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Evolution of a coastal alluvial deposit in response to the last Quaternary marine transgression, Bahía Blanca estuary, Argentina

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ABSTRACT

The purpose of this research is to analyze the seismostratigraphic and paleoenvironmental features of an ancient fluvial deposit characterized by the presence of paleochannels and sedimentary structures in Bahía Blanca estuary, Argentina. To this end, high-resolution seismic methods were used. Paleochannels exhibiting v-shaped cuts were found at different topographic positions at the base of this deposit. It was observed that channel silting is indicative of the relative change of river base level and the consequent migration of fluvial tributaries. This alluvial deposit is composed of low compacted fine sand and its middle–upper facies is characterized by the presence of horizontal and discontinuous wavy reflectors. The upper boundary of this deposit is an erosive discontinuity resulting from Holocene sea-level rise during which the mouth of old fluvial courses underwent changes. The deposit was subsequently buried by sandy and clayey silt sediments. The paleodrainage at subbottom indicates that this deposit is associated with an ancient river mouth. Based on the seismostratigraphic and lithological characteristics and the paleochannel structures found in the study area, it can be concluded that the deposit analyzed is an alluvial sequence formed in the period from the Middle-Late Pleistocene to Holocene marine transgression.

Introduction

Coastal depositional 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 geological processes during the Quaternary was key to the current morphological and sedimentological configuration of coastal regions. Previous stratigrahic studies on fluvial-marine environments have thoroughly analyzed sea-level rise and fall Quaternary periods (Hori et al., 2002; Wellner and Bartek, 2003; Dalrymple and Choi, 2007; Abrahim et al., 2008). In particular, those areas where ancient incised valleys and paleochannels have been seismostratigraphically identified, are key to the study of the sedimentary record of the continental margins associated with sea-level variations (Zaitlin et al., 1994).

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 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 sedimentological observations on continental shelves around the world, systems of buried incised valleys could be identified (Green, 2009). On the other hand, several studies which have focused on seismic data, boreholes and drill cores, have contributed to identifying buried channel structures (Subba Raju et al., 1991; Riggs et al., 1992; 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 Bahía Blanca estuary, sea oscillations affected the hydrological, morphological and sedimentary conditions of the old fluvial environments. The latter have been reported in seismostratigraphic investigations evidencing the

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presence of fluvial paleochannels prior to Holocene transgression (Aliotta et al., 1999, 2004; Spagnuolo, 2005; Giagante et al., 2008).

In view of the above, the aim of the present study was to carry out 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 Holocene sea-level rise.

The study area covers a sector of the outer part of Bahía Blanca estuary, which is composed of a dense net of tidal channels that are separated by low-altitude islands and banks (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. On account of the fact that engineering activities are frequently carried out in this sector, thus affecting its Late Tertiary–Quaternary sedimentary units, the seismostratigraphic study of sequences in this area has become an important source of information to identify the geological evidence imprinted by the Holocene marine transgressive–regressive cycle. The estuary is also characterized by the presence of large tidal

