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Morphodynamics and seismostratigraphy of a deep hole at tidal channel confluence

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ABSTRACT

The sedimentary circulation pattern at a deep hole at a tidal channel junction in an estuary environment is examined using morphosedimentological and seismostratigraphic data. The bottom and sub-bottom acoustic information (side scan sonar and 3.5 kHz profiler) obtained at a tidal channel confluence in Bahía Blanca estuary (Argentina) evidences the depositional and erosive features, bed load sediment transport pathways and morphological evolution of the depression. This important depression in the confluence zone of the channels is characterised by the presence of steep scour faces (14°) at the mouth of both channels and gentle slopes (1.5°) opposite to them. Bed load sediment transport analysis reveals a differential circulation pattern of sand on both sides of the hole, which is associated with the different sediment availability in each channel. The side scan sonar information therefore indicates that there is no available sand in one of the channels whereas the other channel is characterised by the presence of a large amount of sediment coming from its inner area. Deposition therefore occurs on the side where sediment is mobilised as bed load by the ebb current dominance and on the face developed downstream. In the latter, a part from the sediment is deflected inward by the tidal flood currents which produce the deposition of sediment on the gentle side. The rest of the sediment is exported from the system by ebb currents. In contrast, erosion occurs on the opposite side of the hole and at the mouth of each channel and it is manifested by the outcrop of old sedimentary strata. The seismostratigraphic information collected in this study indicates that the depression was originally a fully erosive morphological feature. A descriptive model of the morphological evolution at a channel confluence is presented in this study.

1. Introduction

The channel confluence is a site generally exposed to important changes which affect the hydraulic geometry as a result of complex hydrodynamic conditions. Over the last 30 years, the tributary junction in fluvial environments has been the main issue of numerous studies on flow dynamics (Taylor, 1944; Greated, 1964; Webber and Greated, 1966; Itakura, 1972; Best and Reid, 1984; Best, 1987; Biron et al., 1993a; De Serres et al., 1999). The morphological characteristics of junction zones as well as their sedimentary facies have also been studied in detail (Miller, 1958; Mosley and Schumm, 1977; Ashmore, 1979; Kjerfve et al., 1979; Ashmore, 1982; Ashmore and Parker, 1983; Bryant et al., 1983; Alam et al., 1985, Best, 1985, 1986, 1988). Laboratory experiments as well as physics modelling have revealed that bed morphological features significantly influence flow structure in these zones (Best and Roy, 1991; Biron et al., 1993b). In addition, there are several studies on the morphological changes and hydraulic geometry in tributary confluence zones resulting from river discharge variability (Leopold et al., 1964; Mosley, 1976; Rhoads, 1987; Roy and Bergeron, 1990; Rhoads and Kenworthy, 1995; Rhoads, 1996).

Even though the available literature deals with scour holes at confluences of fluvial channels, comparable features can be observed in estuarine environments. Periodic changes occurring in the current direction in tidal channel confluence zones induce a complex hydro-sedimentological regime which does not occur in unidirectional flows. Although the literature is rich in studies of morphological characteristics, sediment transport and flow dynamics in scour holes at river junctions, little attention has been paid to study this feature at the confluence of channels dominated by tidal currents. The latter has been the focus of attention of only a few studies based on some field data (Shao, 1977; Kjerfve et al., 1979; Ginsberg and Perillo, 1999), which not only analyse flow dynamics but also hypothesize on bed load transport at channel junction. The origin of holes at tidal channel junctions has been discussed but no clear pattern of bed load sediment circulation has been elucidated to date.

This paper describes the dominant bed load transport circulatory pattern over the tidal channel confluence as well as the scour hole genesis and evolution. In addition, we detail the bed morphology

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associated with the sediment availability of each channel and sedimentary facies.

In Bahía Blanca estuary, Argentina (Fig. 1), scour holes are common at junctions of channels which have approximately the same size. In addition, as scour holes exhibit similar characteristics, our focus of attention was centred on a scour hole located inward, in the first bifurcation of Tres Brazas channel. Thorough studies on the seismic characteristics and variability in sediment composition and radiocarbon dating of bioclastic fragments were carried out in an attempt to determine the possible initial evolution of a hole on an existing tidal flat.

Bahía Blanca estuary is characterised by a dense net of tidal channels of different dimensions, generally meander-type, corresponding to interconnected channel systems (Fig. 1). It is a complex of islands of low altitude and tidal flats of clay sandy silt and extensive marshes, resulting from the progradation of mudflats formed during the last postglacial regression (Aliotta and Farinati, 1990; Farinati et al., 1992).

The different types of channels in this mesotidal system include large tidal channels and tidal creeks and gullies, which in general, flow from mudflats towards the large tidal channels. A regional study by Ginsberg and Perillo (2004) demonstrated that current erosive processes produce a lateral migration of these channels of the order of 25 m/y northwards. The water from the secondary large tidal channels flows into the Principal channel (Fig. 1), which is 60 km long and constitutes the access pathway to one of the most important ports in Argentina (Ingeniero White port). Circulation in the estuary is dominated by a quasi-stationary tidal wave with a 3 m mean tidal range (Perillo and Piccolo, 1991). Flood and ebb currents in the inner area of the estuary are reversible with low angular dispersion and a maximum average value of 1.05 and 1.2 m/s (Serman, 1985). Ebb currents in the Principal channel therefore behave as a net sandy sediment transport bed load towards the mouth of the estuary (Aliotta and Perillo, 1987), thus forming large, adjacent sand shoals which constitute a large ebb delta on the marine platform (Aliotta, 1987).

Our study area is located in the junction of the large tidal channels Tres Brazas and Tierra Firme, both of which are on a tidal flat on the southern coast of the Principal channel (Fig. 1). In the region of confluence of both channels, 25 km from Tres Brazas mouth, there is a depression which is a distinctive feature with respect to the other channels forming the estuary because it corresponds to the highest depth value of Bahía Blanca estuary.

