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Morphodynamic behavior and seismostratigraphy of a sandbank: Bahía Blanca estuary, Argentina

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ABSTRACT

Sediment dynamics in Bahía Blanca estuary (Argentina) permit the formation of longitudinal banks, one of which is La Lista Bank, located at the mouth of the La Lista tidal channel. The purposes of the present research were to study the processes and mechanisms involved in the formation and maintenance of this bank, and to identify seismic sequences which could be indicative of its origin and current morpho-evolutionary trend. To this end, different methods and techniques, such as side-scan sonar, 3.5 kHz profiler and bottom sediment sampling were followed. The analysis of seismic-acoustic records revealed bottom features (sand dunes, sand ribbons, current marks, escarpment) which, based on our analysis of current measurements and our estimations of transport as bedload, have contributed to tracing a sediment circulation pattern in the study area. Taken together, these findings allowed us to identify the areas dominated by erosion, sediment transport or depositional processes. Bedload material was found to be exported to the outer sector and held on the flanks of the bank, particularly in its southern part. Inference on the morpho-evolutionary trend in the study area was based on evidence related to migration patterns and changes observed on the flanks and inner structure of the bank. The morphological evolution of La Lista Bank is associated to a residual sediment transport pattern with trajectories opposite on its two flanks, which results from the action of ebb tides in the northern flank and flood tides on the southern flank. This process induces a gradual increase in the bank height and longitudinal growth. The La Lista Bank evolution agrees with the motion sequence and development pattern proposed by Caston (1972) for a linear bank, except that this model is repeated as the bank grows. The seismostratigraphic data presented here indicates that the origin of this bank is associated with the Holocene marine regression process.

1. Introduction

Tidal banks are located in areas which are characterized by the presence of high amounts of sand as a result of sand-transporting hydrodynamics (Pattiaratchi and Collins, 1987; Hanna and Cooper, 2002; Berthot and Pattiaratchi, 2006a). They are elongated sedimentary bodies which are generally aligned with the water flow. Their morphology is the product of a non-linear interaction between tidal currents, sediment transport and bottom topography (Berthot and Pattiaratchi, 2006a).

Sandbanks are important marine sediment sources and are key to navigation and natural coastal defenses (Deleu et al., 2004). Research into their behavior and on erosion–transport–deposition processes is thus of great importance. Predicting sandbank evolution is highly relevant for engineering and coastal management work (Horrillo-Caraballo and Reeve, 2008). Sandbanks are either symmetric or asymmetric in their cross-section. They are, in some cases, several thousand meters long and a few meters wide and they may reach heights of several tens of meters (Trentesaux et al., 1999). There are many records of sand bodies from tidal environments evidencing a varied range of geometries (Stride, 1963; Rubin and McCulloch, 1980; Belderson et al., 1982; Stride et al., 1982; Yang, 1989; Ikehara and Kinoshita, 1994) which seem to result from eustatic changes at sea level (Nio, 1976; Nio and Nelson, 1982; Van den Berg, 1982; Nio and Yang, 1991). Sandbank origin, evolution and stability have been studied in detail in continental shelf areas (Houbolt, 1968; Caston, 1972; Swift, 1975; Huthnance, 1982; Williams et al., 2000; Deleu et al., 2004). In contrast, sandbanks in estuaries, albeit found commonly (Ludwick, 1974; Swift and Ludwick, 1976) have been poorly studied to date.

Estuarine bank location is determined by estuarine geomorphology. The existence of a trapping zone has been found to be key to estuarine bank formation (Mallet et al., 2000). In a comprehensive study on these sand bodies, Dalrymple and Rhodes (1995) concluded that they form in areas where there is no net longitudinal sediment transport.

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These authors therefore understand that those sectors of tidal channels in which residual ebb and flood transport occurs in opposite directions are optimal areas for their formation. As to the origin of estuarine tidal banks, only a few studies have been carried out to date, taking into account sequence stratigraphy (Dalrymple, 1992; Correggiari et al., 1996; Trentesaux et al., 1999). All in all, research on estuarine sandbanks appears to be insufficient and therefore further related studies are necessary to complement those already conducted in the field.

In view of the above, the purposes of the present research were to study the processes and mechanisms involved in the formation and maintenance of estuarine tidal banks, and to identify seismic sequences which could be indicative of their origin and present a morpho-evolutionary trend.

Our study area is located in Bahía Blanca estuary (Fig. 1), which occupies a large low coastal sector of Buenos Aires Province, Argentina. Its most distinctive morphological feature is the presence of a network of tidal channels which is separated by islands and large tidal flats. In general, the smallest channels flow from the inner plain to the largest channels, all of which drain into the Principal Channel path to the port complex in this region within which Bahía Blanca and Punta Alta cities are also located. The general circulation pattern in the estuary is dominated by a semidiurnal tidal wave (Perillo and Piccolo, 1991) with a mid-range in the Principal Channel of 3.04 m during spring tide and 2.50 m on neap tide. The reversing currents have vertically averaged maximum speeds ranging between 1.20 and 1.05 ms^{-1} for ebb and flood conditions, respectively.

Sediment dynamics in the study area permit the formation of longitudinal banks in the estuary's mouth sector. The main channels are therefore important sources of sediment and the channels, in turn, form large longitudinal banks in their mouths. The morphological similarity of banks exhibited by different tidal channels in the study area seems to indicate that they all follow the same dynamic pattern for their formation and maintenance. In view of this, the present research focuses on a typical bank, located at the mouth of a secondary channel called La Lista (Fig. 1).

2. Methods

Data were collected during different marine surveys (2005–2009) conducted on board the ship *Buen Día Señor*, which belongs to the *Instituto Argentino de Oceanografía* (IADO). A DGPS connected to navigation software was used to obtain positional data. Bed morphological features were analyzed using a SyQwest 200 kHz Bathy-500MF multi-frequency hydrographic survey echosounder and a side-scan sonar (SonarLink Seamap) with a 105 kHz model 272 towfish (scanning range of 100 m). The bathymetric data were referred to the datum plane of Ingeniero White Harbor (2.59 m below mean sea level).

Geological sub-surface data were collected from high-resolution seismic profiles using a 5430A Geopulse transmitter (3.5 kHz) of 10 kW maximum output and 0.1 ms pulse width. The seismic records were interpreted following that of Mitchum et al.'s (1977) study. The seismic sequences were correlated with lithostratigraphic data collected from boreholes (Nedeco-Arconsult, 1983) in the study area.

For the granulometric classification of the study area, sediments from the surface bottom were sampled using a snapper type sampler and an oceanographic sampler which was designed by Aliotta et al. (1997). The analysis of sediment samples was performed in the laboratory following the methods applied by Folk (1974). Statistical analysis of the data was made according to that of Folk and Ward's (1957) study and sediments were characterized as in that of Shepard's (1954) data which was modified by Vozza et al. (1974).