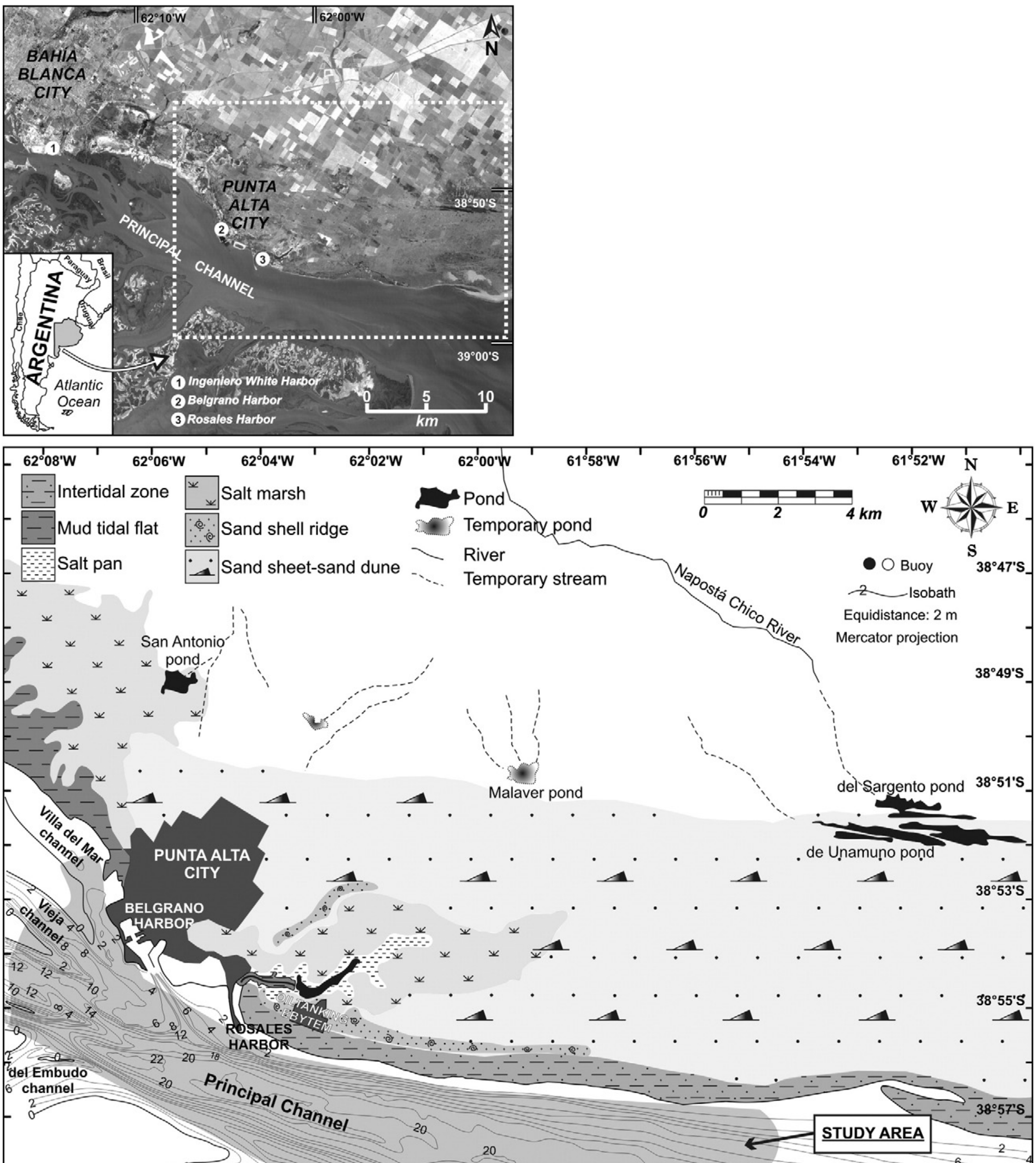

Figure 1. Location of Bahía Blanca estuary. Geomorphological characteristics of the study area and adjacent coastal sector.

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sandy clayey silt flats which were formed during the last postglacial regression (Aliotta and Farinati, 1990; Farinati et al., 1992). In the northern sector of the study area, there are drainage basins coming from different fluvial systems whose discharge flows drain off either into ponds or directly into the estuary.

Geological setting

Geological units formed during the Late Tertiary–Quaternary are currently part of the surface context in Bahía Blanca region (Fig. 1). The Pampiano Formation, of Pliocene–Pleistocene age, is one of the most characteristic sequences in this area. This unit corresponds to deposits which are widely extended in the Pampean area in 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 Pampiano Formation at the subbottom (Aliotta et al., 2004; Spagnuolo, 2005; Lizasoain, 2007; Giagante, 2009). Its lithological characteristics, which were correlated by drilling logs, are similar to those found in the continental region. The "sedimentos Pampianos" within the submarine 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 coast north of our study area 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 Bahía Blanca area, particularly in the western sector of Bahía Blanca estuary, were also analyzed (Spalletti and Isla, 2003). In addition, by means of seismostratigraphic analyses conducted in the marine sector, fluvial events as well as paleochannel structures could be identified both in the estuary (Aliotta et al., 2004; Spagnuolo, 2005; Giagante et al., 2008) and continental shelf (Aliotta et al., 1999). 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 cycle. Likewise, the evolutionary process of the fluvial systems in the estuary is key to the sedimentological and morphological setting of the coastal margin.

Geological evidence indicates that the Holocene marine transgressive–regressive cycle has imprinted its particular features in the area where Bahía Blanca is located. The principal morphosedimentary characteristic of this cycle is the presence of sand ridges containing abundant remains of biogenic material, which are located 6–7 m above average sea level and are relatively continuous and parallel to the current littoral (Aliotta and Farinati, 1990; Farinati and Aliotta, 1997; Aliotta et al., 2003, 2006; Spagnuolo et al., 2006; Aliotta et al., 2008). 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 resulted from the progradation of clayey silt sediments during the last marine postglacial regressive event (Aliotta and Farinati, 1990). Their radiocarbon ages range between 3300 and 3900 ^{14}C yr BP. were determined from fossils in life position (Farinati et al., 1992; Aliotta et al., 2004). At the subbottom, the materials deposited during the transgressive–regressive cycle are arranged mainly in subhorizontal layers having large lateral continuity, although in some sectors they follow the substrate slope.

At present, the morphological configuration of the study area (Fig. 1) shows, in particular, a seafloor which is characterized by the presence of a relatively deep channel and shallow sectors. As of 10 m deep and parallel to the coast (northwest–southeast), there is a sector of the Principal channel whose bottom increases gradually from west to east along the navigation area, with values ranging from 13 m to 22 m. Isobaths are located relatively parallel to the coastline in the central-southern sector and towards the southeast to the marine area, forming the seafloor with a 1° slope to the center of the channel.

In the northwestern sector, isobaths display a configuration which is dominated by the alternation of banks and tidal channels ~9 m deep. They both have a dominant northwest–southeast lineament direction. Within this area, particularly on the seafloor, south of Belgrano harbor, there is a large platform located between isobaths 5 m and 7 m. This platform is connected to the navigation area of the Principal channel by means of a pronounced 2° slope.