2. Methods

The data analysed in the present study were collected during different marine surveys conducted on board the ship *Buen Día Señor*, which belongs to the Instituto Argentino de Oceanografía (IADO). A bathymetric survey was carried out in order to learn further about the geomorphological submarine topography pattern registered by Ginsberg (1991) in Tres Brazas and Tierra Firme channels. To this end, a digital echosounder (200 kHz) OCEAN DATA BATHY 500 was used. The depth values measured from the echosounder records were corrected taking into account the Datum Plane (2.24 m below mean sea level) of the area and using the tidal record corresponding to Puerto Belgrano Tidal Station. In addition, a thorough analysis of the bed morphological features was carried out using a sidescan sonar (EG&G model SMS 960) set to a 100 m range.

Geological sub-surficial information was obtained from high-resolution seismic profiles (3.5 kHz), with a GEOPULSE TRANSMITTER 5430A of 5 kw maximum output and 0.1 ms pulse width. The geophysical 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.

Sedimentological data included bottom sediment samples in the survey area and those along a stratigraphic profile located on the northern flank of the inner sector of Tierra Firme channel (Fig. 1). In the former case, sediment was collected following lines transverse to the channels and using a Shipek grab sampler. Ten of the lines were made in Tres Brazas channel and eight in Tierra Firme channel. Four

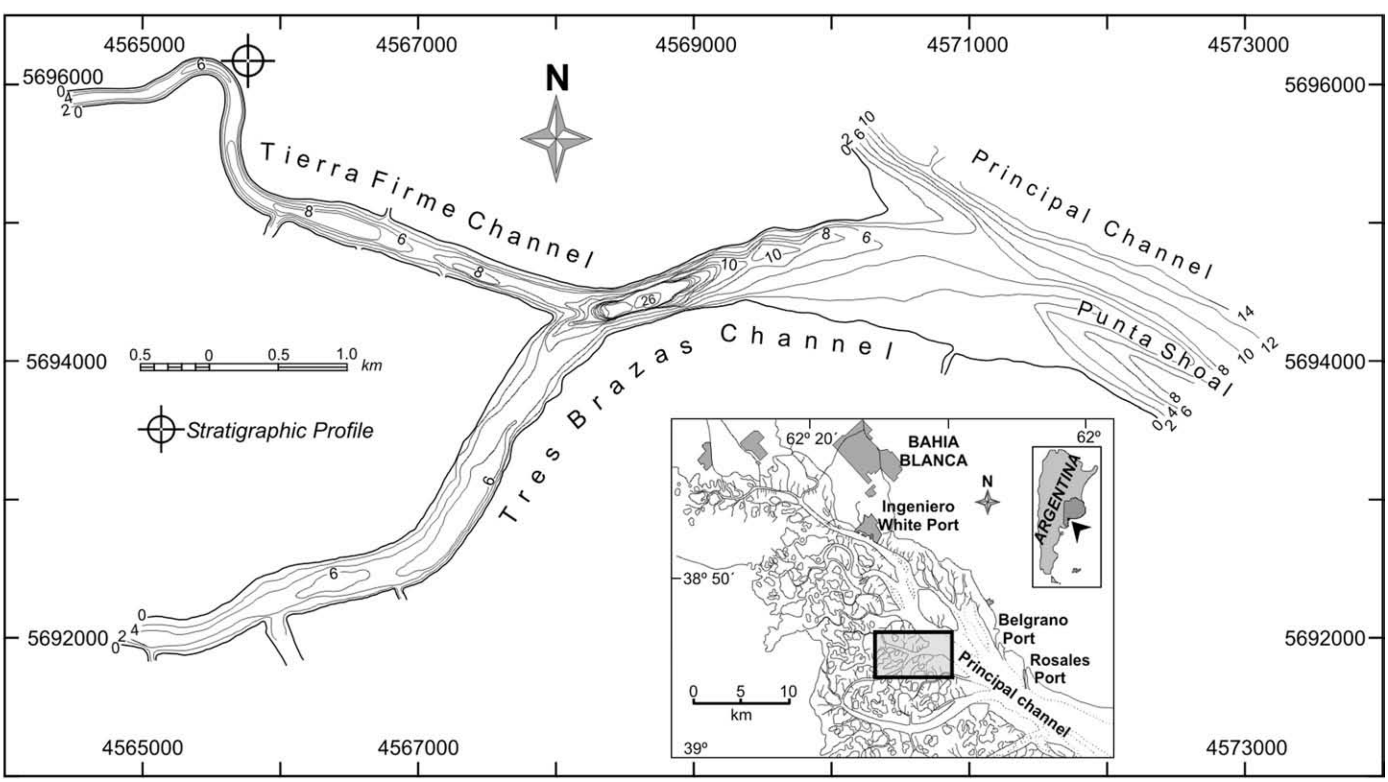

Fig. 1. Location of Bahía Blanca estuary and bathymetry of the study area.

samples were taken for each transect. A drag sampler was used at the sites where bedrocks were outcropping.

The total stratigraphic profile was 6.4 m long. The sediments were sampled in the Holocene material bank exposed, between the approximate limits of low water and supratidal zone. The selection of samples was made taking into account the characteristics of the macroscopic material. In order to assess the continuity of these sediments at the sub-bottom, a screw bit sampler was used to drill down to a depth of 3.4 m. Ten sediment samples were obtained along the stratigraphic sequence. 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 analysed in the laboratory according to Folk (1974). Data were analysed statistically following Folk and Ward (1957) and sediments were characterised according to Shepard (1954).