3. Results and discussion

3.1. Morphological features and sediment circulation

The morphological features described are based on bathymetric surveys carried out by Vecchi et al. (2008). It shows that La Lista Bank stands out in the mouth area of La Lista Channel (Fig. 1). This sediment body was found to have a general NW–SE orientation, parallel to the Principal Channel and delimited between isobaths 1 and 8 m with a length of ~4 km and a maximum width of ~800 m. An 800 m-wide and 9 m-deep channel could be observed at the southern end of this sediment body. In its northern portion, La Lista Bank was found to display a distinctive zig–zagged pattern which became elongated towards the south. All along its length, its cross-section was observed to evidence changes, being asymmetric mainly in the northern and middle sections (Fig. 1, a–a′, b–b′ and c–c′). It was also observed that the first portion showed, in general, that the average slope is lower in the north (0.5°) than in the south (2.5°). In the middle section of the bank (Fig. 1, c–c′), asymmetry was found to be reversed, with the greatest inclination (4.5°) being in the NE flank. In contrast, in the southern portion of the bank a symmetric topographic profile with 2° inclined flanks (Fig. 1, d–d′) was observed. The crest was left exposed only during the lowest tides in spring.

Sedimentologically the bed of the mouth of the La Lista Channel was sandy (Fig. 2) with the largest grain sizes being found on the bank. In contrast, fine sand was found in the central portion of the La Lista

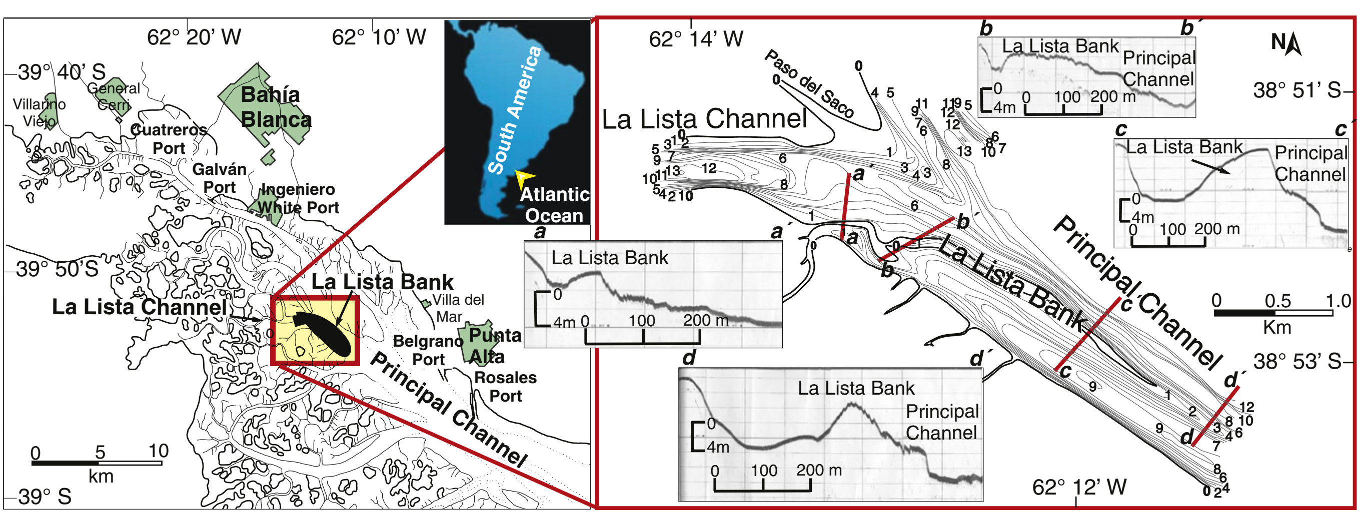

Fig. 1. Location of the study area. Echo-sounder cross-sections of La Lista Bank.

Channel and in the confluence with the Principal Channel. Clay–silt and sand–clay–silt materials predominated on both flanks of the channels. The crest of the bank was composed of medium-sized sand with abundant shell fragments. On the northern flank fine sand predominated, while in the southern flank there was silty, clayey sand. Marginal channel sediment ranged from clayey silt in the southern sector to silty, clay–sand in the inner sector.

The analysis of seismic–acoustic records revealed different bottom characteristics, sedimentary structures and erosional features. The movement of the bottom sediment induced the formation of a series of rhythmic morphological features, i.e., sedimentary tidal bedforms. In the assumption that bedforms are in equilibrium with the current hydrodynamic conditions (Ikehara and Kinoshita, 1994), their distribution, arrangement and morphology are an important source of information on currents. Furthermore, since bedform dimensions are believed to be proportional to current intensity, those related with strong hydrodynamic conditions are the largest ones (Flemming, 1978; Twichell, 1983).

Bedform asymmetry is the result of inequality between ebb and flood currents, thus making it possible to infer sediment transport from such asymmetry (Allen, 1968a, 1968b; Bokuniewicz et al., 1977; Swift and Freeland, 1978; Langhorne, 1982; McCave and Langhorne, 1982; Twichell, 1983; Harris, 1988a, 1988b). Previous research concluded that medium-and large-sized dunes can be considered relatively stable, as their net movement is not affected by tidal changes (Bokuniewicz et al., 1977; Fenster et al., 1990; Fenster and Fitzgerald, 1996). The direction of residual sediment transport as bedload can therefore be estimated through the asymmetry of bedform profiles on account of the fact that lee slope position remains the same throughout the tidal cycles (Dalrymple and Rhodes, 1995).

Following Ashley's (1990) study, the dune-types found among the depositional forms were classified as small-, medium- and large-sized dunes. In the study area, the dunes were of different sizes (Fig. 2) and had both straight and sinuous crests. Small asymmetric dunes with heights (H) lower than 0.4 m and a wavelength (L) of 8 m were found widely distributed in the area. Medium- and large-sized dunes with H ranging between 0.4 and 1.5 m and L varying from 5 to 18 m were in general found at the mouth of La Lista Channel. They exhibited marked asymmetry with lee slope facing east, and crestlines had an N–S orientation which gradually rotated in a NE–SW direction as they approached the Principal Channel. The asymmetry of large–medium dunes within La Lista Channel is indicative of residual sediment transport as bedload towards the outer zone, this being, in turn, indicative of a circulation pattern mostly linked to the action of ebb currents.

