

## DYNAMICS AND SEDIMENTATION OF THE MESOTIDAL ESTUARY OF VILLAVICIOSA (ASTURIAS, NORTHERN SPAIN)

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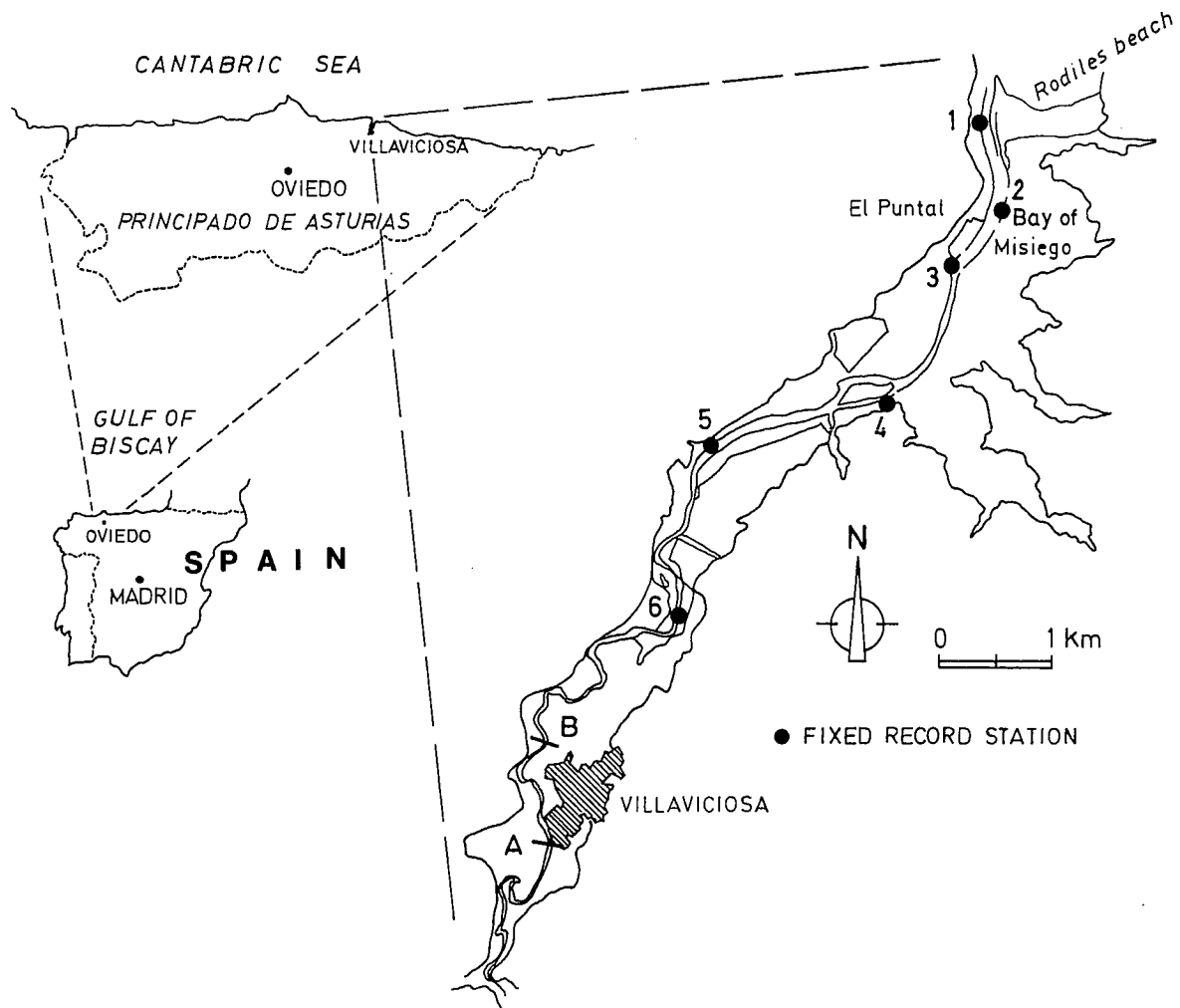
**Abstract:** The Villaviciosa estuary is a small, funnel shaped, shallow mesotidal estuary confined by an exposed beach/eolian dune system. It displays a longitudinal morphological zonation: mouth complex, sandy bay, mixed and muddy flats (mainly reclaimed marshes) and an upper meandering channel. It is a predominantly vertically homogeneous and hyposynchronous estuary. The mouth complex is constructed by waves (beach) and winds (dune fields). During medium and spring high tides, from half rising to half falling tides, surficial horizontal currents in the bay area are originated. Strong currents flow independently, generating the flood-tidal delta and the spillover lobe. Sandy, mixed and muddy flats generate from outer or main channel (more energetic) to inner or lateral (sheltered) areas. The main morphosedimentary units are: i) mouth complex: exposed pocket beach and eolian dunes, a mouth sandy bar and the inlet; ii) sandy bay: sandy flats, a sandy shoal bordered by the main, minor and secondary channels, developing a flood-tidal delta, an ebb-tidal spillover lobe, estuarine beaches and eolian dune fields; iii) tidal flats: unvegetated muddy flats, *Enteromorpha* flats, *Zostera* flats and by halophytic vegetation, mainly reclaimed marshes, crossed by the main channel, minor channels and tidal creeks; and, iv) the upper channel: main meandering channel, and reclaimed marshes and tidal creeks. The estuarine mouth is represented by well sorted sands (marine influence), and toward the upper estuary (fluvial influence) grain size decreases and sorting worsens to the inner estuary. Skewness is negative in more energetic areas and positive in areas with dominant settling processes and in transitional areas. Percent carbonate content (bioclasts) is higher (maximum values are correlated with more energetic areas) in the outer estuary, decreasing upstream (fluvial influence).