3. Results

3.1. Morphology and stratigraphic characteristics

Based on the general pattern displayed by Tres Brazas and Tierra Firme channels, both have a meandering configuration (Fig. 1). From the confluence zone onwards, Tres Brazas channel bends slightly towards the southwest whereas Tierra Firme channel exhibits an initial straight sector followed by a sinuous streamway with a small radius of curvature (300–400 m). In the area close to its mouth, Tres Brazas channel is characterised by an asymmetric cross-section with maximum thalweg near the north bank, which diminishes up to 5 m depth (Fig. 1). In this area, which is connected to the south bank, there is an elongated sand shoal (Punta shoal). The latter displays a 4 km-long curved spit-like configuration and extends towards the outer area of the estuary. The average depth in Tres Brazas channel is 10 m, whereas that in Tierra Firme channel is 9 m, with the mouth area being approximately 200 m wide.

The banks of both channels evidence, in the inner part, an erosive-type process, with stepped slopes and escarpment. The sidescan sonar showed well defined sedimentary stratification with either an apparent parallel–sub-parallel configuration (Fig. 2A) or with inclined layers evidencing, in some cases, stratigraphic discordance (Fig. 2B). The lateral continuity of these layers is interrupted either by small tidal creeks of different evolutive state (Fig. 2A) or by sediment rotational sliding (Fig. 2C). The areas of the channels where erosive flanks predominate are shown in Fig. 3.

On the other hand, acoustic records permitted the identification of different bedforms in both channels. They are mainly asymmetric dunes, whose distribution, pattern and morphology provide information on bottom currents on the assumption that they are in equilibrium under the current hydrodynamic conditions (Boothroyd, 1985; Ikehara and Kinoshita, 1994). In addition, sediment transport as bed load could be inferred from its asymmetry (Allen, 1968a,b; Bokuniewicz et al., 1977; Swift and Freeland, 1978; Harris, 1988a,b). Taking these concepts into account, the examination of the asymmetry of these dunes provides information on sediment transport as bed load as well as on the sedimentary circulation pattern in the study area. From the different nomenclatures available for the description of these features (Allen, 1968a; Boothroyd and Hubbard, 1975; Ashley, 1990; Berné et al., 1993), the scheme of Ashley (1990) in which height (H) and wavelength (L) are the most important parameters, was chosen for our study.

Two main bedform scales were identified in the study area, namely, medium dunes (0.5 m$<L<$10 m; 0.4 m$<H<$0.6 m) and large dunes ($L>$10 m; 0.75 m$<H<$0.6 m). The former (L=8–10 m; H=0.4–0.6 m) were found in the inner sector of Tres Brazas channel (Fig. 3A), particularly, on a relatively thin sand belt. Under different tidal conditions, these dunes always displayed an asymmetric profile with the lee side towards the Principal channel. On the other hand, large

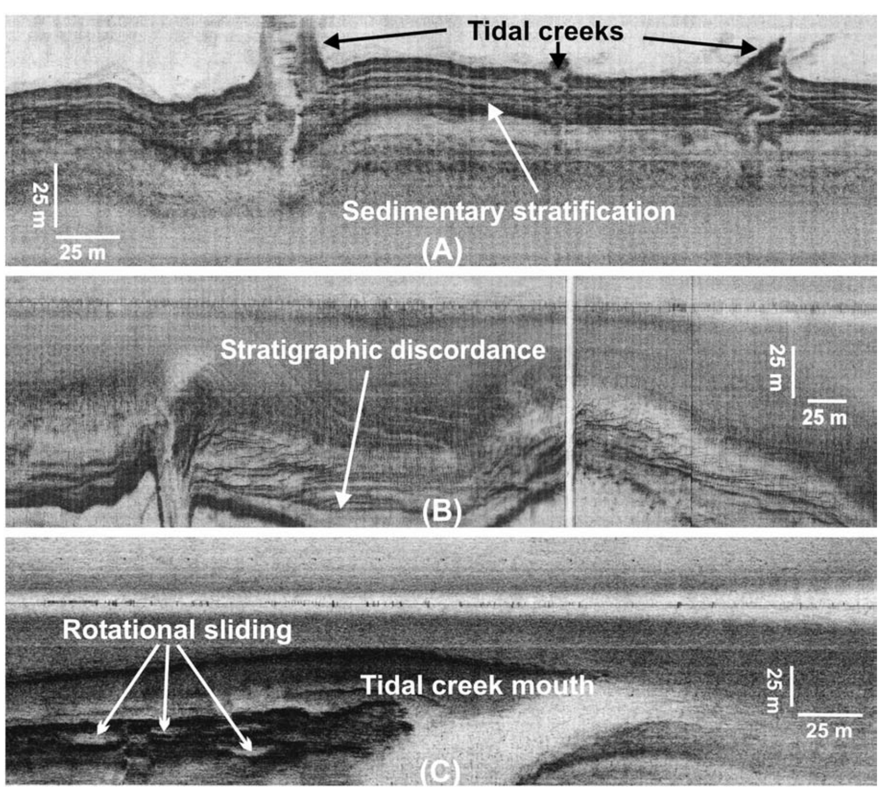

Fig. 2. Sidescan sonar records showing sedimentary structures of the channel banks. (A) Stratified sediments; (B) laminated bedding with stratigraphic discordance; (C) rotational slumping of channel banks.