The presence of sand ribbons (300 m length and 30–40 m wide) on a substrate with high-acoustic reflectivity and a thin sand-cover in the

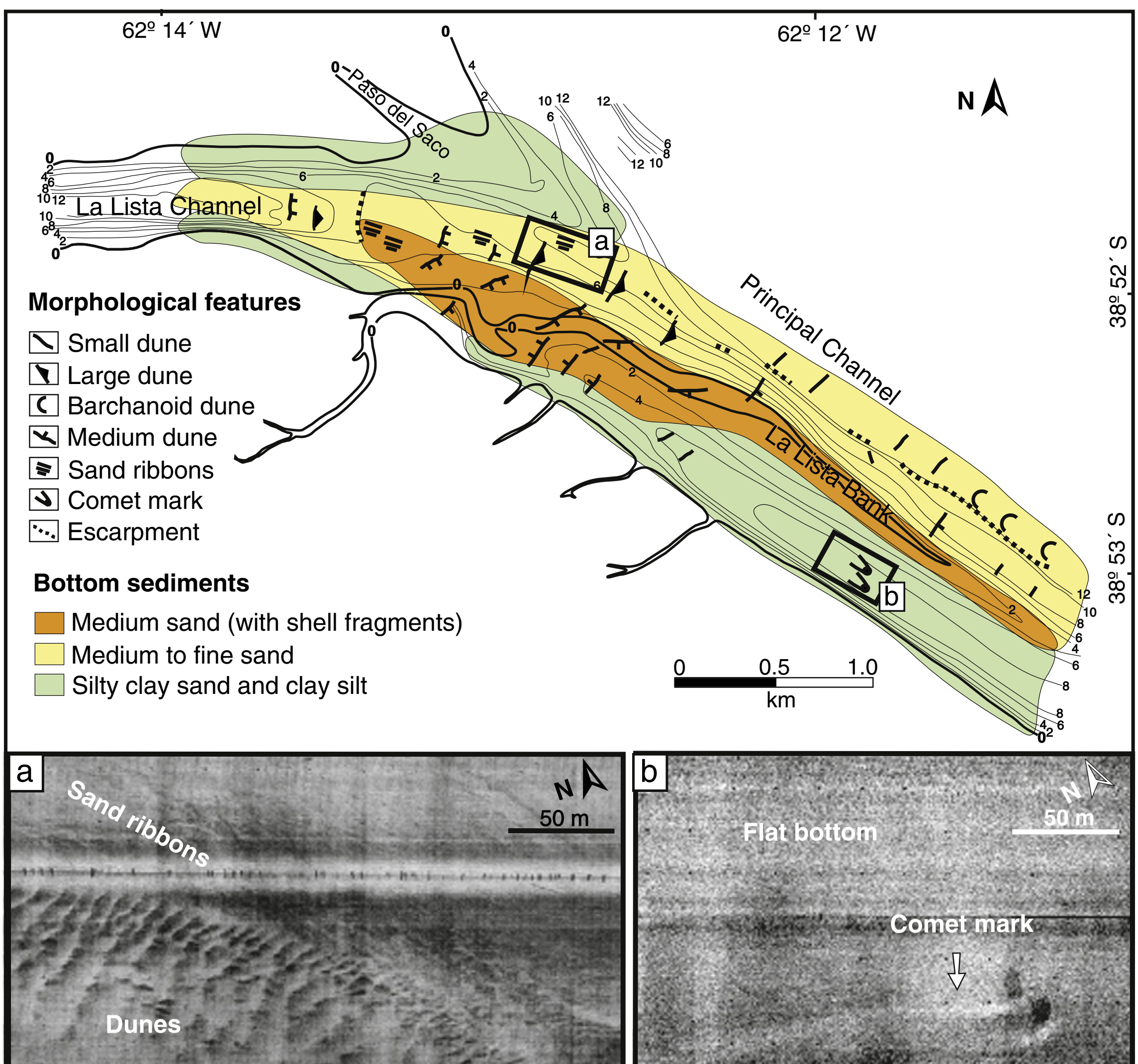

Fig. 2. Principal types of surface sediments. Seabed morphological features in the study area; (a) and (b): side-scan sonar records.

mouth of La Lista Channel indicates that the area is exposed to strong hydrodynamic conditions. It was observed that sand ribbons form in high current velocity areas as well as in helical flow generation sectors (Allen, 1966, 1968a; Wilson, 1972; Amos and King, 1984). Both the ebb currents and the topographic step at the mouth of La Lista Channel are key to the hydrodynamic conditions under which turbulent flows are produced, thus forming these bedforms.

Dunes of different sizes were also found on both sides of La Lista Bank (Fig. 2), being larger on the northern flank ($0.1<H<0.5$ m and $3<L<10$ m) (Fig. 2a) than on the southern flank ($H=0.2$ m and $2<L<5$ m). Bedforms on the northern slope were found to be asymmetric (SE-oriented lee slopes) and those located near the bank crest were observed to migrate towards the southern flank and crossing the bank crest with a 30° average angle. Large dunes ($1.5<H<2$ m and $20<L<25$ m) with asymmetric profile, SE-oriented lee slopes and barchanoid crests were found in the deepest area surveyed at the Principal Channel (Fig. 2).

Small- and medium-sized dunes ($0.2<H<0.5$ m and $2<L<10$ m) in the marginal channel on the south of the bank, with crests varying from straight to sinuous and asymmetric profiles with NW-oriented lee slopes are indicative of sediment transport towards the inner sector. Likewise, the presence of current marks (comet marks), having lengths of ~200 m and widths ranging between 5 and 25 m, is also evidence of flood current predominance (Fig. 2b).

The analysis of bottom current measurements in the study area (Vecchi et al., 2008) evidenced time–velocity asymmetry. Currents in the La Lista mouth area, near the northern flank of the bank, were found to evidence velocity asymmetry. In addition, ebb currents in this sector had higher values (0.50 m s^{-1}) than those of flood currents (0.40 m s^{-1}), thus resulting in ebb current dominance. In contrast, time asymmetry in the marginal channel (south of the bank) as a result of longer flood duration (7 h) with respect to ebb duration (5 h) was found to produce residual currents towards the inner sector of the estuary.

The sediment circulation pattern at the sea bottom evidenced by bedforms is in agreement with the sediment transport estimates calculated from the data obtained from current measurements carried out at different stations in the study area by Vecchi et al. (2008). In the aforementioned research, sediment transport estimation as bedload was done using Bagnold's (1966) formula which was modified by Gadd et al. (1978). Net sediment transport in the La Lista mouth area was 2.188 g m^{-1} s^{-1} in the ebb direction while in the marginal channel, south of the bank, it was 0.451 g m^{-1} s^{-1} in the flood direction (Fig. 3). Thus, most of the material was found to move along the northern flank of the bank towards the outer sector of the estuary. Emphasis is put on the fact that the asymmetry of large-sized dunes on the northern flank of the bank and the structures formed in the marginal channel of the south are indicative of opposite residual sediment transport in both flanks of the bank. The integration of the current velocity data with bedforms surveyed allowed us to outline a quantitative estimate of bedload sediment transport in the surroundings of the La Lista Bank (Fig. 3).

