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LARGE TRANSVERSE BEDFORMS IN A MESOTIDAL ESTUARY

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ABSTRACT

Large transverse bedforms occur on shallow continental shelves, tidal inlets and large estuaries as a result of the strong currents in water sufficiently deep. Although Bahía Blanca Estuary is not a large estuary, its topographical and hydrodynamical characteristics allow the development of a dune field including, among other bedforms, very large dunes. Such large bedforms are rare in this kind of estuary.
Large, submerged dunes of Bahía Blanca Estuary were studied to acquire additional knowledge of the different morphologies found in nature, their relationships with the dynamics of the area and the mechanisms involved in their formation. To do this, the dunes field was surveyed in detailed and classified according to height, spacing, superposition, sediment characteristics, flow structure and history. Side scan sonar and echo-sounder records were used to analyze the height and spacing and shape of the dunes. The results of several current meters deployed in the study area were used to analyze the flow structure. The current velocities and the characteristics of the bottom sediments were related to the bedforms in order to understand the factors controlling their formation.

Keywords: subaqueous dunes, side scan sonar, tidal currents, bottom sediments, Bahia Blanca Estuary.

Palabras claves: dunas subácueas, sonar de barrido lateral, corrientes de marea, sedimentos de fondo, Estuario de Bahía Blanca.

RESUMEN EXPANDIDO

Grandes geoformas en un estuario mesomareal

Las grandes formas de fondo que se encuentran en las plataformas continentales someras, entradas de marea y en grandes estuarios, son resultado de las fuertes corrientes en aguas suficientemente profundas. El Estuario de Bahía Blanca es un estuario con características topográficas e hidrodinámicas que permiten el desarrollo de un campo de dunas compuesto, entre otras geoformas, por dunas muy grandes. Tales geoformas son raras en este tipo de estuarios.

Las grandes dunas sumergidas presentes en el Estuario de Bahía Blanca fueron estudiadas con el fin de adquirir un conocimiento de las diferentes morfologías encontradas en la naturaleza, su relación con la dinámica del área y de los mecanismos involucrados en su formación. Para ello, el campo de dunas fue relevado detalladamente y clasificado de acuerdo a la altura, espaciamiento, superposición, características del sedimento y la estructura del flujo.

Registros de sonar de barrido lateral y sonda ecográfica fueron utilizados para analizar la altura, el espaciamiento y forma de las dunas. Los resultados de varios correntógrafos fondeados en el área de estudio fueron utilizados para conocer la estructura del flujo. Las velocidades de las corrientes y las características de los sedimentos de fondo fueron relacionadas con las geoformas con el fin de comprender los factores que controlan su formación.

El tamaño de las geoformas reconocidas varía desde muy grandes a pequeñas dunas. En la trayectoria donde se encontraron las dunas muy grandes, la forma de las mismas cambia desde dunas con crestas relativamente rectas en las zonas profundas (hacia la boca de estuario) a dunas sinuosas en aguas menos profundas (hacia el interior del estuario). Todas las geoformas encontradas, inclusive las dunas muy grandes, se desarrollan en profundidades menores a 20 m, y sus modificaciones tanto en forma como en tamaño pueden estar relacionadas con un cambio en la velocidad de las corrientes. Las dunas muy grandes se desarrollan en arena gruesa, mientras que donde predomina la arena muy gruesa no hay presencia de geoformas. Existe una superposición de formas de fondo, encontrándose dunas medias sobre la rampa de las dunas muy grandes.

Este trabajo confirma que una sola variable no explica la existencia o ausencia de geoformas, ya que el tamaño de una duna está determinado por una compleja interrelación entre la profundidad, la velocidad de la corriente y el tamaño y disponibilidad de los sedimentos.

INTRODUCTION

In the symposium "Classification of Large-Scale-Flow-Transverse Bedforms" held in 1987 as a meeting of SEPM in Texas, the flow-transverse bedforms were

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defined as repetitive structures that develop on a sediment bed under a unidirectional current. The consensus of the participating symposium members was that, despite the wide spectrum of bedforms (fluvial, coastal and shallow marine environments), all large-scale flow-transverse bedforms are sufficiently similar in the formative processes as to be assigned the single term "dune" (Ashley, 1990). Perillo (2001) in his study about the searching of a nomenclature of bedforms, agree with the term "dunes" for the transverse geoforms generated by water flows in comparison with those generated by wind.

Large-scale bedforms usually occur on shallow continental shelves and epicontinental platforms that are affected by strong geostrophic currents, occasional storm surges and tidal currents. In these environments, the water depths allow development of bedforms of impressive dimensions (Flemming, 1978; Stride, 1982; Harris et al., 1986). The shape of the large bedforms reflects the relative strengths of the dominant and the opposing currents and, in some cases, wave modification. It is common to find in the literature the detection of these bedforms in the Belgian continental shelf (Lanckneus et al., 1994; Gao et al., 1994, Collins et al., 1995, Hennings et al., 2000), the North American shelf (Goff et al., 1999) and on the Spanish shelf (Lobo et al., 2000).

Another environment where large-scale bedforms can develop is the tide-dominated coastal embayment in which water movement is fast and deep enough (Ashley, 1990). There, coastal water bodies are partially enclosed by topography and have a free connection to the sea with low fresh water run-off volume relative to the tidal volume. In general, the greater the tidal range the greater the maximum flow strength.

The distribution of dunes within estuaries was widely presented by Dalrymple and Rhodes (1995). They affirm that dunes are particularly abundant in tide-dominated estuaries where they are widespread on the elongate sand bars which occur at the mouth. They are also abundant at the mouth of wave-dominated, coastal-plain estuaries and rias and they are particularly widespread in the tidal inlets and tidal channels. However, very large-scale bedforms (spacing 100-300 m) occasionally occur in estuaries (Ashley, 1990). Dalrymple et al. (1978) studied bedform hydraulic stability in the Bay of Fundy, Boothroyd (1985) and Knebel et al. (1999) described several bedforms in different estuaries of North America. Aliotta and Perillo (1987) found a dune field in the mouth of Bahía Blanca Estuary characterized by dunes up to 6 m in height and spacing between 80 and 200 m. The present investigation is focused in another large bedform field recently discovered in the Bahía Blanca Estuary, located northwestward the previous one.