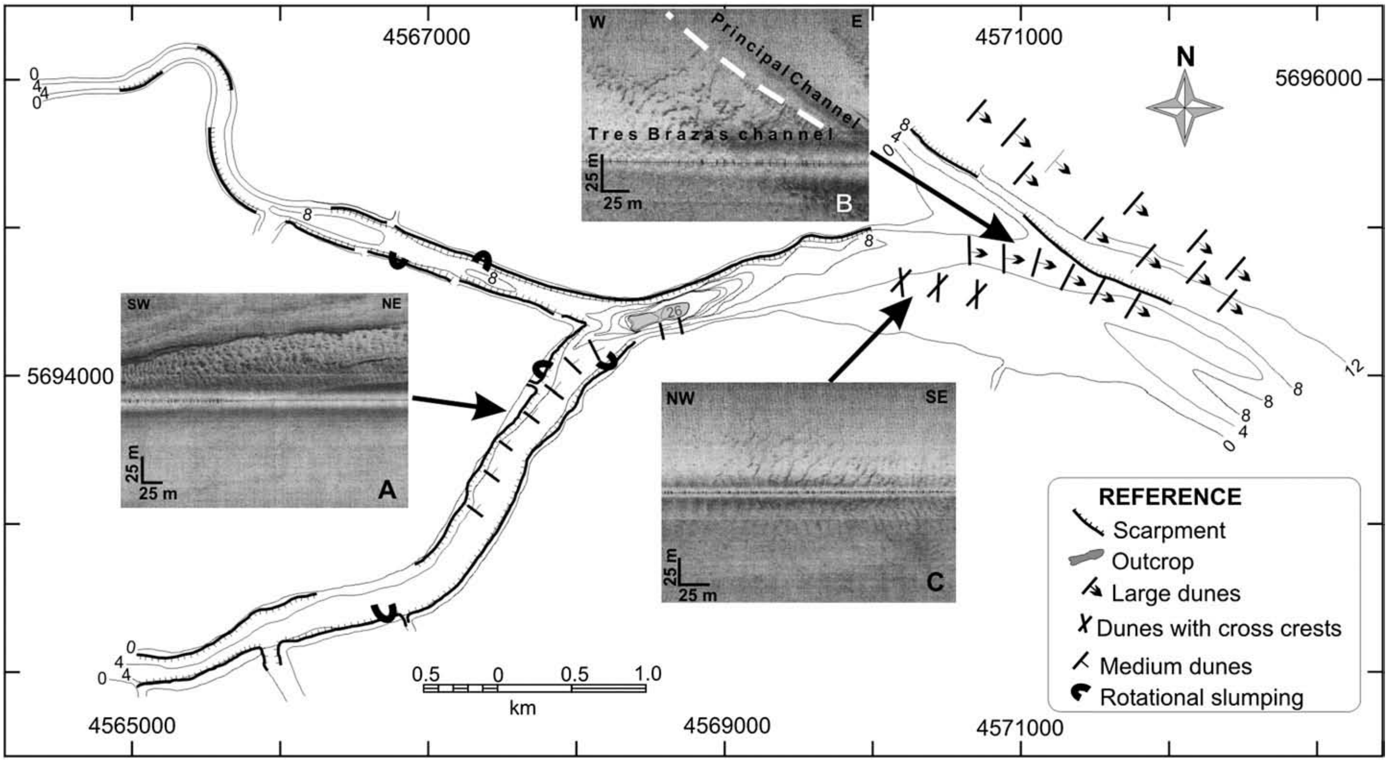

Fig. 3. Map showing geomorphological features. A, B and C, examples of side scan sonar records of asymmetrical medium and large dunes.

dunes (L = 12 m and H = 0.8 m) were found in the mouth of Tres Brazas channel and on Punta shoal (Fig. 3B). Their crestlines form a very sinuous, barchanoid structure with low lateral continuity. Their profile is asymmetric with the ebb current. Large dunes are, in general, formed at a 5–6 m depth towards the inner part of Tres Brazas channel, and at higher depths they disappear, thus forming a sand bottom flat. On the southern flank of the mouth of Tres Brazas channel, at a depth ranging between 2 and 4 m, north–south- as well as northeast–southwest-oriented dunes, varying from medium to small, are observed with criss-crossing crestlines (Fig. 3C).

The bathymetric map (Fig. 1) shows the presence of an important depression in the confluence zone of Tres Brazas and Tierra Firme channels. This zone has an elliptical, long conformation with a maximum depth of 26 m and extends from the confluence of the channels to the Principal channel. Towards the inner area of Tres Brazas and Tierra Firme channels, a pronounced 14° inclination topographic step can be observed. The average slopes corresponding to the northern and southern flanks of the depression vary between 8° and 4°, respectively, whereas the bottom, which is located towards the mouth of Tres Brazas channel, has a 1.5° slope.

At the base of the depression, the side scan sonar records showed an irregular, reflective texture evidencing the presence of sedimentary compacted material, whose outcrops (Fig. 4a) constitute terrace-like structures of up to 0.5 m. The northern slope of the hole is composed