The emerged coastal area adjacent to the marine sector under study is characterized by different morphological and sedimentary features derived mainly from the Holocene marine process (Fig. 1). A widely distributed intertidal zone from west to east can be clearly identified in this sector. This intertidal zone is partially covered by a large aeolian sand sheet where dunes frequently form. In the coastal area adjacent to Rosales harbor there is a small tidal channel, from whose margins, a muddy plain and an area with a salt flat and marsh surrounding it, extend. These features are observed at low topographic levels. Another common characteristic of the coastal environment in the area is the presence of sand shell ridges (Spagnuolo, 2005). The north coast of the estuary is also characterized by the presence of ponds, some of which are temporary as a consequence of the ephemeral contribution of the water courses in the zone. In addition, the Napostá Chico River, which has a ephemeral flow, is the main fluvial system in the northern sector of study zone.

Methods

The data analyzed in the present study were collected during geophysical surveys carried out in the marine zone of Bahía Blanca estuary (Fig. 1) on board the ship *Buen Día Señor*, which belongs to the *Instituto Argentino de Oceanografía* (IADO). The base map used contains navigation charts of the Argentine Naval Hydrographic Service as well as georeferenced aerial photographs. A differential global positioning system (DGPS) connected to navigation software was also used.

A digital–analogical echo sounder (Bathy-500MF de 200 kHz) was used to define the bathymetric characteristics of the study area. Seismic data of the marine subbottom was also acquired using high resolution seismic profiling operating with a frequency of 3.5 kHz. The emission source used was a transmitter GEOPULSE 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.

Tidal correction of bathymetric data was also perfomed. Depths were referred to the Datum Plane of Belgrano harbor (2.44 m below mean sea level), (Fig. 1). Data processing and analysis of seismic records were carried out following Mitchum et al. (1977). Discontinuity surfaces and sequence boundaries could therefore be identified and seismic reflector configurations and their type of termination were interpreted. These termination types showed different toplap, onlap and erosive truncation reflection terminations. Taking into account the sedimentary sequences recorded in the marine sector and the propagation velocities for different materials (Reynolds, 1997), thickness estimation of the seismic facies was carried out for an average speed of 1650 m/s.

Results

The sedimentary deposit at the subbottom (Fig. 2a) forms a sequence (FS) which has particular seismostratigraphic characteristics that are

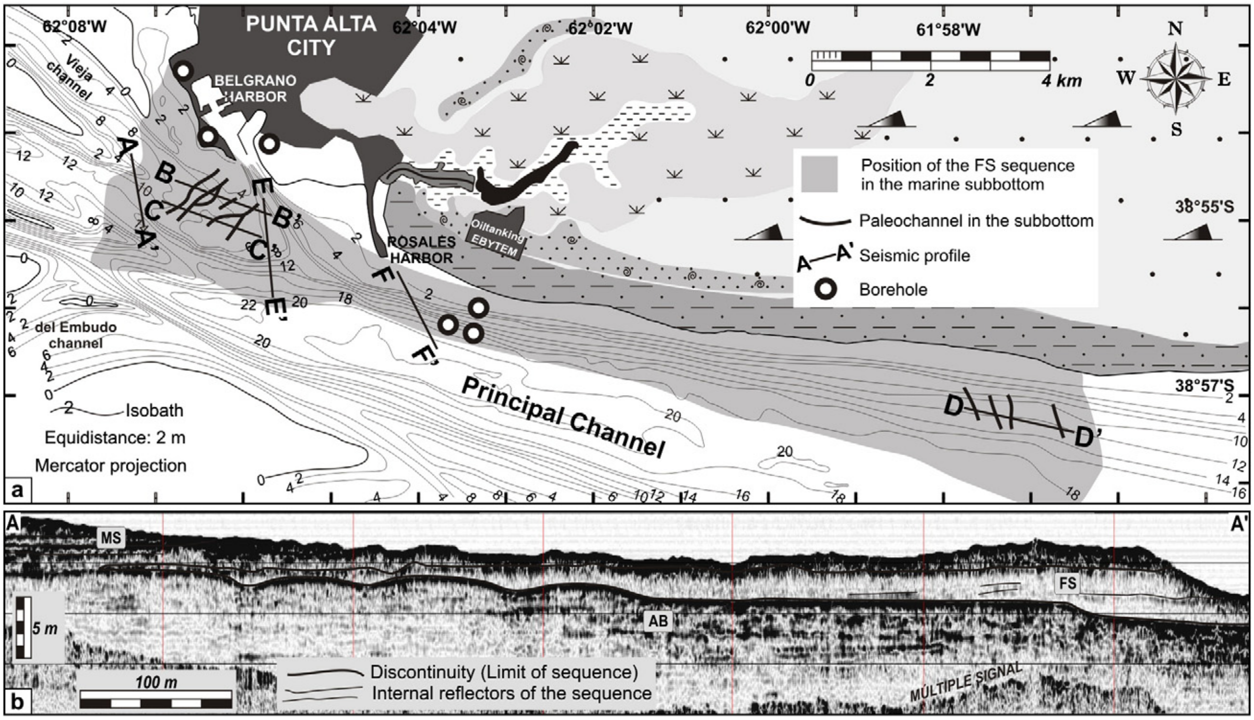

Figure 2. a. Location of examples of the seismic profiles (Figs. 2b, 3, 4 and 7). b. Identification of seismostratigraphic sequences (AB, FS, MS).