Where these features are present is important to carry out intense studies in order to get an adequate understanding of the mechanisms involved. Thus, the aim of the study carried out in the recently field found in Bahía Blanca Estuary is to acquire additional knowledge of the different morphologies found at this site and their relation to the dynamics of the area. This study follows the classification scheme recommended by Ashley (1990) (Table 1), which by adequately describing the different morphologies found in nature, allow more precise comparisons among different bedforms and places. Accordingly, the First Order descriptors, shape and size, were determined for the bedforms in the Bahía Blanca Estuary as well as Second Order descriptors, that is superposition (simple or compound) and sediment characteristics (grain size and sorting). The Third Order descriptors include bedform profile, dune orientation and flow characteristics. Besides the description of the dunes field, the factors controlling spatial and temporal variation within the estuary were also investigated.

STUDY AREA

The Bahía Blanca Estuary is located on the eastern coast of Argentina (Fig. 1). The tides are semi-diurnal with a tidal range varying between 2.3 to 1.4 m at the estuary mouth and between 3.8 and 2.7 m at the

First Order Descriptors (necessary)				
Size: Spacing	small 0.6-5 m	medium 5-10 m	large 10-100 m	very large >100 m
Height	0.075-0.4 m	0.4-0.75 m	0.75-5 m	> 5 m
Shape: 2-Dimensional				
3-Dimensional				
Second Order Descriptors (important)				
- Superposition: simple or compound				
- Sediment characteristics (size and sorting)				
Third Order Descriptors (useful)				
- Bedform profile				
- Fullbeddedness				
- Flow structure				
- Relative strengths of opposing flows				
- Dune behavior-migration history				

Table 1. Descriptive classification of dunes (from Ashley, 1990). Height is calculated from the spacing using the equation $H=0.0677\ L^{0.8098}$ (Flemming, 1988).

Tabla 1. Clasificación descriptiva de dunas (extraído de Ashley, 1990). La altura es calculada a partir del espaciamiento utilizando la ecuación $H=0.0677\ L^{0.8098}$(Flemming, 1988).

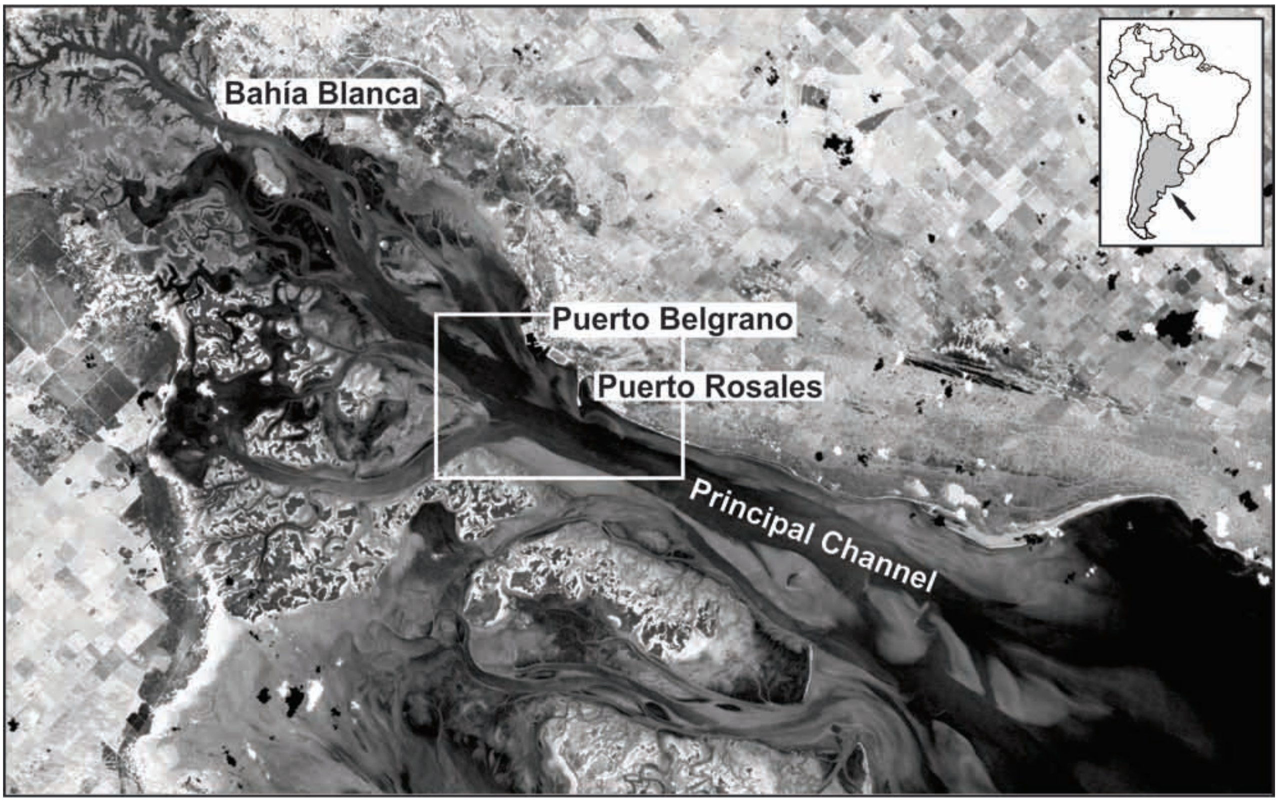

Figure 1. Satellite Image showing the Bahía Blanca Estuary. The study area is marked with a frame.

Figura 1. Imagen satelital del Estuario de Bahía Blanca. El área de estudio está marcada por un recuadro.

estuary head, spring and neap tides respectively. Therefore, the estuary is dynamically classified as mesotidal with two small freshwater sources, the Napostá Grande River and Sauce Chico Creek, which provide an annual mean runoff of 1.9 and 0.8 m^3s^{-1}, respectively (Perillo et al., 1987). Based on the salinity and temperature distribution alone, the Bahia Blanca Estuary is divided in two sectors (Perillo and Piccolo, 1999). The inner sector is classified as a partially mixed estuary during normal runoff conditions with a strong tendency to become sectionally homogeneous during low runoff. The outer reach is sectionally homogeneous.