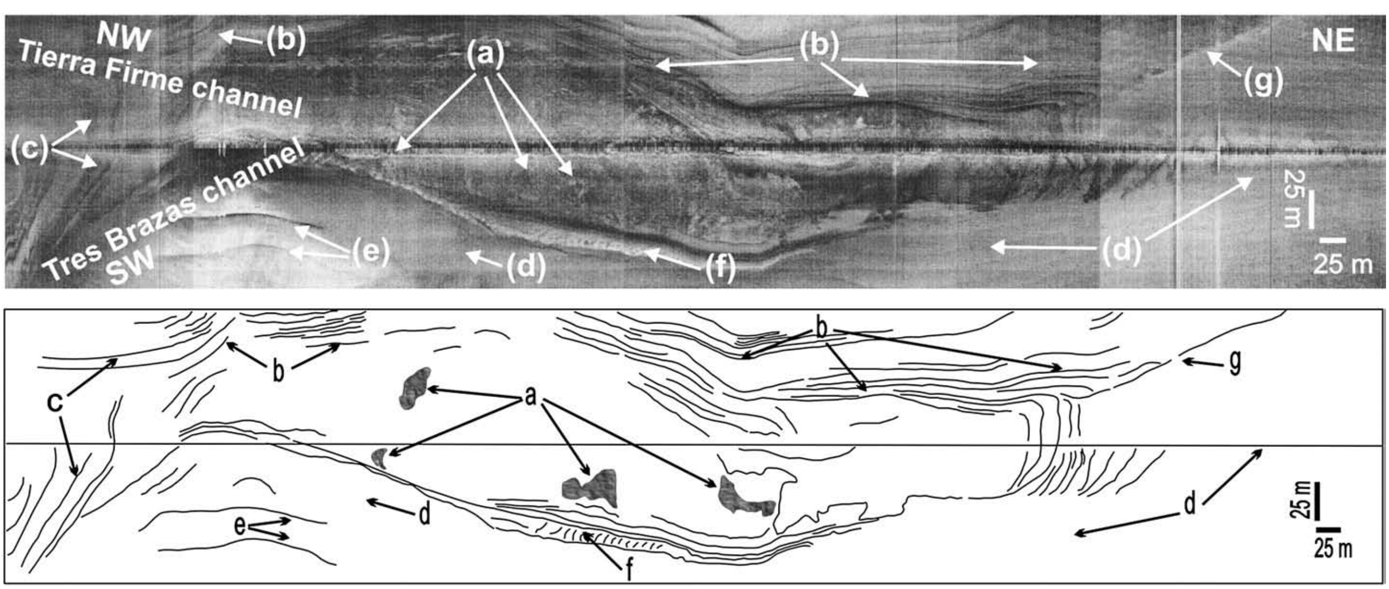

Fig. 4. Side scan sonar record and interpretation along Tres Brazas and Tierra Firme channel confluence. (a) outcrops; (b) and c) scarps and steps; (d) sedimentary cover; (e) stepped levels; (f) sandy belt and (g) discontinuity.

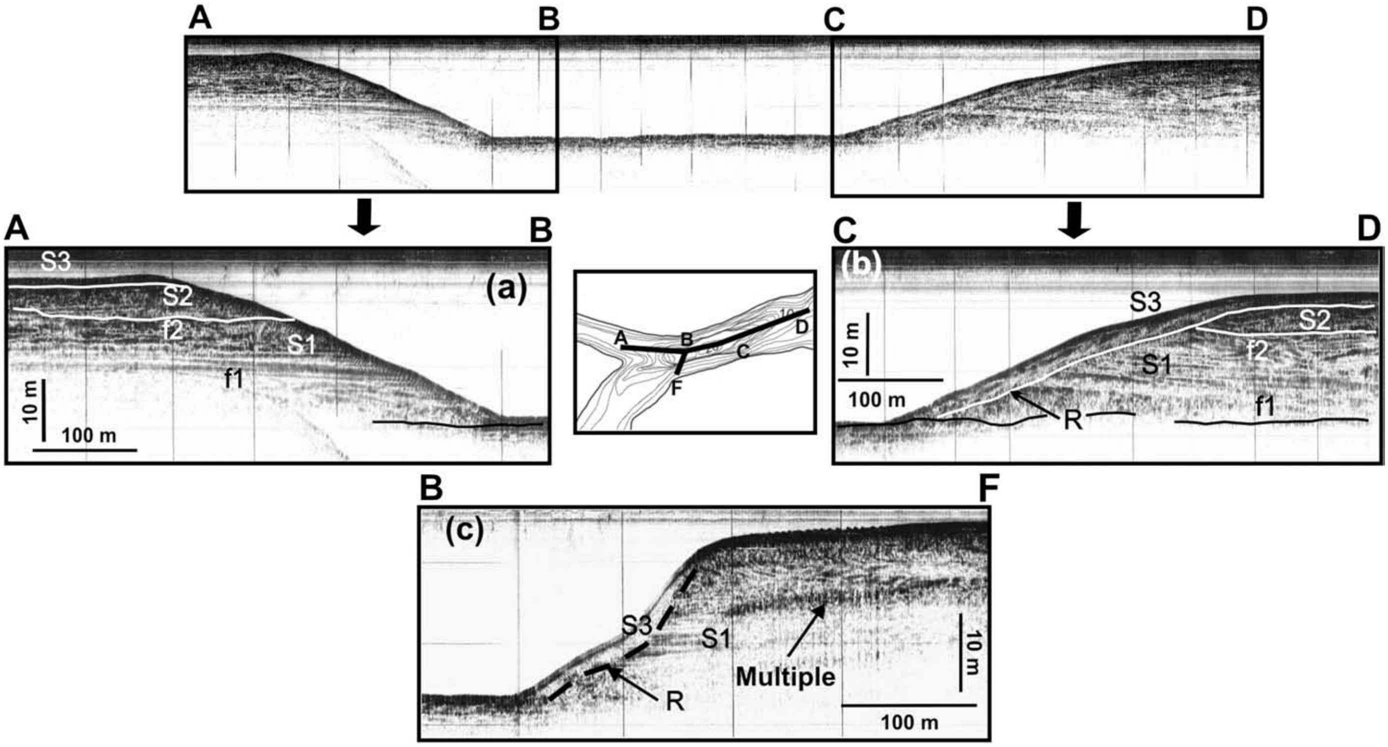

Fig. 5. 3.5-kHz sub-bottom records obtained across the hole. (S) Seismic sequences; (f) seismic facies; (R) Erosive discordance.

of small steps or scarps with marked lateral continuity (Fig. 4b), which, towards the inner area of both channels, generate a V-shaped configuration at the bottom (Fig. 4c). In contrast, on the southern flank there is a uniform sedimentary veneer (Fig. 4d), which, in certain sectors, leave stepped levels partially non-covered (Fig. 4e). Small-medium dunes are formed on a 400 m-long sandy belt, in the deepest part of the southern flank (Fig. 4f). In addition, scan sonar records on the north-eastern side of the deep hole were used for the determination of discontinuity between the material of which the steps of the northern flank of the hole are composed and the overlying sandy sediment that forms the southern flank (Fig. 4g).

The seismic profile longitudinal to the hole shows the stratigraphic characteristics that typify the sub-bottom (Fig. 5). The presence of seismic sequences whose top-base boundaries correspond to discontinuity surfaces is manifested through the interruption of downlap and toplap reflectors. In addition, through the seismic profile it was possible to determine that the bottom surface all along the northern flank is in discordance with stratification. Thus, the layers which in general have a high lateral continuity, are truncated and outcrop on the surface at the bottom (Fig. 5a), forming steps and small scarps all along the bank slope of the channel. On the other hand, the seismic profile on the north-eastern side of the hole (towards the outer zone of Tres Brazas channel) indicates that the outcropping stratification on the northern flank is covered with a sandy-sediment deposit up to 4 m thick (Fig. 5b, S3), which overlies with its downlap reflectors on easily identified erosive discordance. The absence of lateral continuity of the weak reflectors in the zone of highest depth of the hole, confirms the high strength of this material.