clearly different from those of upper and lower sequences (Fig. 2b). 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. Discontinuous wavy reflectors and v-shaped structures corresponding to small incisions were also identified in AB. Seismograms indicated that the AB upper boundary (i.e. FS floor) was characterized by a discordance of a strong acoustic signal and high lateral continuity. 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 Pampiano Formation. This sequence, which belongs to a continental paleoenvironment, is widely distributed in the coastal-marine region of the estuary, and is similar to the brown sandy clayey silt sediments, with calcareous materials, typical of the northern coast in Argentina (Cavallotto et al., 2005).

The basal boundary of FS is an erosive discontinuity surface evidenced by its high reflectivity and the presence of paleochannels (Fig. 3). The latter, such as those recorded in the western sector of our study area (Figs. 3a and b), were clearly shown in seismograms parallel to the coast. The incisions identified in this sector are located from 14 m below sea level, the largest of which has an apparent width of 270 m and an estimated depth of 10 m (Fig. 3a_1). 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 among depressions forming these incisions, thus forming topographic heights (Figs. 3a and b, *FR*). The latter were found to be arranged in a flat plane, giving rise to a flat relief among paleochannel deposits (Fig. 3a_2). The analysis of the seismic profiles perpendicular to the coast indicated that these planes could have formed part of a large regional plane with a smooth slope towards the south.

Paleochannels were also identified at the eastern end of the study area (Fig. 4a) although they were found to be located at a shallower depth (from 12 m) with respect to those at the western end. It was observed that the v-shaped incisions in this zone had a relatively symmetrical configuration. 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.

In agreement with the erosive nature of FS basal boundary, small incisions, irregularities and topographic steps were also found in the seismic profiles perpendicular to the coast (Fig. 4b). Another outstanding characteristic of this discontinuity surface was its tendency to become deeper towards the south. The sediments forming FS displayed a relatively transparent acoustic signal. This is a distinctive feature which makes this sequence different from other ones of the seismostratigraphic column identified in Bahía Blanca estuary (Giagante, 2009). Nevertheless, reflectors indicative of sedimentation processes acting in this erosive surface were found in the filling of paleochannels. Aggradation–progradation sedimentary structures and slightly oblique reflectors (Figs. 3a and b), both indicative of river bed silting, were found to dominate in the areas in front of Belgrano harbor (western sector). Onlap terminations were also found to be frequent in these structures. In some of the paleochannels, the filling material contained sedimentary structures having an asymmetrical configuration and was arranged as chaotic seismic facies with high acoustic reflectivity (Fig. 3a_1). These structures resulted from the irregularities of the erosive surface forming the paleochannels, the depositional energy conditions and the sediment granulometry (Schwarzer et al., 2006; Nordfjord et al., 2005; Green, 2009). The seismostratigraphic configuration of the filling material of paleochannels 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 (Fig. 4a) exhibited not only acoustically transparent sediments but also poor and slightly wavy reflectors. These seismostratigraphic characteristics are indicative of the material homogeneity which could be due to the presence of finer sediments and a decrease in depositional energy conditions with respect to the filling material in the western zone of our study area.

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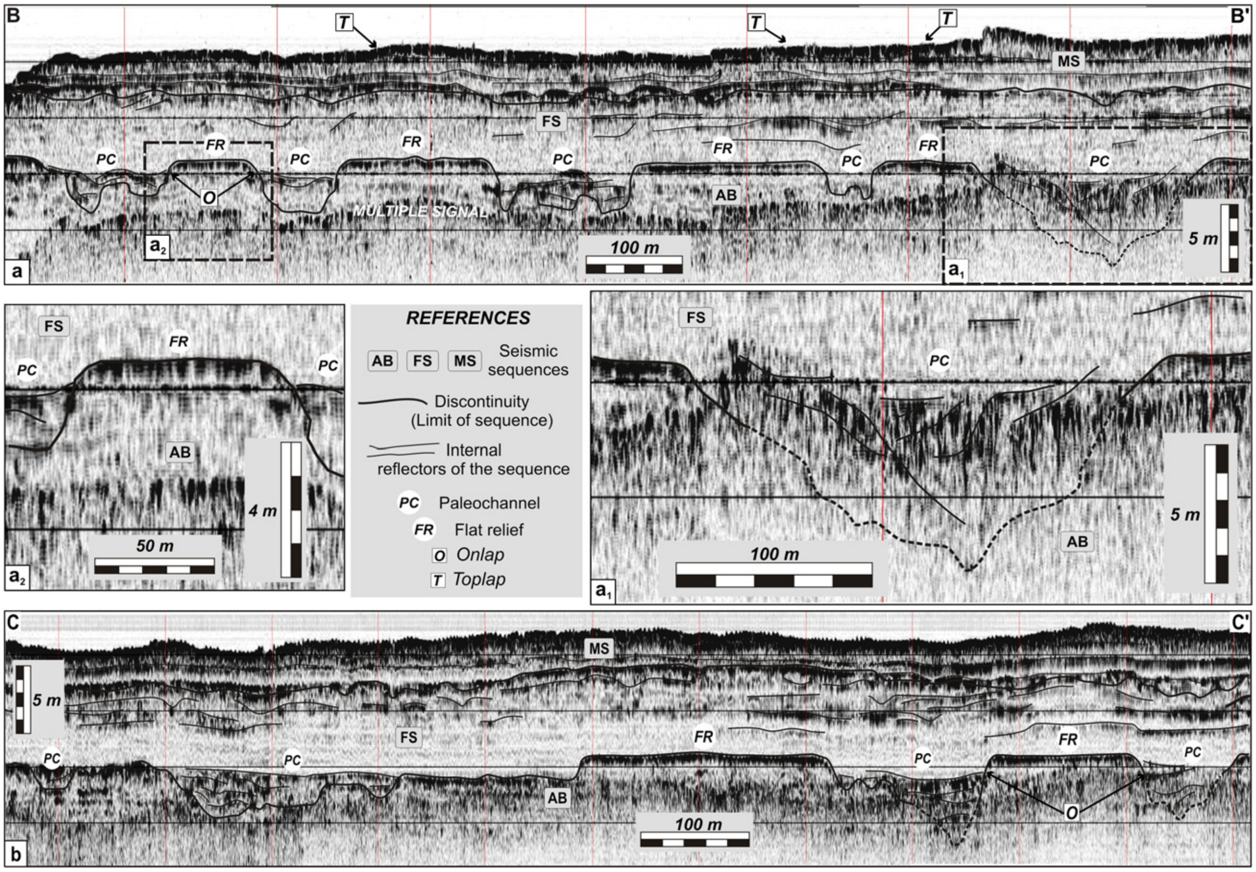