The Principal Channel is about 200 m wide at the head and 3 to 4 km wide at the estuary mouth. Several sectors of the navigation channel, which is 100 km in length, are maintained at a minimum designed depth of 13.6 m below mean low water at spring tides by periodic dredging operations. However, at the study zone, the Principal Channel is 24 m deep. The estuary is ebb-dominated with the maximum mean ebb and flood current velocities close to 100 and 80 cm s^{-1}, respectively (Nedeco-Arconsult, 1983). At the estuary head Perillo and Piccolo (1999) detected a strong tidal asymmetry in the duration of flood and ebb depth-mean longitudinal velocities.

The oceanic waves entering through the estuary mouth reach to Puerto Belgrano, while locally wind-generated waves only are present from Puerto Rosales to the estuary head (Nedeco-Arconsult, 1983). The dune field studied here is located near the Puerto Rosales zone. The Principal Channel here has a water depth of 24 m. The study area comprises an 8 km long channel section indicated in figure 1.

METHODOLOGY

Geomorphologic characteristics in the study area are defined by bathymetric and Side Scan Sonar (SSS) surveys made on July, 1998. Bathymetric profiles were taken using a 208 kHz Raytheon echo-sounder while an EG&G SMS 960 SSS was also employed. The later operates at 110 kHz with a pulse length of 0.1 msec. In all the survey lines, the SSS was set to a range of 100 m. A SatLoc GPS working differentially in real time with an error of $\pm$ 3 m. The SSS tracks are shown in figure 2. The information of the SSS was obtained as sonographs. These records were made on direct mode. Thus, the areas of shadows or low backscattering strength appear as light tones, whereas high backscattering strength is indicated by darker tones or black.

A total of 74 bottom samples were obtained by means of a Shipek Bottom Sampler on the whole study area. Seventeen samples were collected within the dune field; five of them in close proximity to the very large dunes. After washing through a 0.063-mm sieve, the samples were dried and sieved at 1/2-phi intervals. The pipette method was employed in those few cases where the mud fraction exceeds 10% of the total sample. Textural parameters were calculated based on the percentile statistics described in Folk and Ward (1957). Bartholdy et al., (2002) affirmed that the use of sieve data for the hydraulic interpretation of grain size trends relative to dune dimensions is an acceptable technique.

In order to analyze the hydrodynamics, tidal currents were continuously recorded at a frequency of

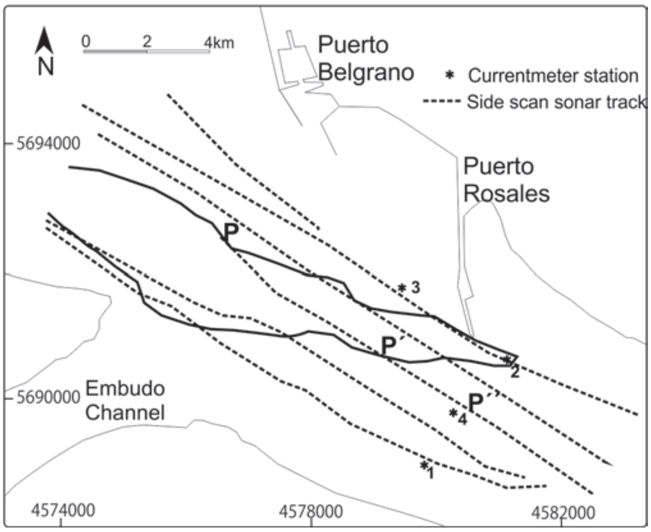

Figure 2. Side scan sonar tracks over the study zone. The position of the currentmeter stations is also shown. The coordinates are in Gauss-Kruger projection.

Figura 2. Los recorridos realizados con sonar de barrido lateral son mostrados en el área de estudio, como también la posición de las estaciones de correntógrafos. Las coordenadas están en proyección Gauss-Kruger.

0.5 Hz during two tidal cycles by fifteen deployments of an InterOcean current meters (model 135). All the current meters were located 1 m above the bottom. Those anchored at the Principal Channel margins were placed at 7 m depth, while the deployments in the middle of the channel were at 20 m depth.

RESULTS

The study zone presents a complex geomorphology mainly in the northwest part of the study area, as can be seen in the bathymetric map (Fig. 3). Toward the southeast, the deepest water occurs near the southern coast. From the deepest area to the northern coast, a gently sloping area from 20 to 15 m depth is present, changing abruptly into a steeper gradient between 15 to 5 m.

The dune field is located in the middle part of the estuary, in an area that extends westward from the Puerto Rosales shore-connected breakwater for nearly 8 km (Fig. 3). It is developed in depths between 10 to 20 m. No bedforms were found at depths greater than 20 m. The dune field has an elongate shape and it is comprised of dunes of different sizes. The northern side of the field is nearly parallel to the 10 m isobath while the southern limit initially goes along the 10 m isobath, crosses the channel and borders seaward the 20 m