Caston (1972) suggested that ebb–flood current dominance on each side of a sandbank generates differences in the rate of sediment transport, thus causing deformation of the bank crest. Thus, the crest tends to have a sigmoid (zig–zag) configuration and eventually divides itself into two or more parallel small banks, separated by channels. According to Caston's model, an unequal, residual sediment transport occurring in the opposite directions on both flanks of La Lista Bank could have caused the current slightly sigmoid configuration of the northern bank portion. Likewise, dune features on the northern flank and crest area suggest that part of the sediment circulating in the north tends to move towards the southern flank, crossing the bank, thus leading to clockwise residual sediment circulation. Such a sediment circulation pattern around the sediment body could have contributed to both its evolution and maintenance.

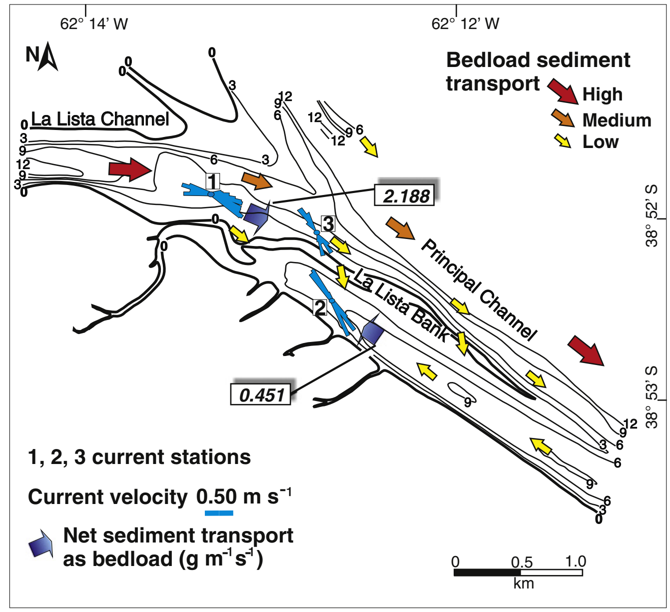

Fig. 3. Comparative scheme showing current sediment mobilization capability in the study area. Current vector decomposition is shown at stations 1 and 2. Current frequency is shown at station 3. Qualitative scheme of sediment transport as bedload around La Lista Bank is also presented.

3.2. Seismostratigraphy

The acoustic basement (AB) of our study area, at approximately 13 m below the datum plane of Ingeniero White Harbor, was found to have not only a smooth slope towards the SW but also some intermittent sub-horizontal and irregular reflectors (Fig. 4). Drilling data showed that AB consists of a set of highly compacted and partially cemented sediments composed of a 0.30 to 0.90 m-thick layer of reddish brown cemented clay, and 4.30 m-thick stratum of cemented sand, and gray-brown silty fine sand located beneath (Fig. 4, a–a′ and c–c′; Nedeco-Arconsult, 1983). The compaction of AB explained its acoustic behavior, which prevents seismic wave propagation from occurring.

On top of AB, horizontal and sub-horizontal reflectors were observed, characterizing S1 (Fig. 4, a–a′ and c–c′). S1 presented some acoustic transparency. It was found to coincide with a maximum of 4 m of dark gray, moderately compacted, fine-to-medium sand as well as of some silt layers in borehole data (Nedeco-Arconsult, 1983).

Lithological features of AB and S1 materials seemed to indicate that AB and S1 are associated to the Pampiano Formation (Plio-Pleistocene) (Fidalgo et al., 1975). Several researchers have, in fact, identified this formation, which is genetically linked to fluvial and aeolian processes in the sub-bottom area of Bahía Blanca estuary (Fidalgo et al., 1973; Aliotta et al., 1991, 1992; Lizasoain and Aliotta, 1995; Aliotta and Lizasoain, 1998; Spagnuolo, 2005; Giagante et al., 2008).

In the upper part, AB and S1 were found to exhibit erosion discordance throughout the study area, the origin of which could be associated with an old fluvial system prior to the Holocene marine transgression (Aliotta et al., 1996a, 1996b, 2002, 2004; Briceño et al., 2005; Giagante et al., 2005; Spagnuolo, 2005). In addition, over AB and S1 a paleochannel was found (S2) with filling material consisting of ~3.30 m of fine sandy silt (Nedeco-Arconsult, 1983) (Fig. 4, a–a′ and b–b′). Its reflectors were found to be well-defined, parallel to sub-parallel and inclined, and they had divergent configuration which could have been the result of residual vertical aggradation as a consequence of sea-level rise.

In a previous study, Giagante et al. (2008) identified two sequences (S2a and S2b) which, according to their lithological and seismostratigraphic characteristics such as the presence of paleochannels, could be correlated with S2 in the present study (Fig. 5, b–b′). These