Figure 3. Seismic profiles showing typical paleochannel structures and seismostratigraphic facies of FS and MS sequences. Location of profiles in Fig. 2a. a. Profile B-B'. a_1. Zoom of a paleochannel structure. a_2. Detail of flat relief. b. Profile C-C'.

The FS mid-upper section was found to be characterized by the presence of weak, intermittent reflectors mainly in horizontal position and subparallel to each other although in some sectors they evidenced lateral continuity. Some of these reflectors occasionally exhibited slight inclinations and small concavities, thus indicating oblique sedimentary structures. The latter were clearly identified in the western sector of the sequence analyzed (Figs. 3a and b).

On the other hand, FS thickness was variable. It decreased significantly towards the east and west ends, this being shown in a

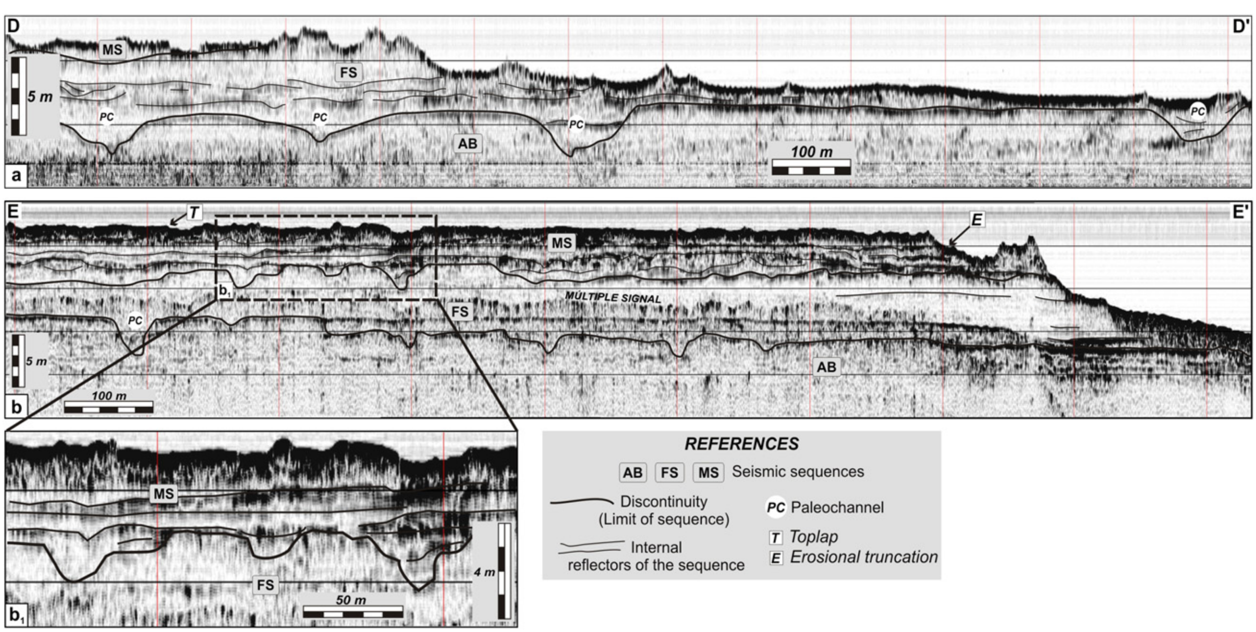

Figure 4. Characteristic seismic facies of FS and MS sequences. Location of seismic profiles in Figure 2a. a. Profile D-d'. b. Profile E-E'. b_1. Detail of small channels located at the base of the MS sequence.