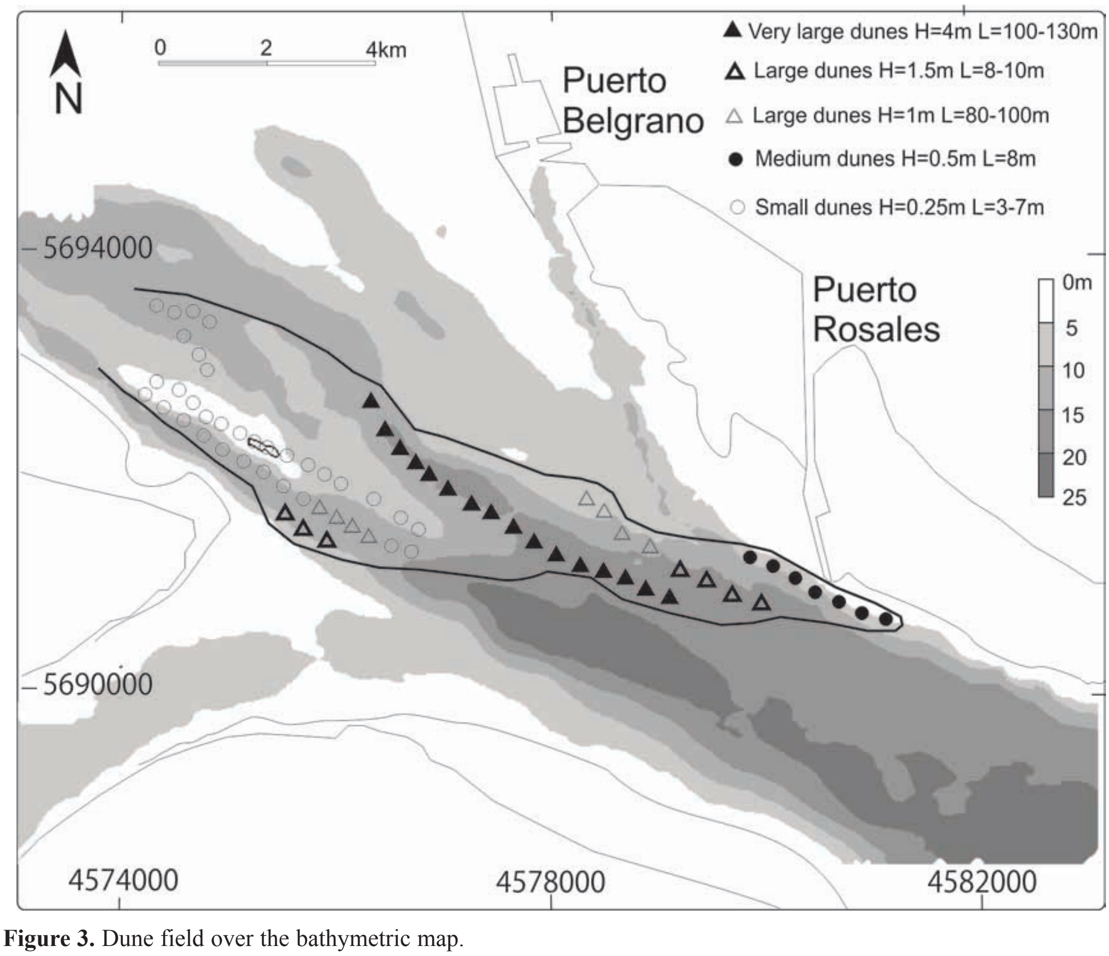

Figure 3. Dune field over the bathymetric map.

Figura 3. Campo de dunas sobre el mapa batimétrico.

isobath.

The smallest dunes were 0.25 m in height with a spacing between 3 to 7 m. They are found only on the southern coast at depths shallower than 15 m. On this coast two groups of large dunes are also present. One group is characterized by 8-10 m spacing and heights of 1.5 m (medium dunes), while in the second one the dunes have 80-100 m spacing and heights of 1 m (large dunes). They are located near the Embudo Channel outflow. The most conspicuous feature is the formation of very large dunes with a spacing of between 90 and 300 m. They have nearly 5 m in height and were found in water 17 to 20 m deep. Bordering these huge bedforms smaller dunes are present.

Where very large compound dunes are present (left side on Fig. 4a), the average stoss-side slopes are between 1º to 2.5º, while lee-sides are very much steeper (6.7º to 14º). Some of these dunes show a small crestal platform where the stoss side slope flattens.

All the very large dunes have the lee side toward the mouth of the estuary, showing an outward transport (Fig. 4a). Figure 4 also shows an asymmetric trochoidal profile revealing the effect of having a continuous supply of sediment.

Median grain size, sorting and skewness were used to characterize the sediments. The median was chosen because it appears in several equations for sediment transport. The spatial distributions of the median grain size have been mapped in figure 5 which reveals significant trends. A zone of coarse and very coarse sand bordered by finer sediments can be observed, reflecting the intensity of the hydraulic regime, as we will discuss later, in which the grains were transported and deposited.

Figure 5 also presents the dune field overlaying the distribution of the sediment size in the area. It can be seen that the very large dunes occur where the gain size is greater than 2 phi, and, in some places, greater than 1 phi (coarse sand). The small dunes were found in sediments with grain sizes between 2 and 3 phi. The coarsest sediment, with a high content of small shells, occurs outside the dune field, above the northern limit.