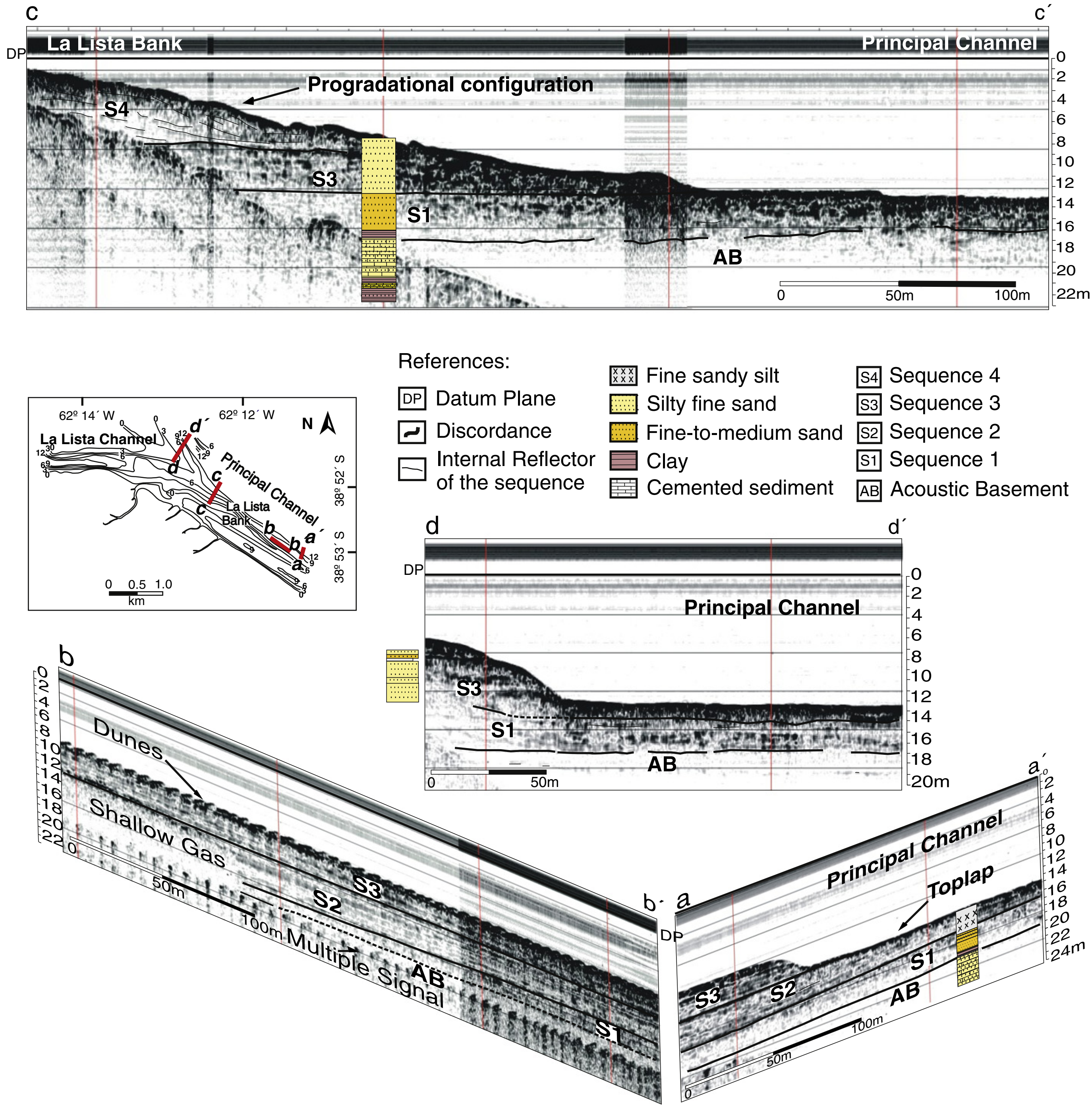

Fig. 4. Seismic profiles in the Principal Channel showing the acoustic basement and the seismic sequences S1, gas-trapping S2, S3 and S4; correlation between seismic sequences and borehole materials.

researchers also demonstrated that S2a and S2b have sediments that are deposited on top of the Pampiano Formation and that they are associated with deltaic sediments from a Colorado River ancient basin. S2 could thus be related to fluvial–deltaic deposits of this river basin. Gas accumulation zones associated to S2 sediments were also identified. It was observed that shallow gas masquerades reflector sequence (Fig. 4, b–b′), thus resulting in anomalous seismic signals. These gas accumulations were found at an average sea bottom depth of 4 m forming large bags either ~130 m long or in the shape of larger deposits (up to 475 m long). Methane has been found to be the main component of these accumulations (Kaplan, 1974; Davis, 1992; Floodgate and Judd, 1992; Premchitt et al., 1992; García-Gil et al., 2002; Aliotta et al., 2006). In agreement with observations on other parts of the Bahía Blanca estuary by Briceño et al. (2005), Gigagante et al. (2005), Aliotta et al. (2006) and Lizasoain (2007), it was observed that in our study area gas is, in general, related with paleochannels. Aliotta et al. (2006) associated the presence of gas-containing sediments with paleoenvironmental evolutionary processes related to Holocene sea-rise during which continental organic matter burial occurred as a result of the action of transgressive sediments.

S3 (~6 m-thick) is the base of La Lista Bank and has well-marked, horizontal and continuous reflectors (Figs. 4 and 5). This sequence was observed across the entire study area exhibiting erosional truncations in the Principal Channel, as well as layers of regular thickness,

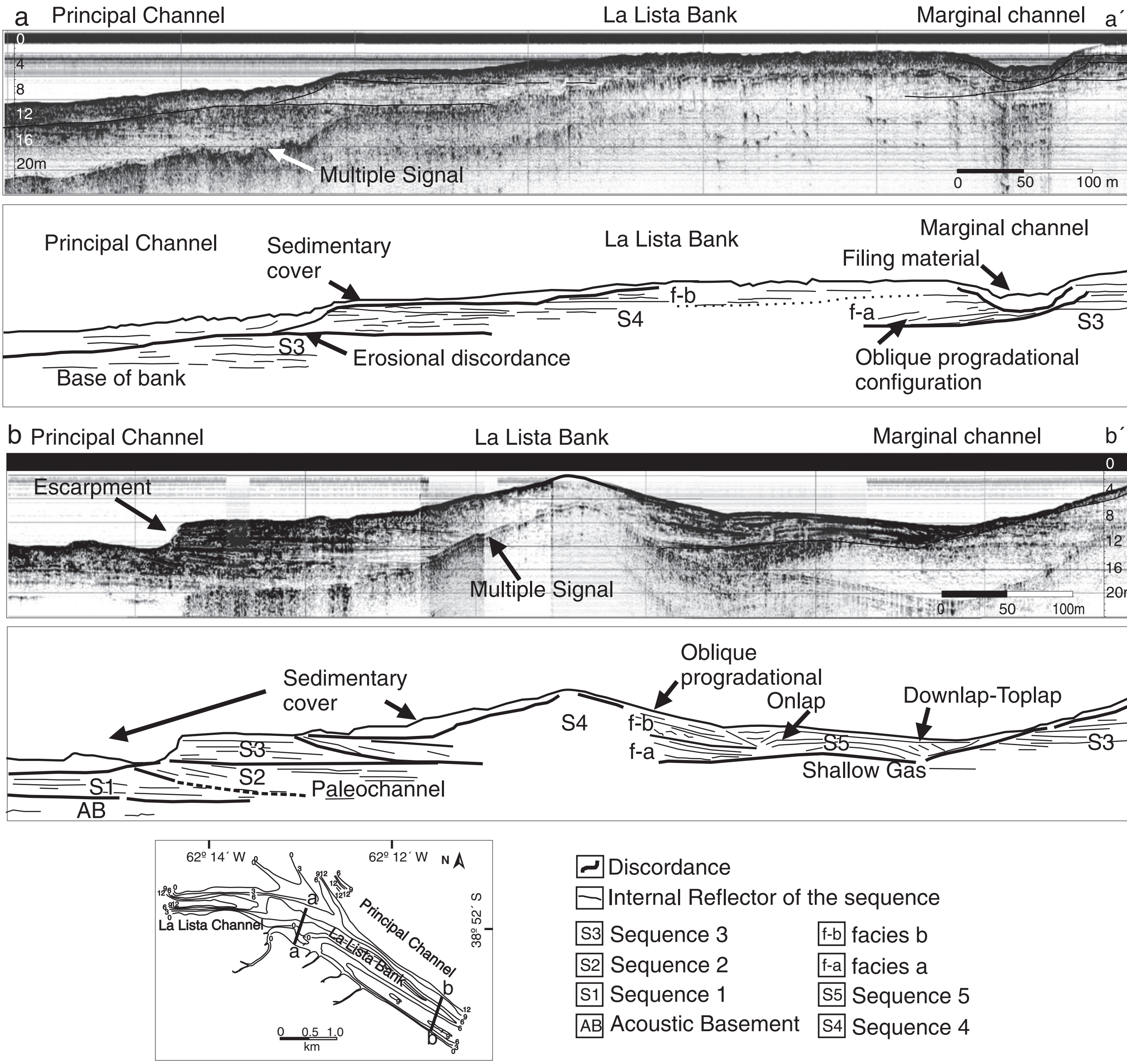

Fig. 5. Identification of the acoustic basement, seismostratigraphic sequences (S1, S2, S3, S4 and S5), and facies (fa and fb) in the seismograms transverse to La Lista Bank.

forming part of the sediments of the southern margin of the Principal Channel and La Lista Channel (Fig. 4). The sediments in S3 were observed to correspond to the gray, slightly compacted silty fine sand found in boreholes (Nedeco-Arconsult, 1983) (Fig. 4, c–c′ and d–d′).