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progressive wedging (Figs. 2b and 4a). It was observed that thickness decreased in both sectors as a result of the shallowing of the materials forming the substratum. On the other hand, 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 the lithological characteristics of FS. These borehole data showed that this unit is composed mainly of fine sand and silt-enriched layers and that it is slightly compacted. Both the semi-transparent configuration of this seismostratigraphic sequence and its low-amplitude reflectors evidenced these lithological characteristics.

The upper boundary of this sequence was indicated by a strong amplitude reflector. One of the irregularities of this boundary was the presence of v-shaped, ~2.5 m deep cuts (Fig. 4b) 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 (Figs. 3a, b and 4b). This seismic configuration was also evidenced in the materials filling the small channels located at the base of the sequence, showing their silting up (Fig. 4b_1). A clearly defined horizontal stratification exhibiting continuity all along the study area was observed towards shallower sectors. This arrangement is typically found in seismic profiles that are either parallel or perpendicular to the coast.

MS thickness was found to be variable all along the study area, reaching 5.5 m in some sectors. The upper boundary of this unit usually coincided with the seabed. In certain sectors, this discontinuity surface truncated the wavy-inclined reflectors of the unit, thus forming toplap configurations (Figs. 3a and 4b, *T*) whereas the depressions on the seafloor truncated the layers of the sedimentary unit (Fig. 4b, *E*). 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 actual depositional conditions.

Interpretation and discussion

The geological processes involved in the formation of the sedimentary units analyzed in the present study occurred on a dark gray to light brown, cemented clayey silt substrate. The seismic–lithologic correlation with existing boreholes in the study area (OILTANKING EBYTEM, 2000) has allowed us to associate these sediments – herein called AB sequence – with the Pampiano 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 of which has several paleochannels.

The incisions on the floor of FS (Fig. 3) were identified in the seismic profiles that were parallel and perpendicular to the adjacent coast. The pronounced slope of the paleochannels 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.

The action of old rivers with a dendritic drainage pattern gave rise to paleochannels (Fig. 5, sector I) whose irregular configuration suggests that they were formed during a high-energy erosive process. Furthermore, the analysis of the distribution of these paleochannels shows that they seem to be related to the coastal–continental sector emerging towards the north of our study area (Fig. 5). The regional morphological observations of the emerged area allowed us to identify lineaments which at present are the temporary fluvial courses ending at different ponds. Likewise, the orientation of these channels seems to indicate that they are also associated with the incisions found in the submarine sector.

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 (Fig. 6a) 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 our study area is included. 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). On the other hand, Vital and Stattegger (2000) defined stages of evolution for the Late Quaternary and categorized a relative sea-level fall, probably 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 present study, 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 marine shelf 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, 1996; Corrêa et al., 2004).

The prevailing paleoenvironmental conditions in the studied coastal 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 (Fig. 3). 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 (Bayón and Zavala, 1997; 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. 5, sector II). Also, the configuration of the channels in this sector and the seismostratigraphic characteristics 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 watercourses. From a paleoenvironmental point of view, the upper section of the unit corresponds to deposits close to