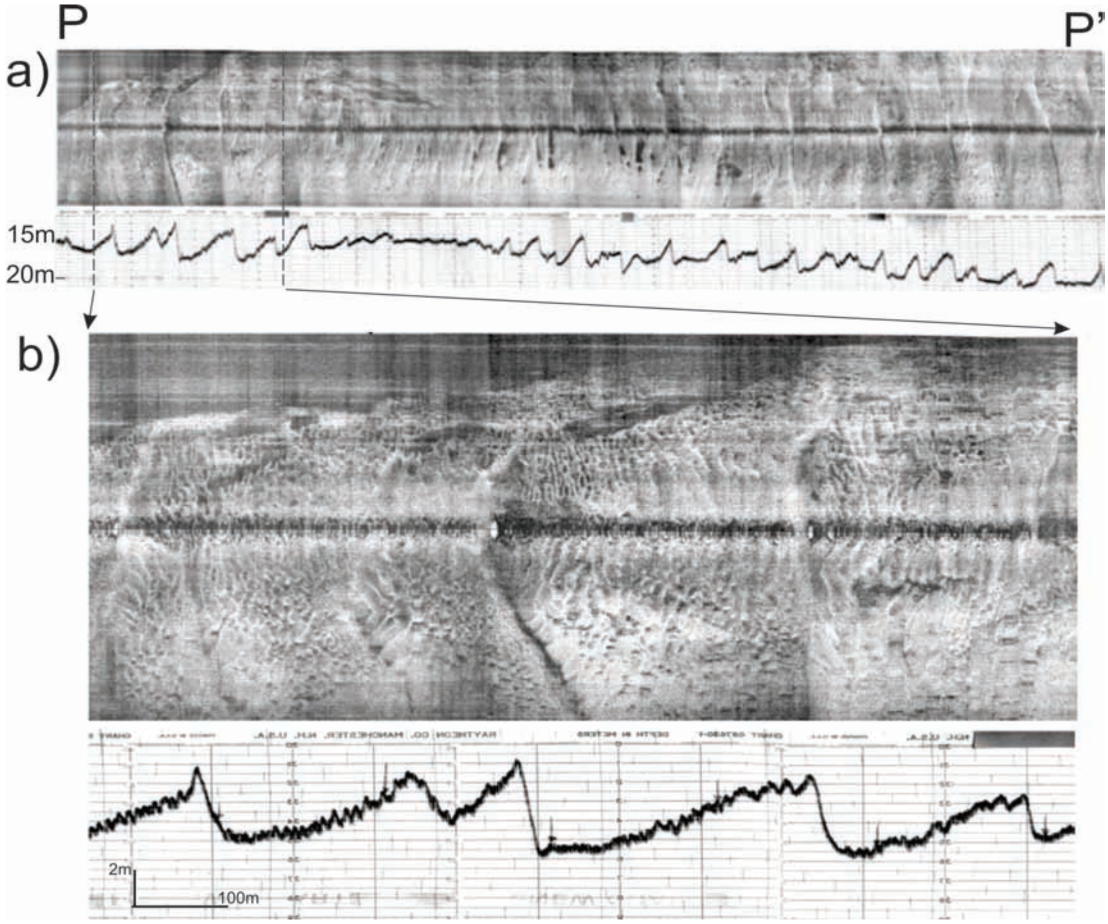

Figure 4. a) Side scan sonograph and the corresponding echo-sounder record of the very large dunes. The track of the surveys can be seen in Fig. 2. b) Zoom of the sector where the very large dunes with the megaripple fans over them can be observed.

Figura 4. a) Sonografía y el correspondiente registro de ecosonda de las dunas muy grandes. El recorrido puede observarse en la Fig. 2. b) Zoom del sector donde se encuentran las dunas muy grandes con las megaóndulas en abanico sobrepuestas .

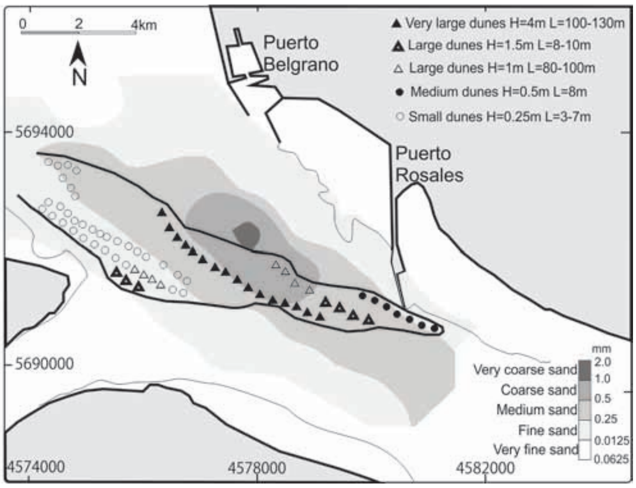

Figure 5. Location of the dune field over the distribution of the median grain size in the study zone.

Figura 5. Ubicación del campo de dunas sobre la distribución de la mediana en el área de estudio.

Plotting sorting against median grain size reveals that sediment sorting increases from 0.2 to 4.5 phi (very well to extremely poorly sorted) (Fig. 6a). However, the very well and well sorted samples have median size between 1.5 to 3 phi corresponding from medium to fine sand. The sample sizes close to the very large dunes show sorting values from poorly to very poorly sorted classes (1.5 to 3 phi). Meanwhile the sediment samples taken from the rest of the dune field show low values of sorting, very well sorted to poorly sorted. On other hand, the plotting of skewness against median presents a wide range of values over the study area (Fig. 6b). However, the sediment samples close to the very large dunes have a fine skewness, indicating that they have a tailing toward the fine sediments.

A different dynamic behavior between the two sides of the Principal Channel was discussed by Cuadrado et al. (1999). These authors found that currents on the northern coast were faster than those on the southern side. They also found current speed differences along the northern channel coast; tidal currents at the western side of Puerto Rosales shore-connected breakwater were faster than those measured at the eastern side.

In order to illustrate tidal current behavior, the results from four representative current meters of the fifteen deployed in the study zone, are shown in figure 7. Three of them were moored on both flanks of the channel (two on the northern coast and one on the southern one), while one was deployed in the middle of the channel. The difference between the two margins can be distinguished since the maximum current velocity on the northern coast reach 50 cm s^{-1} during ebb as flood tide, meanwhile the maximum velocity on the southern coast reach 20 and 15 cm s^{-1} for two different ebb cycles. During flood the velocity reaches nearly 30 and 40 cm s^{-1} for two different cycles. Also on this coast there is an asymmetry on time, as the flood last longer than ebb.

At both sides of Puerto Rosales breakwater, maximum current velocities reach 50 cm s^{-1} during both tidal stages. The most important difference between both sides is the duration of the maximum speeds through the tidal cycle. While maximum values at the west side last nearly 5 hours, maximum speeds on the east side are maintained for not more than 3 hours followed by a sharp deceleration. In the center of the channel, the maximum flood and ebb measured velocities are similar (45 cm s^{-1}) lasting 350 min and 400 min flood and ebb, respectively.

The combination of the SSS and echo-sounder records reveals the details of the bottom characteristics. The water depth along the track where the very large dunes were found is shallower towards the head of the estuary (northwest). Therefore, the very large dunes are found at different depths (Fig. 6a). The ones located landward the estuary (left side) are found at 17 m depths, while those located seaward the estuary (right side) are found at 20 m depth. The very large dunes are present all along this track except in depths shallower than 15 m where they are absent (second fourth of Fig. 4a). The large dunes disappear toward the estuary mouth, although depths remain almost constant (Fig. 8).