3.2. Sediments

Based on the general distribution pattern of sediments in the study area, the following four types of bottom sediments were identified.

Type I: includes clay sandy silt, which corresponds to the cohesive material of which the channel flanks are composed, forming the above-mentioned scarps and beds. The mean grain size varies from 6.41 Ø to 6.81 Ø whereas the standard deviation indicates poorly sorted sediments (2.15 Ø–2.83 Ø).

Type II: includes fine-to-very-fine sand with silt-clay percentages lower than 10% in the inner zone and southern bank of the mouth of Tres Brazas channel (Punta shoal). The mean grain size of these sediments is not higher than 3 Ø and, they are, in general, classified as well sorted (average 0.42 Ø).

Type III: includes fine-to-very-fine sand with silt-clay percentages varying from 26% to 38% silty sand/clay sand. This type is found in the deepest sectors of the inner area of Tres Brazas and Tierra Firme channels. Average mean grain size corresponds to 4.76 Ø and its standard deviation reveals poorly sorted sediment (2.51 Ø).

Type IV: includes grab samples from the bottom of Tres Brazas channel, indicating that the outcropping rock corresponds to reddish-brown coloured siltstone with thin sand laminae and a variable degree of calcium-carbonate cementation. Bryozoa colonies, annelida tubes (Serpulids) and Cirripedia (Balanus) were found on the sedimentary rock-exposed face.

The sedimentary material from the sub-bottom corresponding to a vertical stratigraphic profile made on the erosive flank of Tierra Firme channel (Fig. 1) is composed of dark grey–brownish silty sand. A deposit - classified as clay silty sand - with a horizontal parallel bedding made up of thin laminae of fine-to-very-fine sand and mud (silt+clay) outcrops in the intertidal zone, which is characterised by scarpment levels. A stratum approximately 30 cm thick with high concentrations of mono-specific biogenic material corresponding to the genus *Littoridina australis* was found close to the low water level at the outcropping base. Although this material (radiocarbon age of 1560±40 ^{14}C yrs B.P.) was found in a rather chaotic manner, no signs of erosion were observed in it. In addition, significant signs of bioturbation, with a high concentration of fragments of tubes of callianassa and *Tagelus plebeius* in life position, were observed on the upper plane of the slope. The latter were dated to1160±40 ^{14}C yrs B.P. The boundaries of the supratidal sector (storm level) are marked by a 1-m high step, where sediment is yellowish–brownish and slightly compacted, and is classified as clay silty. Light brownish sandy silt, which serves as the base for the shrub-like vegetation in the island, is found on these materials.

4. Discussion

Several important changes in bed morphology are produced in the confluence of either fluvial or tidal tributaries, the most significant being the formation of a deep scour hole resulting from remobilisation at the bottom. In his studies on river confluence, Best (1986, 1987, 1988) claims that the morphological features typical of these areas include the following elements: i) avalanche faces which correspond to the mouth of each confluent and represent depositional zones; ii) a deep central erosion where flows meet forming a face with a very much inclined slope, and iii) a bar within a flow separation zone formed below the current in the downstream junction corner of both affluents. Even though most of these elements, except for the bar, were also found in the junction of tidal channels, they were all arranged in the sector opposite to that of fluvial environments. Thus, it could be observed that, in the study area, the flanks constituting the mouth of each confluent exhibit the maximum slopes whereas the avalanche face, corresponding to the lowest slope, develops downstream against the most inclined flanks. This morphological difference between both environments gives support to the hypothesis that the evolution of tidal forms is inverse to that of fluvial environments, and that it may thus be related to the action of tidal currents.

In this respect, in rivers where the flow of water exerts its influence in only one direction, the morphological evolution of holes is downstream (Best, 1987). In contrast, in tidal channels, where flow direction is periodically reversed, there are dynamic conditions of equilibrium whose effects could be related to the morphological characteristics of the area. Evidence in support of this is the formation of two flood-dominated channels in the bifurcation area of the channels. Kjerfve et al. (1979) hypothesized that holes primarily scour from excessive macro-scale turbulence during the flood portion of the tidal cycle, when the flow in the main channel branches into tributaries and it is highly variable in speed and direction. On the other hand, Ginsberg and Perillo (1999) observed that at the channel juncture flood dominance is related to its time asymmetry. This is due to the fact that although these currents are not as strong as ebb currents, their duration is 30% longer. Furthermore, these two studies agree that sediment deposition on the gentlest side slope of the hole is due to the action of ebb currents.

However, results from our research do not agree with this conclusion. Our data indicate that different sediment transport processes operate in the hole. The acoustic information on the marine bottom and sub-bottom reveals the presence of present-day depositional and erosive features as well as mechanisms of formation and evolution of the large depression that characterises the confluence of both channels in the study area. In the northern flank of the hole and towards the inner area of both channels, erosion therefore predominates, manifesting itself by the outcrop of old sedimentary strata corresponding to the so-called seismic sequence S1 (Fig. 5), where two facies are identified. One is the lower facies (f1), with parallel–sub-parallel bedding and high lateral continuity which is associated with flood flat facies. The other facies is the upper f2 and is characterised by cross-bedding and a complex sigmoid-oblique seismic progradational pattern (according to the classification of Mitchum et al., 1977), which is indicative of a lateral migration of ancient stream beds, probably close to datum level. Previous studies on drillings carried out in the Principal channel (Nedeco-Arconsult, 1983; Aliotta et al., 1996) reveal an alternate fine sand and silt composition of these materials. The latter formed the ancient fluviodeltaic Pleistocene environment prior to the last post-glacial transgression of widespread distribution in the sub-bottom of the region (Aliotta et al., 1999, 2003). Marine transgressive materials, represented by the seismic sequence S2 (Fig. 5) and corresponding to sand containing different proportions of fragments of shells and pebbles, overlie the above-mentioned sediments (Nedeco-Arconsult, 1983; Aliotta et al., 1996).