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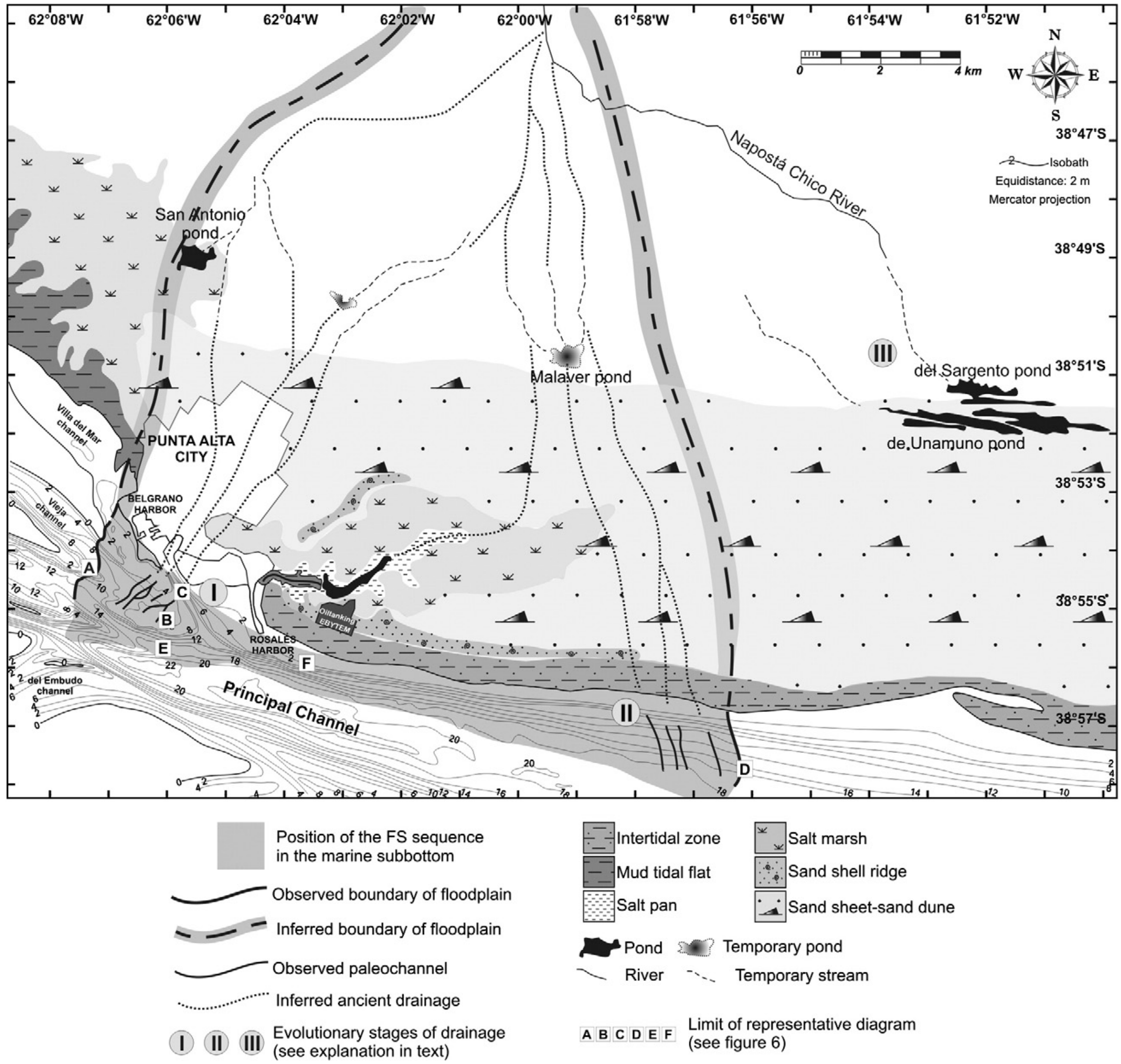

Figure 5. Evolutionary stages of the ancient drainage system associated with FS sequence.

the river base level. In this respect, observations from Posamentier et al. (1988) and 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 (Schumm, 1993; 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 Holocene (Fig. 6b).

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. 5). 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. On the other hand, according to Nichols and Fisher (2007), the seismostratigraphic configuration of the unit at the subbottom as well as its areal distribution pattern (Fig. 5) can be correlated with the distal area of fluvial deposits. Based on the seismic data collected in the present study it was possible to determine the east and west boundaries of FS, thus assigning it a lobe-shaped configuration.

The 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. 2b). This is, in general, associated with relatively uniform sedimentation processes in which deposited materials have high lithological similarity and low grain-size disparity.

At the beginning of sea-level rise during the 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 distal sector (Fig. 7). 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 (Fig. 7). On the other hand, 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. In addition, recent research on palynological associations in zones adjacent to our study area reported on the presence of vegetation associated with coastal dunes and inter-dunal lagoons (Quattrocchio

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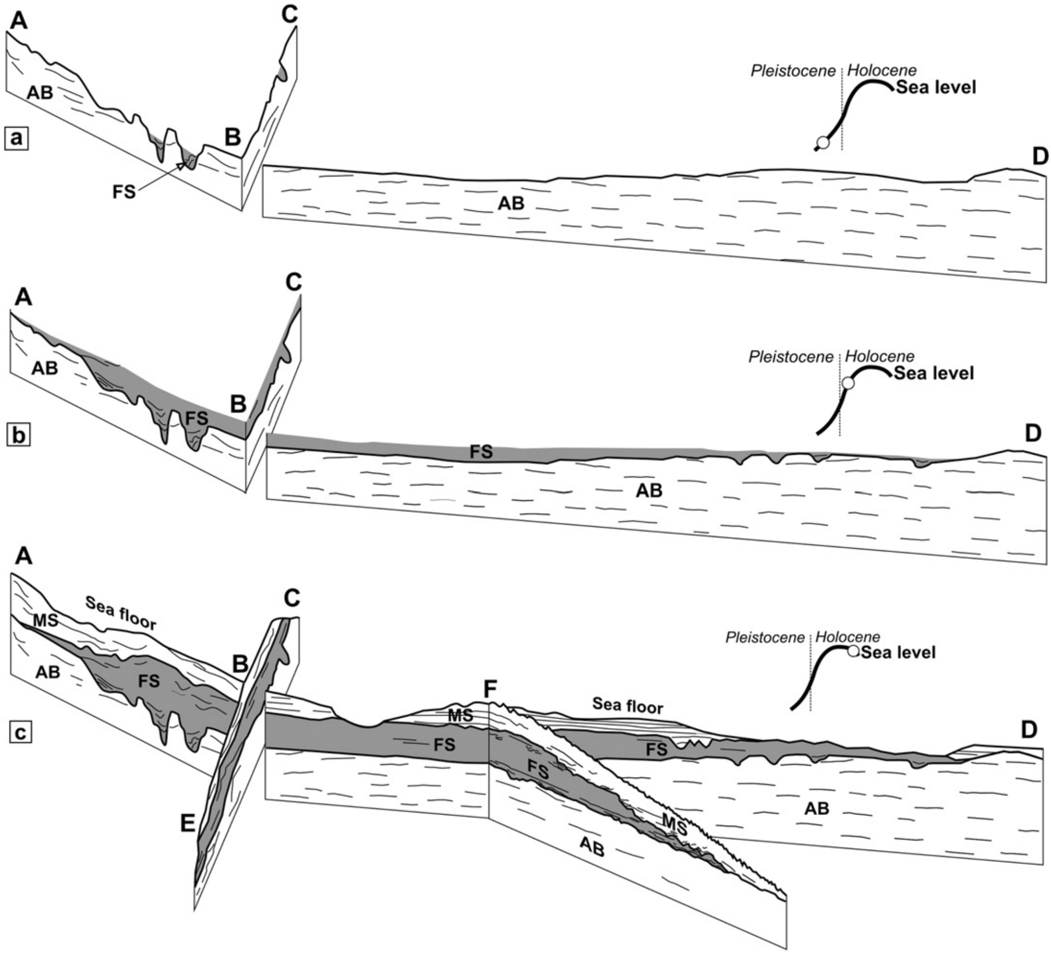