The shape of bedforms is different along the echosounder record shown in Fig. 4a. Towards the mouth of the estuary (right side of Fig. 4a) the dunes are separated by flat areas in between. The dunes here

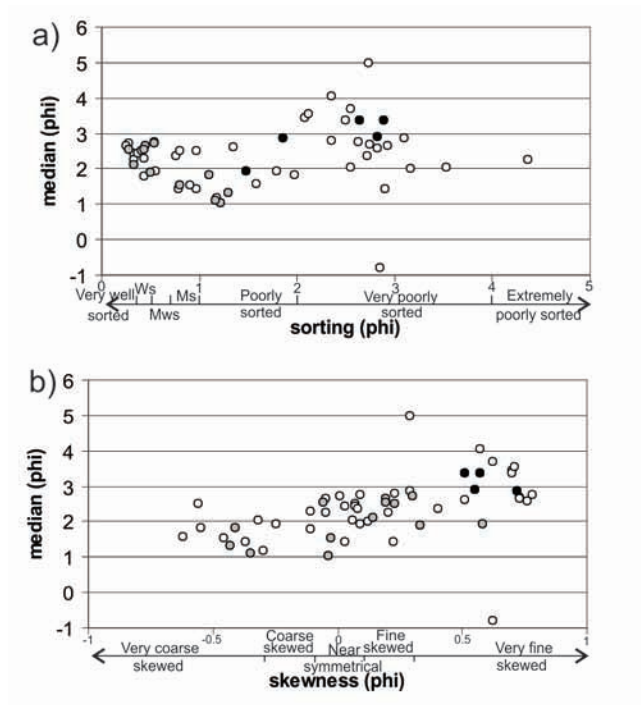

Figure 6. a) Sorting against the median. Ws = well sorted. Mws = Moderately well sorted. Ms = Moderately sorted. b) S k e w n e s s against the median. The white circles are the sediment samples over the whole study area. The grey circles are the bottom samples extracted within the dune field and the black circles are the samples obtained close the very large dunes.

Figura 6. a) Selección vs mediana. Ws=Buena selección. Mws = Moderada buena selección. Ms = Moderada selección. b) Asimetría vs mediana. Los círculos blancos indican las muestras de sedimento de toda el área de estudio. Los círculos grises indican las muestras extraídas dentro del campo de dunas y los círculos negros son las muestras obtenidas cerca de las dunas muy grandes.

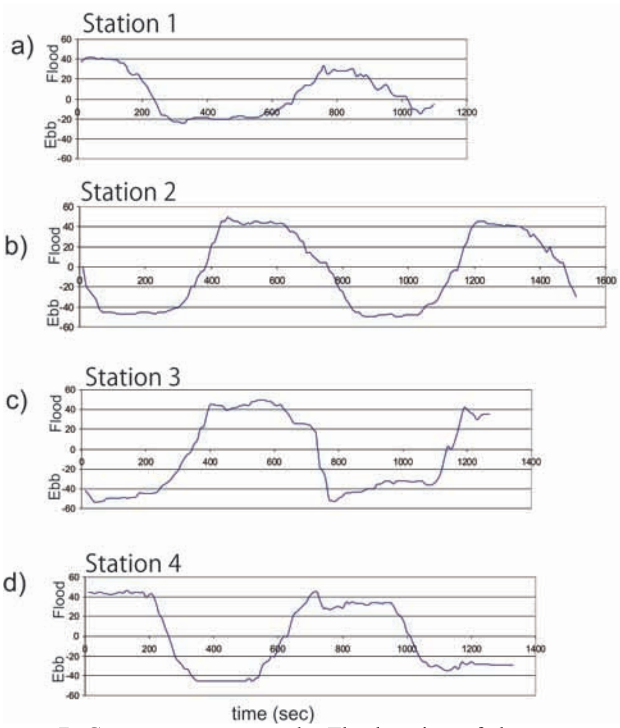

Figure 7. Current-meters records. The location of the current-meter station is shown in Fig. 2. a) Station 1 located on the southern coast. b) Station 2 located on the northern coast, eastward the Puerto Rosales breakwater. c) Station 3 located on the northern coast, westward the Puerto Rosales breakwater. d) Station 4 located in the center of the Principal Channel.

Figura 7. Registros de correntógrafos. La ubicación de las estaciones de los correntógrafos se muestra en la Fig. 2. a) Estación 1 ubicada en la costa sur. b) Estación 2 ubicada en la costa norte, al este del rompeolas de Puerto Rosales. c) Estación 3 ubicada en la costa norte, al oeste del rompeolas de Puerto Rosales. d) Estación 4 en el centro del Canal Principal.

are relatively straight crested. They become sinuous and then, further into the estuary, characterized by scour pits and straight lee faces (left side of figure 4a). The very large dunes, developed in the most interior part of the surveyed area, bear smaller, superimposed medium dunes on their stoss side. These are 0.5 to 1 m height with increasing the spacing between crests toward the large dune crest. Their crestline is curved opposing to the curvature of the major bedform (Fig. 4b). From where the large bedforms appear and toward the northern coast, the sonograph shows an abrupt change from light gray where the very large dunes are present to dark grey where no bedforms are found (upper left sector of Fig. 4a). Moreover, a slight line seems to separate the two areas.

DISCUSSION

Large flow-transverse bedforms with spacing up to several hundred meters have been widely documented as occuring on continental shelves, and in tidal inlets and large estuaries often superimposed on sandbanks (Trentesaux et al., 1999; Hulscher and van den Brink, 2001; Zeiler et al., 2000). However, these sites are completely different from the Bahía Blanca Estuary, which is characterized by a channel of 24 m maximum depth, enclosed by parallel flanks with an unobstructed connection to the sea and a low fresh-water input. In Bahía Blanca Estuary the very large dunes were found in the middle of the estuary at depths between 15 to 20 m.

It is well known that the dune size is determined by a complex interplay of water depth, current speed, sediment grain size, sediment availability and flow history, all superimposed on the innate stochastic variability of the bedforms. No single variable can explain the distribution and presence of dunes (Dalrymple and Rhodes, 1995). The shape of the dune field presented in this paper differs from the dune field found southward some years ago by Aliotta and Perillo (1987). It has an elongate form that crosses through the Principal Channel. Water depth seems to exert a spatial control as the dunes field is limited to areas above the 20 m isobath. However, large dunes disappear southwards despite the fact that the sea floor remains at a 20-m depth. This feature suggests that dune size is related to more than one variable.