The hole sector of lowest slope, towards the Principal channel, is affected by deposition of sandy material. This process is manifested by a prograding seismic configuration, characterised by oblique clinoforms which evidence a progressive lateral development of slightly sloping depositional surfaces with their downlap termination on the erosive discontinuity (R) that forms in the fluviodeltaic (S1) and marine transgressive materials (S2) (Fig. 5b). This prograding clinoform pattern is similar to that produced by the accretion and migration of banks in tidal environments (Marsset et al., 1999; Tessier et al., 1999). The seismic data collected in the present study also reveal that the above-mentioned discontinuity (R), which is acoustically transparent and is covered by 2–3 m of fine sandy sediment, continues laterally in the sub-bottom of the southern flank of the hole (Fig. 5c).

The sandy material on discontinuity (R), which represents the present-day hydrosedimentological processes, corresponds to the seismic sequence S3 (Fig. 5). The latter indicates, in particular, those sectors that are currently affected by deposition. Before deposition, the scour process, which occurred in the ancient underlying materials corresponding to the fluviodeltaic and transgressive marine environment and which generated the stratigraphic discontinuity surface (R), is related to the period of formation of the hole. It can therefore be concluded that this bedform was originally a fully erosive morphological feature.

The maximum depth of the hole is geologically controlled by sandy silt material of high compaction and partially cemented with calcium-carbonate, which, in view of its mineralogical and micropaleontological characteristics, is related to Plio-Pleistocene sediments (Ginsberg, 1991). This material outcrops on the bed scour hole and forms part of a large rocky basement of regional distribution (Aliotta and Farinati, 1990; Aliotta et al., 1996, 2001) upon which sediments of the ancient Quaternary paleo-environments (sequence S1 and S2) were deposited (Fig. 5).

The seismostratigraphic characteristics observed in the channel confluence of the study area contribute to better understanding not only the initial state of formation of a scour hole in a tidal environment but also how it evolves. The initial state of formation of the hole studied in the present research is related to the period subsequent to the last post-glacial marine transgressive maximum, where mean sea level reached approximately 5 m above the present (Aliotta et al., 2003; Spagnuolo, 2005). During this period (approximately 5000–6000 yrs B.P.), the coastal region formed an extensive bay with numerous sand shell ridges on its coast due to the action of waves (Aliotta and Farinati, 1990). The marine regressive process subsequently led to an increasing infilling mechanism of the large muddy tidal flats of the estuary. Taphofacies with a radiocarbon age ranging between 2000 and 3000 ^{14}C yrs B.P. (González et al., 1983; Farinati and Aliotta, 1997) were found in the sediments constituting marshes (2.0–2.5 m above sea level). In agreement with these findings, in the vertical profile made in the present study, the molluscan shell levels registered indicate an age of 1500–1200 ^{14}C yrs B.P. for the islands and tidal flats of the estuary.

On the other hand, the extensive tidal flats that prograded during the middle to late Holocene, began to be affected in the regressive phase by the action of tidal currents. In addition, with the water runoff on the large flats a drainage system was formed with subsequent flow concentration. The erosive effects of such flows on the clay sandy silt sediments formed the tidal channels. Tres Brazas channel thus initiated the development of its streambed whereas Tierra Firme channel could be considered a tidal creek (Fig. 6I).

The current scour also led to an increasing growth of the two channels. When the currents in the channels reached high flow velocities, turbulence conditions could have originated in their confluence (Fig. 6II). As a result, the turbulent flows produced during ebb tide periods are the same as those produced at river junctions. In

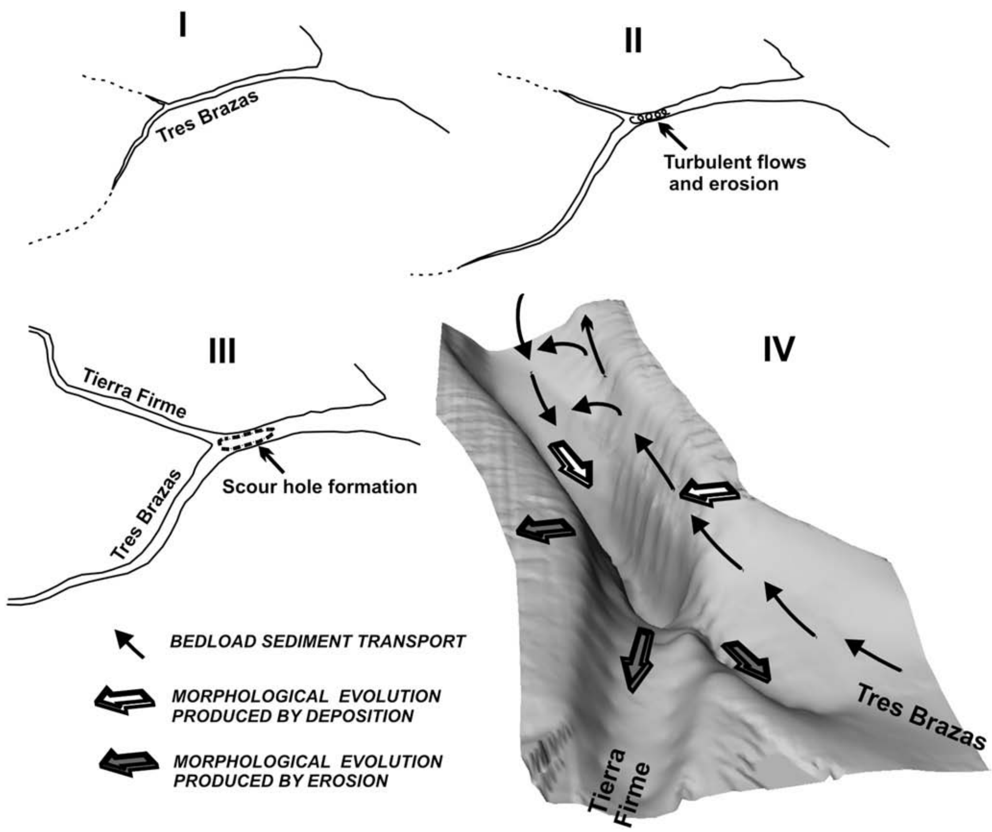

Fig. 6. Sketch showing the different stages of the hole evolution.