After channel burial (S2), sea levels continued rising, thus leading to the growing development of tidal flats which gave rise to the formation of S3. Malacofauna isotopic dating indicates that marine ingression, which was key to tidal flat formation, affected the coastal area of Bahía Blanca estuary during Middle–Late Holocene, after 7500 ^{14}C years BP (González et al., 1983; Farinati, 1985; Aliotta and Farinati, 1990; Aliotta et al., 2004; Spagnuolo, 2005).

The sediments of the S4 and S5 sequences were found above S3. S4 materials and their facies were associated with La Lista Bank sand deposits (Figs. 4, c–c′ and 5). The lower facies of S4 (f–a) was identified grouping the innermost reflectors of the bank (Fig. 5, a–a′). It was found to have well-marked, parallel to sub-parallel, horizontal reflectors on both flanks of the bank, showing toplap-type reflector terminations and oblique progradational configuration. Seismic facies f–b was located on top of f–a (Fig. 5, a–a′), exhibiting well-marked reflectors having either a horizontal parallel configuration or an oblique and sigmoid progradational configuration. In general, f–b was found to be thicker on the southern flank, exhibiting, in some sectors, toplap terminations (Fig. 5).

Seismic records revealed that La Lista Bank largely occupies an old, erosive, horizontal and irregular surface which outcrops in certain deep sectors of the Principal Channel and behaves as the upper boundary of S3. The presence of an erosional base in a sandbank is one of the typical seismostratigraphic features in this type of sediment body. Several studies conducted in different parts of the world have identified discontinuity surfaces resulting from the erosive action of Holocene sea-level rise and upon which sandbanks form (Houbolt, 1968; Laban and Schuttenhelm, 1981; Davis and Balson, 1992; Van de Meene, 1994; Collins et al., 1995; Park et al., 2003; Berthot and Pattiaratchi, 2006a, 2006b). It can therefore be inferred that, as it occurred in other coastal regions of the study area, after sea-level rise and its subsequent erosive effect on the seabed and channel flanks, there followed a regressive stage allowing the accumulation of sand (S4) in the mouth of La Lista Channel, thus favoring bank formation.

The filling material from the marginal channel located in the south of the bank as well as the material from the upper levels of the flanks form sequence S5 (Fig. 5,b–b′) whose thickness (maximum 4.20 m) decreases until practically disappearing in the north of the marginal channel. S5 sediments were found to interdigitate with S4 sediments and were observed to be deposited on an erosional discontinuity affecting f–a, f–b and part of S3. S5 facies is acoustically transparent with well-defined, continuous, parallel to sub-parallel reflectors, having downlap and onlap terminations and either a horizontal, oblique or hummocky-type configuration (Fig. 5, b–b′). S5 reflectors, which are in general parallel to the sea-bottom indicate that this sequence, is the result of the current hydrosedimentological conditions in the area, such as the occurrence of modern infilling and sediment deposition in the upper levels of flanks.

3.3. Evolutionary pattern and morphodynamics

The high-resolution seismic data analyzed and the morphological features identified in the present study, reveal the evolutionary process of the bank as well as the sediment dynamics occurring in the study area. Plio-Pleistocene sedimentary sequences, identified as AB, S1 and S2, represent a continental sedimentary paleoenvironment which was highly influenced by an ancient fluvial drainage system. Numerous seismic configurations of the paleochannel present in the sub-bottom of Bahía Blanca estuary (Aliotta et al., 1991, 1992; Lizasoain and Aliotta, 1995; Aliotta and Lizasoain, 1998; Spagnuolo, 2005; Giagante et al., 2008, 2011) are evidence of a large alluvial plain composed of numerous fluvial dendritic courses which was formed in this coastal area of the Southern Atlantic. These ancient fluvial incisions were formed in periods during which the sea level was at least ~30 m below the current sea level and during which the environmental conditions were under a continental regime. These fluvio–deltaic deposits gave way to sediments of the Holocene marine transgression. Rising sea levels in a first stage originated the development of tidal flats, which gave rise to the deposition of the sedimentary sequence identified as S3. Malacofauna isotopic dating indicates that marine ingression, which was key to tidal flat formation, affected the coastal area of Bahía Blanca estuary during the mid to late Holocene, after 7500 ^{14}C years BP (González et al., 1983; Farinati, 1985; Aliotta and Farinati, 1990; Aliotta et al., 2004; Spagnuolo, 2005).

The evolutionary process continues with coastal progradation which was the most important process in the northern coast of Argentina during sea-level fall (Cavallotto et al., 2004) when these littoral areas were converted to tidal flats and marshes. The regressive process, particularly in the Bahía Blanca zone, produced the shallowing of the coast and the formation of large tidal flats containing sandy clayey silt sediments. In this environment, dominated by tidal action, numerous channels began to develop.

Thus, based on the ancient continental sequences observed (BA, S1 and S2) and marine transgressive sediments (S3) in the area of the mouth of La Lista Channel, it could be concluded that a spit-type bar deposit began to form (Fig. 6, a; S4 sequence). The oldest sediments of the bank (S4, f–a facies), which were identified from the seismic records, were found on the southern flank of La Lista Channel in the mouth area (Fig. 5, a–a′). S4 reflectors were observed to have an oblique progradational configuration, thus evidencing the accretionary process experienced by the first bank materials. On the other hand, progradational seismic configurations are interpreted as lateral constructions which, according to Mitchum et al.'s (1977) study, are indicative of highly depositional environments with significant sand availability.

