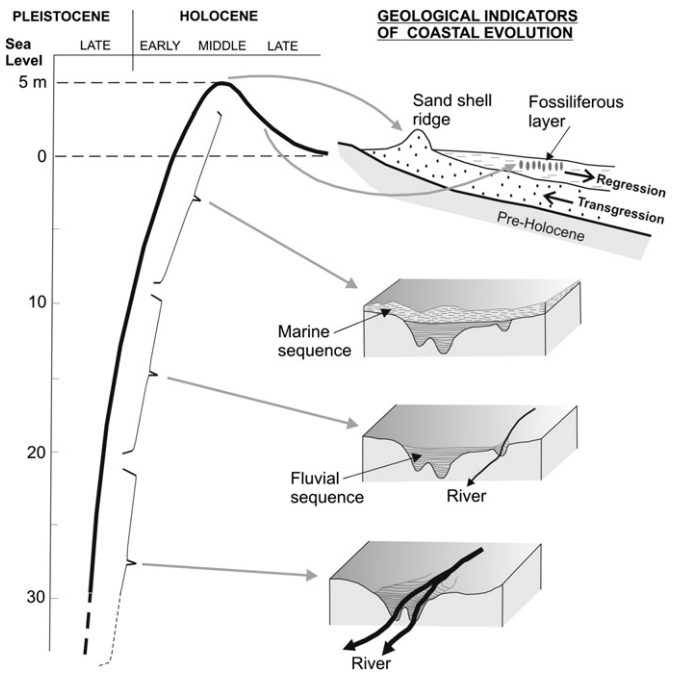

Fig. 9. Geological indicators of coastal evolution related to the sea level change during the Late Pleistocene–Holocene.

The progressive decrease of sea level in the Late Holocene originated a great sandy silt coastal flat, due to the very gentle slope of the flooded littoral zone. Its sedimentary facies formed the habitat of large concentrations of marine molluscs. Sedimentary processes such as erosion or deposition acting in estuarine environments (tidal flats) may induce imbalance in the ecosystem. Thus, the sudden influx of fluvial sandy sediment was responsible for the mass mortality of a *T. plebeius* population. These levels with fossils in life position represent significant paleontological indicators of marine regressive process (Fig. 9, D) and show the transition between marine and continental paleoenvironments. Finally, with the progradation of the Late Holocene tidal flat with fine sediments and the termination of the marine regressive event, a broad coastal plain typical of the current morphological configuration of the coastal area of the Bahía Blanca estuary was formed.

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