contrast, during flood tide turbulent flows are produced because water discharge divides itself into the two tributaries. In addition, current turbulence seems to be the cause of an important scour on the sub-bottom sediments in the confluence zone, thus provoking the formation of the hole with its increasing depth and width (Fig. 6III). The area of stratigraphic discontinuity (R) separating the oldest sediments (sequence S1 and S2) from those deposited by present-day sedimentological processes (sequence S3) seems to be indicative of this erosive mechanism.

The hydrosedimentological processes in the channel junction area revealed modifications with respect to those involved in the formation of the hole. Although the morphological and seismic lines of evidence discussed above are indicative of ebb dominance in both channels, only in the inner part of Tres Brazas channel is there a significant availability of sandy sediment mobilised as bed load transport. This transport pattern is evidenced by the formation of dunes (Fig. 4f). The sandy sediments coming from the inner zone of Tres Brazas channel are mobilised on the southern flank of the scour hole (Fig. 5c). These materials contribute to forming a surficial layer which covers, in erosive discontinuity, stratified materials corresponding to the Pleistocene deltaic paleo-environment (Fig. 4e).

The circulation of sediments from Tres Brazas channel on the southern bank of the hole (Fig. 6IV) may be compared to the sediment transport mechanism of fluvial confluences reported by Best (1988) and De Serres et al. (1999). In the latter, the turbulence processes downstream led to a concentration of current vectors and the consequent transport of sediment at both sides of the streamway. In contrast, on the northern flank of the hole an absence of mobile sedimentary material is observed and old sedimentary strata outcrop (Figs. 4b and 5a). This is due to the low contribution of sandy sediment coming from Tierra Firme channel. The differences in the availability of bed load sediment transport between Tres Brazas channel and Tierra Firme channel therefore produce an erosive effect on the northern flank of the hole, whereas the materials coming from Tres Brazas channel tend to move to the southern flank, thus having an accretionary effect on it (Fig. 4d).

Outcropping of the ancient sedimentary strata also occurs in the flood channels (Fig. 4c), towards the inner zone of both channels, producing a highly erosive effect (Fig. 6IV). This process is associated with scour resulting from turbulent flows produced during the ebb current and, in agreement with the hypothesis of Kjerfve et al. (1979) regarding tidal channel confluence, with the erosive scour effect induced by turbulence during flood current events. This process is due to the division of flows which are forced to enter into channels of shallower depths.

The seismic configuration of S3 on the flank of the hole located towards the Principal channel evidences a sandy sedimentation process with prograding clinoforms (Fig. 5b). The presence of downlap terminations on the ancient Quaternary materials indicates that the deposition of these sediments occurs under flood current conditions. The latter seem to affect, to a certain extent, the materials coming from the inner area of Tres Brazas channel, depositing them on the flank of the hole (Fig. 6IV). On the other hand, the presence of criss-crossing dunes crests in the sector located between the hole and the mouth of the Tres Brazas channel (Fig. 3c) could be due to the interaction between the sediment released by the flood current on the south channel of Punta Shoal towards the inner area, and the material exported from the system by the ebb current.

In conclusion, Fig. 6IV shows the bed load sediment transport and the morphological evolution of the hole resulting from the above-mentioned deposition-erosive processes.

The strong currents coming from the Principal channel in the mouth of Tres Brazas channel seem to exert their influence on the sedimentary dynamics of the area, thus producing either a change or rotation in the orientation of the bedform crests. The materials exported from the channel become the source of contribution of the spit-type sandy bar that originates in the right margin of Tres Brazas channel mouth. Its subaqueous prolongation forms the so-called

Punta shoal (Fig. 1). In this way, the sediments going out from Tres Brazas channel do not straightforwardly fall into the bottom of the Principal channel but tend to be transported by ebb currents along the upper plane of the steep slope which constitutes the southern flank (Fig. 6IV).

5. Conclusions

The origin and evolution of the hole in a tidal environment can be summarised as follows. The hole is originally a fully erosive morphological feature. In the initial state of its formation the tributary channel has the smallest size and it is thus, at this stage, a tidal creek. The current turbulence in the confluence zone causes an important scour on the bottom sediments, thus increasing its size. As the tributary increases in size and both channels reach similar dimensions, the flow from the tributary and the main channel together attain strong hydrodynamic conditions. As a result, flow dynamics seem to produce a confluence morphology consisting of: steep faces at the mouth of each confluent channel produced by erosion; a deep central scour; and a stoss slope downstream at the junction due to deposition.

A pattern of sedimentary dynamics at tidal channel confluences is proposed according to which most of the morphological features typical of fluvial environments are also found in tidal environments although they are arranged oppositely. These elements are the erosive faces at the mouth of each channel and the depositional face downstream and opposite to the other faces. The dominant control upon the extent of these morphological features at the confluence of tidal channels is shown to be the ratio of the available bed load sediment between the confluent channels. As there is no supply of sediment as bed load by one of the channels, the bar is not formed. The pathways of sediment transport are predominantly around rather than through the hole. Sediment is transported as bed load in the ebb current direction. Of this, a large fraction of the sediment transported by ebb currents around the hole is deflected inward by the tidal flood currents which produce the deposition of sediment on their more gentle slopes. The rest of the sediment is exported from the system by ebb currents.

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