Figure 6. 3D interpretive scheme showing the evolution of FS sequence in response to the last marine transgression. a, b, and c represent different times shown by the circle on the sea-level curve at upper right.

et al., 2008). Concomitantly, 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. 5, sector 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. 6c). Maximum transgression then produced a series of sand shell ridges. These deposits which, in general, contain a high percentage of biogenic material, together with other ones located in different sectors of our study area, are typical morphosedimentary features of Bahía Blanca estuary (Aliotta and Farinati, 1990; Farinati and Aliotta, 1997).

Cavallotto et al. (2004) claimed that in the Holocene, coastal progradation was the most important process in the northern coast

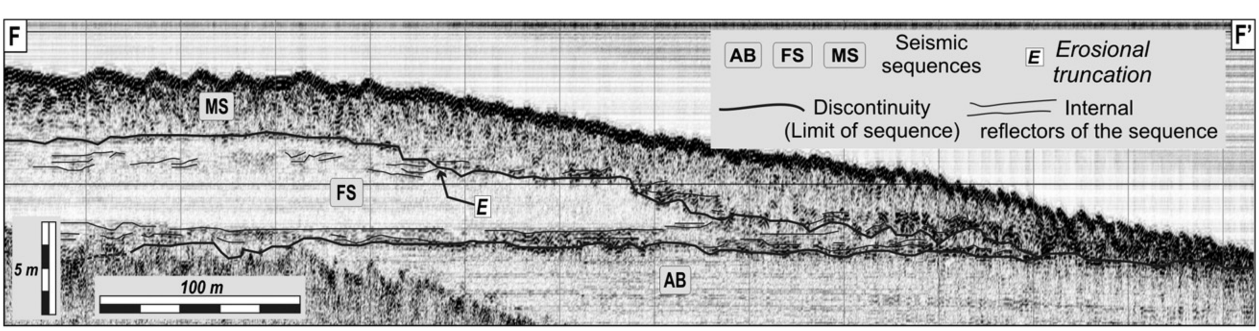

Figure 7. Seismic profile showing the seismostratigraphic relationship between FS and MS sequences in the sector of Rosales harbor. Location of profile in Figure 2a.

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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 sector, produced the shallowing of the coast and the formation of large tidal flats containing sandy clayey silt sediments. At the marine subbottom, these materials were observed to form part of the MS sedimentary facies which covers either all or part of FS (Fig. 6c). Both the origin and current configuration of this MS facies are closely linked to sea-level variations in the Holocene.

Conclusion

In the Late Pleistocene–Early Holocene 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 Southern Atlantic, giving rise to fine to medium sand deposits with silt-enriched levels. These reddish brown to grayish sediments having a varying degree of compaction were found forming FS which evidences an old fluvial sedimentary paleoenvironment. 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 ancient fluvial incisions were formed in periods during which the sea level was at least ~25 m below the current sea level and during which the environmental conditions were under continental regime. Both the silting and 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. The lateral continuity of this seismostratigraphic sequence, its geographical location and the orientation and distribution of paleochannels, are all features that lead us to associate FS with the sedimentary deposits derived from the old drainage system which formed the Napostá Chico River.

On the other hand, in response to the Holocene transgressive event the sea-level rise changed the base level of the hydric system in our study area and river flows decreased as a result of the increasing arid conditions typical of the Early Holocene. Sand availability increased significantly under these conditions in the coastal sedimentary paleoenvironment, thus forming a large sand sheet with extensive, eastwardly migrating, movable dunes. As a result of this process, which was accompanied by Holocene sea-level rise, the drainage system became endorheic and therefore FS at the subbottom demonstrates to be a stratigraphic evidence of the ancient Napostá River mouth.

Finally, in the shallowest sector of our study area, 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 regressive marine cycle were deposited on this discontinuity surface which was characterized by the presence of incipient tidal channels. These sedimentary deposits, as a whole, clearly respond to sea action, and form sedimentary facies which are characteristic of the current morphological configuration of this coastal area in Argentina.

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