The very large dunes are composed of coarse sand; the smaller bedforms are composed of smaller grain sizes, confirming that the dune height progressively decreases as the median grain size becomes finer (Bartholdy et al., 2002). However, Southard and Boguchwal (1990) indicate that this positive correlation between grain size and height reverses at grain sizes above about 0.5 mm, with dune height decreasing as the grain size continues to increase. These authors also found that the dune spacing decreases as sediment becomes coarser. The conclusions of Southard and Boguchwal (1990) are not reconfirmed here. The dune field studied herein indicates that a greatest spacing is related to very large dunes, verifying the assertion of a positive correlation between dune wavelength and grain size (Dalrymple and Rhodes, 1995).

The sediments comprising the very large dunes show poor to very poor sorting. They are strongly fine-skewed, indicating that the variations in the kinetic energy were lower than the mean values. Considering the dunes are not composed by the coarsest sediments found in the study area, it can be stated that the dune field is not under the highest current speed of the area.

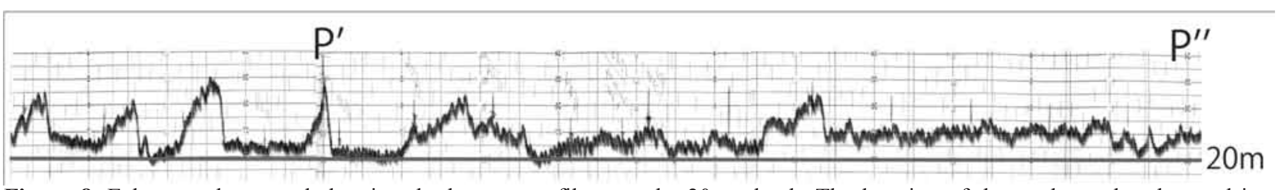

Figure 8. Echo-sounder record showing the bottom profile over the 20 m depth. The location of the track can be observed in Fig. 2.

Figura 8. Registro de eco sonda mostrando el perfil del fondo de 20 m de profundidad. La ubicación del recorrido se puede observar en la Fig. 2.

The minimum current speeds at which dunes occur is typically in the order of 50 cm s^{-1}, rising as the depth and grain size increase (Dalrymple and Rhodes, 1995). This assumption is valid in the studied area, where the maximum current velocity measured on the northern coast reach in general 50 cm s^{-1} being slower for the southern coast. Although these values are not high, it must be considered that the maximum current velocity act for more than three hours.

The current speed has a complex influence on the bedform size, but in general, while other factors remain constant, dune height increases as the mean current speed increases. Salsman et al. (1966) found also that dune height decreases with an increase in water depth. This height reduction was due to the decrease in current speed, eventually reaching values below the lower limit of dune formation. Dune height also typically becomes smaller at edges of dune fields where they pass outward into rippled sand flats (Dalrymple and Rhodes, 1995). This assumption agree with the results found in the present study where the larger dunes are present along an axis extended from the left upper limit to the right lower boundary of the dune field, being parallel to the channel axis. Smaller sizes are found at both sides of the very large dune field.

It is known that the combination of flow depth, current speed, and sediment size are necessary conditions, but not always sufficient for dune development. The major prerequisite is the presence of enough cohesionless sediment to form the dunes. Thus, as it was well documented by Aliotta and Perillo (1987), the presence of only small amounts of mobile sand over a hard substrate may inhibit the formation of dunes. Therefore, the disappearance of bedforms may be due to insufficient sediment availability.That condition can be seen in the sonographs that show the limit of the sand field, exposing a probably hard seafloor in dark-grey (upper left side of figure 4). Other zone probably reflecting sediments scarcity is the sector where the echosounder show dunes separated by flat areas in between (right side of figure 8) setting which was also found previously by Aliotta and Perillo (1987) in the southern dune field.

It is noteworthy that for a given grain size straight crested forms occur at lower speeds, while sinuous forms occur at higher speeds (Middleton and Southard, 1986). In the dune field studied herein there is a change in the shape of the very large dunes along the track where they were found. In figure 4 it can be seen that the nearly straight-crested dunes become sinuous, and are characterized by scour pits. This transformation is apparently related to an increase in the current velocity towards the estuary head. Although the current records do not indicate a difference in the velocity, they do show that the maximum current speeds westward Puerto Rosales breakwater last longer (4 h) than those measured eastward (3 h).

The sinuous forms are the most widely developed type in the small and medium size class. Dalrymple and Rhodes (1995) assumed that as dune size increases, sinuous forms become increasingly uncommon, presumably because current speeds are rarely high enough in the deeper flows. Nevertheless, an excellent example of very large sinuous dune was found in Bahía Blanca Estuary (Fig. 4b).

Dalrymple and Rhodes (1995) also assure that the superposition of smaller dunes on the sides of larger ones is very common in the tide dominated outer portion of estuaries. Thus, in the middle part of the Bahía Blanca Estuary, very large dunes bear on the stoss side smaller, superimposed medium dunes of 0.5 to 1 m height, increasing the spacing between crests toward the crest of the large dune (Fig. 4b). Their crestline is curved opposing to the curvature of the major bedform. This kind of features in marine environment was first recognized by Aliotta and Perillo (1987) as megaripple fans. These authors established that the angle of the lee slope of the large dunes ranges between 10º and 18º. These results agree with that found in the present study where the lee slope of the dune that bears the so called meggaripple fan is 11.3º. Allen (1968), working in rivers, considered that the formation of megaripple fans is due to flow separation on the crest of the dune. The values of stoss and lee-side slope measured on the very large dunes (1º to 2.5º and 6.7º to 14º, respectively) coincide with the lower limit found by Aliotta and Perillo (1987) where the lee slopes were between 6º to 16º, reaching up to 28º and 30º.