The progressive sedimentation of the S4 sequence originated the sand body with gradual progradation of its flanks, simultaneously undergoing elongation towards the SE. Parallel to the bank growth, the flood channel began to form on the south of the bank (Fig. 6b). Here, the shallower reflectors, which are in general parallel to the sea-bottom, indicate that this sequence (S5) is the result of the present hydro-sedimentological conditions in the area, such as the occurrence of modern infilling and sediment deposition on the upper flanks. Thus, the morphological evolution of La Lista Bank is associated with a residual model of sediment transport with opposite paths on both sides of the bank. This process tended to promote a gradual increase both in height and length towards the outer area. In view of the above, it could be assumed that La Lista Bank was formed as a result of sediment accretion particularly on its northern flank until reaching considerable height. La Lista Bank could have subsequently modified the hydrodynamic conditions of the area, behaving as a submerged "barrier" favoring the action of flood currents in the marginal channel (south of the bank). In relation to this, significant accretion could have therefore occurred. Moreover, our seismic analysis showed interdigitation between S4 and S5 sequence sediments (Fig. 7, d–d′), indicating simultaneity in the deposition process between the southern flank and the channel to the south of the bank. Both the downlap and onlap reflector terminations and the horizontal, oblique or hummocky-type configurations of S5 (Figs. 5, b–b′ and 7) revealed the present hydro-sedimentological conditions, i.e., a prevalence of depositional processes. Sediment supply to this area could be related to the action of ebb currents running through the bank and of flood currents coming from the south in the marginal channel.

Considering the current hydro-sedimentological conditions, seismic data from the center of the La Lista Channel showed no significant deposition processes, thus suggesting that this sector behaves as a sediment pathway (Fig. 7, a–a′ and b–b′). The presence of rock outcrops and erosional truncation evidenced non-deposition processes and an incipient erosional process, particularly towards the northern flank of La Lista Channel (Fig. 7, a–a′). These conditions were found to reverse towards the southern area, where a significantly thick sediment layer could be identified covering the flank and forming dunes. These sediments could also be found over part of the channel bed, with oblique progradational configuration, thus indicating sediment progradation and deposition. Taking into account the evolutionary trend of the southern flank of La Lista Channel, it could be assumed that it is dominated by the presence and development of La Lista Bank.

Previous research has provided evidence on the evolution and morphological changes of La Lista Bank (Ginsberg, 1991). By examining the evolution of the northern sector of the bank, between 1977 and 1989, Ginsberg (1991) observed crest partition and subsequent formation of three small-sized, elongated banks, which is consistent with the sequence of movement and development of linear banks proposed by Caston (1972). The comparative analysis of Ginsberg's (1991) geomorphological map and that used in the present study indicates that the hydro-sedimentological conditions to which La Lista Bank was exposed during the last decade promoted the unification of the bank crest. Furthermore, the extent of a continuous sediment supply from La Lista Channel and from adjacent tidal creeks was such that it led to the connection between La Lista Bank and the southern flank of La Lista Channel. The bank crest was found to have a slight curvature in its northern section, highlighting a zig–zag configuration (Fig. 1). Thus, observations from our study lead us to hypothesize that Caston's (1972) model is repeated as the bank grows, giving rise to successive "cut and connect" cycles in estuarine environments. These variations could be linked to the action of erosive processes in the inner sector of La Lista Channel that introduces materials into the system, changing the sediment availability, deposition areas and forms.

At present, the northern flank of La Lista Channel is found to undergo limited sediment addition. Nonetheless, the seismostratigraphic characteristics of the area indicate a relatively important depositional process on this flank from the middle sector to the south (Fig. 7, b–b′). Dunes

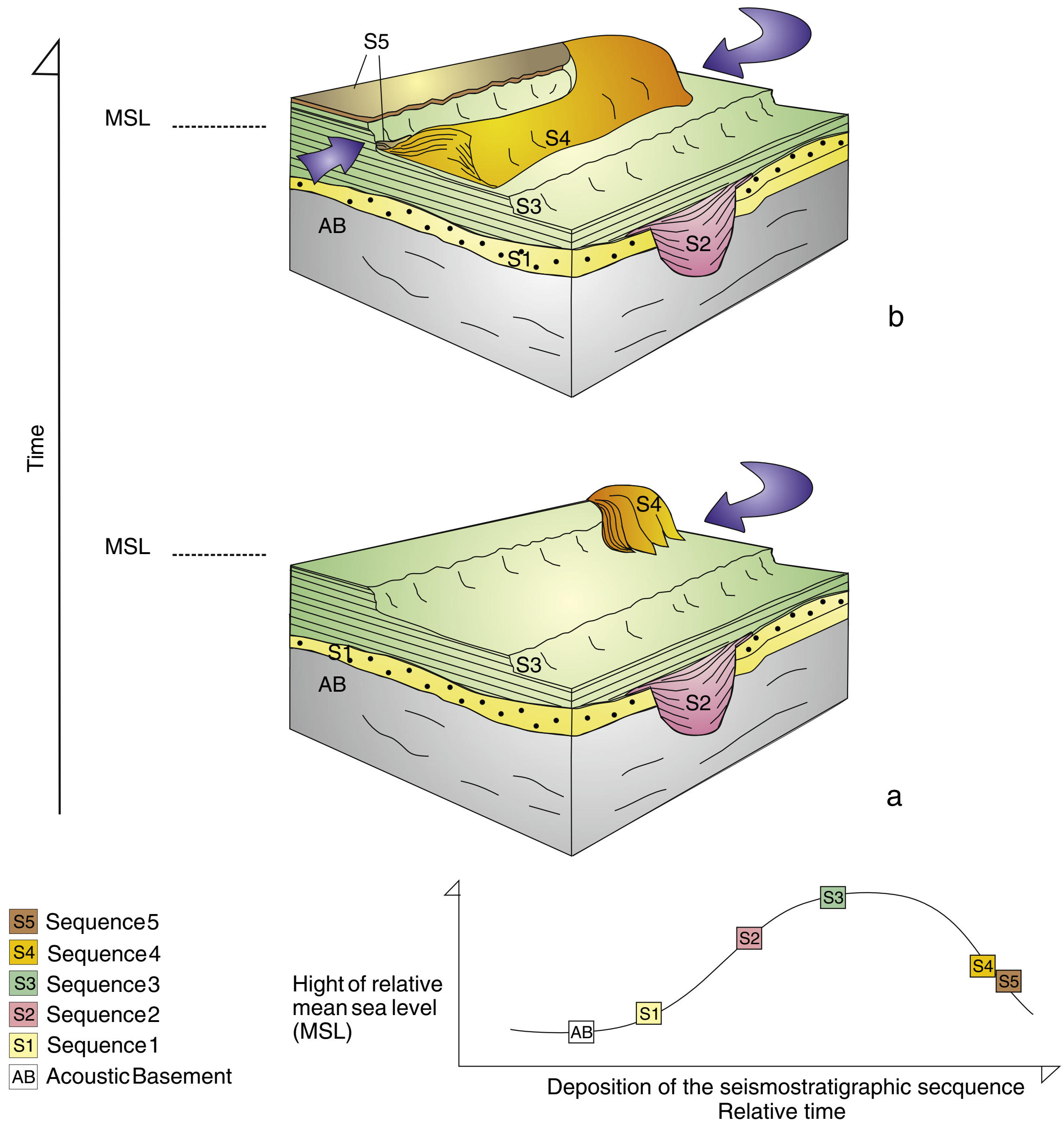

Fig. 6. Evolutionary model of La Lista Bank.

were found not only to evidence sediment transport in this direction but also to contribute to sediment supply, thus favoring the development of a progradational sigmoidal oblique stratification, which is indicative of lateral and longitudinal bank growths. In addition, based on the seismic data collected, it becomes clear that the bank has been adding material on both sides, particularly along its southern portion, this being a process which led to a gradual increase both in height and longitudinal growths of the sediment body.