The superimposed dunes can be explained in the following manner. Estuaries are characterized by unsteady conditions that add confusion to the basic relationships between dune size and flow depth, current speed, and grain size and these conditions may strongly influence the morphology of the bedforms. If the flow depth, current speed, grain size and their combination change, the morphology of the existing dunes will change in such a way as to re-establish equilibrium. As might be expected, the morphological response of dunes to unsteady flow is extremely complex. Thus, the bedforms lag behind the change with the larger features exhibiting a greater time delay than the smaller bedforms. Such phenomena could allow the co-existence of dunes of different sizes that were formed at different times, producing bimodal or polymodal dune-size population. (These are sometimes called compound dunes).

Large and very large, compound dunes are generally asymmetric, with their lee side facing in the direction of the net sediment transport (Dalrymple and Rhodes, 1995). Asymmetrical forms generally retain a consistent facing direction over a tidal cycle because the subordinate current does not transport sufficient sediment to reverse the profile. Most estuarine dunes, regardless of size, are asymmetric, with a gentler stoss side and a steeper lee side. The exact shape and inclination of these faces depend on various factors, including the relative strengths of the dominant and subordinate currents, the size of the dune relative to the net transport direction (obliquity), the presence or absence of superimposed dunes as well as the phase of the tidal cycle at the time that the dune is viewed.

Based on the asymmetry of the dunes, Cuadrado et al. (2001) had inferred the direction of the sediment transport in the studied area. Due to the asymmetry on the large dunes developed in the central portion of the Principal Channel, the sediment is transported towards the mouth of the channel consistent with the ebb dominance. On the other hand, near the coast the sediment transport is towards the inner estuary.

Another survey was made on April 1999 and two

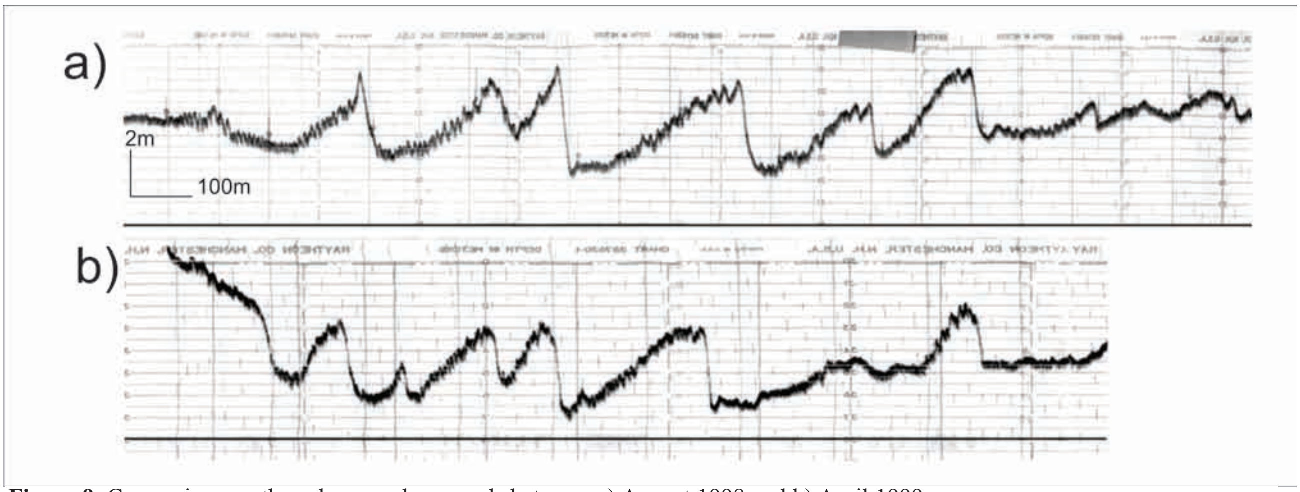

Figure 9. Comparison on the echo-sounder records between a) August 1998 and b) April 1999.

Figura 9. Comparación de los registros de ecosonda entre a) Agosto de 1998 y b) Abril de 1999.

sonar-tracks were compared. The migration direction towards the mouth of the estuary, coincident to the faster ebb current direction, can be clearly seen (Fig. 9). There is almost no difference in the spacing between dunes after eight months. The slight difference may be due to the tracks that did not follow precisely the same lines than in the previous survey. However, individual bedforms can be identified in a same manner that Bartholdy et al. (2002) recognized bedforms for years. In addition, the dune height can vary much more rapidly than the average spacing, because the amount of sediment that must be moved to rise or lower the height of a dune is much smaller than the amount needed to change the wavelength of several dunes. Unfortunately, the dune behavior-migration cannot be established because an accurate position of the dunes could not be obtained with the same precision. This situation will be remedied in future studies.

CONCLUSIONS

Although it is not common to find very large bedforms in an estuary as the Bahía Blanca Estuary, a dune field covered by different dune sizes, including very large ones is present. The estuary is partially enclosed by two flanks with an unobstructed connection to the sea and characterized by a low fresh water run-off volume. It is classified as mesotidal. Under these conditions, currents are adequate to allow the formation of very large bedforms.

According to the First Order Descriptors enunciated by Ashley (1990), the sizes of the recognized bedforms are between very large to small dunes, with a shape changing from nearly straight crested forms in the deeper zones to sinuous forms with straight lee faces in shallower areas. All these bedforms, including the very large dunes, develop at depths shallower than 20 m. Modifications in shape and size result from a change in the current characteristics. The very large dunes are developed on coarse sand, while the sector covered with very coarse sand is bare of bedforms. There is a positive correlation between grain size and dune height. There are compound dunes present. Medium dunes are arranged as megaripple fans mainly on the stoss sides of the very large dunes.

The dunes profiles have stoss slopes ranging from 1º to 2.5º and the lee slopes from 6.7º to 14º. One of the Third Order Descriptors, the fullbeddedness, concern the amount of sediment to create the bedforms. This condition is fulfilled where the very large dunes occur. Seaward the estuary, a scarcity in the sediment is first evidenced by the occurrence of flattened areas between dunes and later by the absence of dunes in despite the almost constant 20 m water depth.

Tidal maximum current speeds in the area are around 50 cm s^{-1} being constant during at least three hours. The lee sides of the large dunes are towards the mouth of the estuary indicating the direction of migration of the field dunes, and particularly the very large ones. The rate of migration will be studied with further surveys.

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