This evolutionary trend may be quantified by a bathymetric comparison with a map provided from the Servicio de Hidrografía Naval Argentino (1977), according to which, during a period longer than 30 years, the bank has become 1 m larger vertically in the north and up to 5 m larger in the south, and it has undergone a significant longitudinal growth of ~1500 m (according to the 0 m and 3 m isobaths).

4. Conclusions

The seismic study on La Lista Bank is a very useful tool for reconstructing its evolution and migration patterns. The origin of this form could be associated with the Holocene marine regression process during which current ebb dominance caused sandy sediment transport towards the Principal Channel. Thus, based on the ancient continental sediments observed (identified as BA, S1 and S2 sequences; Fig. 6) and the marine transgressive sequence (S3) in the area of the mouth of La Lista Channel, it is concluded that a spit-type bar deposit began to form (S4 sequence; Fig. 6a). This sediment body gradually prograded its flanks, simultaneously undergoing elongation towards the SE. Parallel to the bank growth, the flood channel began to form in the south of the bank (Fig. 6b). Thus, the morphological evolution of La Lista Bank is associated with a residual model of sediment transport with opposite paths on both sides of the bank. This process tended to promote a gradual increase both in height and length towards the outer area.

The presence of dunes and sand ribbons at the mouth of La Lista Channel is considered to be indicative of a significant sediment mobilization process, which, due to ebb current dominance, tends to move to the northern flank of La Lista Bank. A large portion of this material is transported outwards from the estuary, thus contributing to the

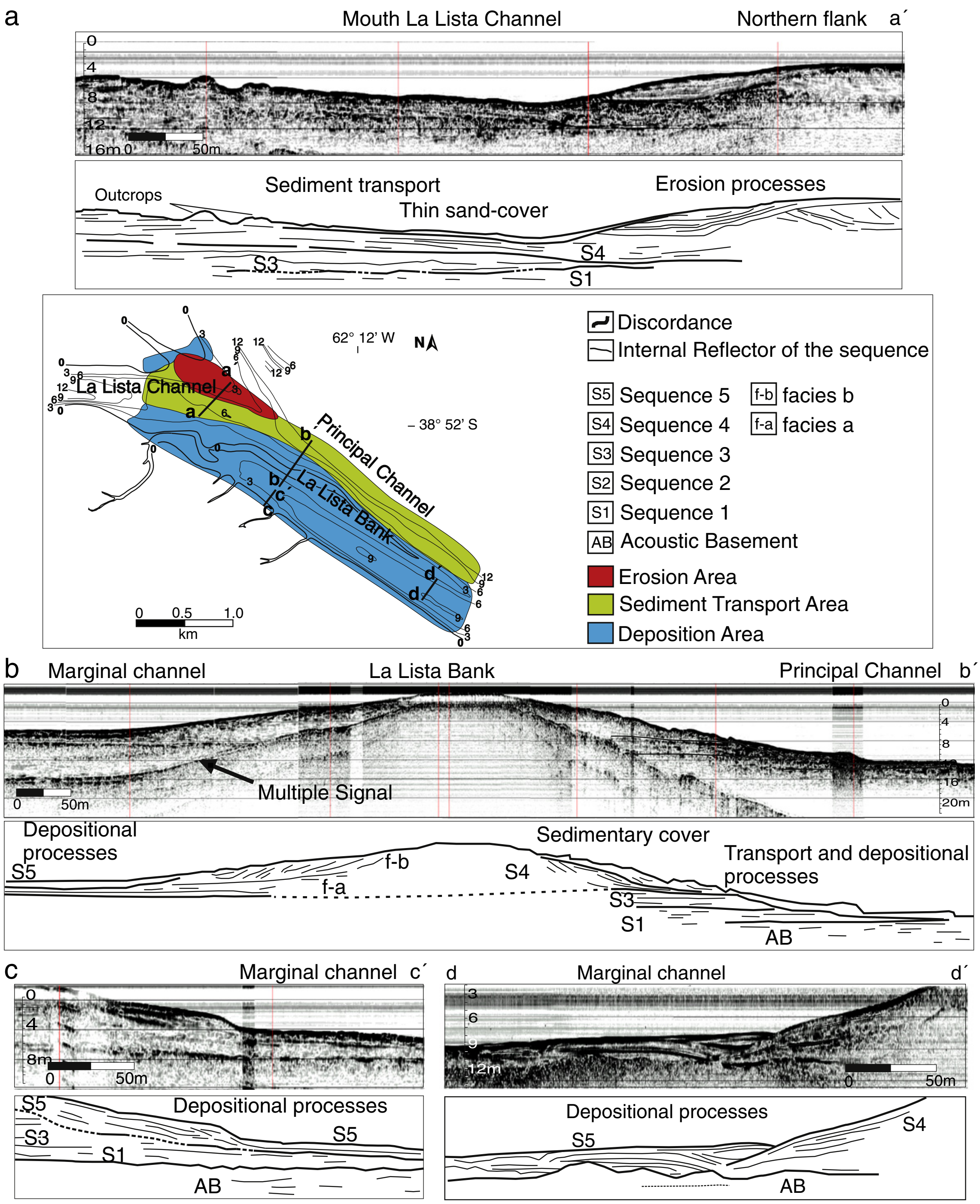

Fig. 7. Location of erosional, depositional and transport processes at the mouth La Lista Channel and at the Principal Channel. Interpretation of La Lista Bank seismic profiles.

longitudinal development of this sandbank. When transversely crossing the bank crest, another portion of this material is deposited on the southern flank where flood current is dominant. Thus, this sediment transport pattern shows a movement in the opposite direction on both sides of the sand body, inducing an apparent clockwise circular motion (Fig. 3).

This joint study which focuses on the subsurface seismic facies and bed morphological features of La Lista Bank (sand dunes, sand ribbons, outcrops of underlying sediment layers, etc.) has greatly contributed to tracing the morpho-evolutionary pattern in the area where the bank forms. Based on the evolutionary trend identified in this research, it could be concluded that this sandbank will evolve in the ebb current direction and that, due to erosion processes, receding will occur on the northern flank of La Lista Channel. Taken together, findings from the present research can be useful tools to further trace the morpho-evolutionary trend of sandbanks in other estuarine environments.

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