**Key words:** Estuary, morphological zonation, dynamics, morphosedimentary units, textural parameters, bioclasts, Gulf of Biscay, NW Spain.

**Resumen:** El estuario de Villaviciosa es de dimensiones reducidas y tiene forma de embudo. Es somero, de carácter mesomareal, confinándose por un sistema de playa expuesta con un extenso campo dunar eólico. Presenta una zonación morfológica longitudinal característica: complejo de desembocadura, bahía arenosa, llanuras mixtas y fangosas (marismas mayoritariamente antropizadas) y un canal superior de carácter meandriforme. Desde el punto de vista de las mezclas de agua y del comportamiento de la onda mareal, es verticalmente homogéneo e hiposincrónico, respectivamente. El complejo de desembocadura se construye por olas (playa) y vientos (campos dunares). Durante las mareas medias y vivas, desde la media marea ascendente a la descendente, se generan giros superficiales horizontales en la bahía arenosa, mientras que en el fondo actúan fuertes corrientes, que generan un delta de flujo y un lóbulo horquillado ("spillover lobe"). Las llanuras arenosas, mixtas y fangosas se extienden paulatinamente desde las áreas externas y el canal principal hasta la cola estuarina y las áreas laterales. Las unidades morfosedimentarias diferenciadas son: i) complejo de desembocadura: sistema de playa/dunas, barra arenosa de desembocadura y paso de desembocadura o "inlet", ii) bahía arenosa: llanuras arenosas, bancal arenoso bordeado por los canales principal, secundario y menores, donde se desarrolla el delta de flujo y la barra horquillada de reflujo, playas y campos dunares estuarinos, iii) llanuras mareales: llanuras mareales sin vegetación, llanuras de *Enteromorpha*, llanuras *Zosterales* y con vegetación halofítica, marismas mayoritariamente antropizadas, atravesadas por los canales principal y menores, y iv) el canal superior: canal principal meandriforme, así como marismas antropizadas y sus canales mareales. La desembocadura está ocupada por arenas de grano grueso bien clasificadas (influencia marina), decreciendo el tamaño medio de grano y empeorando la clasificación (influencia fluvial) hacia la cola. El valor de las asimetrías es negativo en las áreas más energéticas y positivo donde predominan los procesos de decantación y en las de transición. El contenido carbonatado bioclástico es mayor en el estuario externo en correspondencia con las áreas más energéticas, decreciendo aguas arriba del estuario.

**Palabras clave:** Estuario, zonación morfológica, dinámica, unidades morfosedimentarias, parámetros texturales, bioclastos, Golfo de Vizcaya, NW España.

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**Figure 1.** Location of the estuary of Villaviciosa in the Gulf of Biscay (NW of Spain). The main localities and geographic points are included, as well as the tidal stations (1-6) where tidal wave surficial salinities, and tidal currents were recorded. The tidal (A) and salinity (B) limits correspond to spring tides during low river discharge.

The estuary of Villaviciosa is a good example of a fully developed estuary that is undergoing both processes of erosion of its exposed beach/eolian dune system and infilling of sediments in the sandy bay, as is evidenced by estuarine dune fields. This sedimentary environment is the result of the accumulation of a previously incised fluvial valley by differential erosion of the basin consisting of fine siliciclastic sediments of Permian age overlain by Jurassic calcareous rocks and with main Alpidic fractures along NE-SW trends.

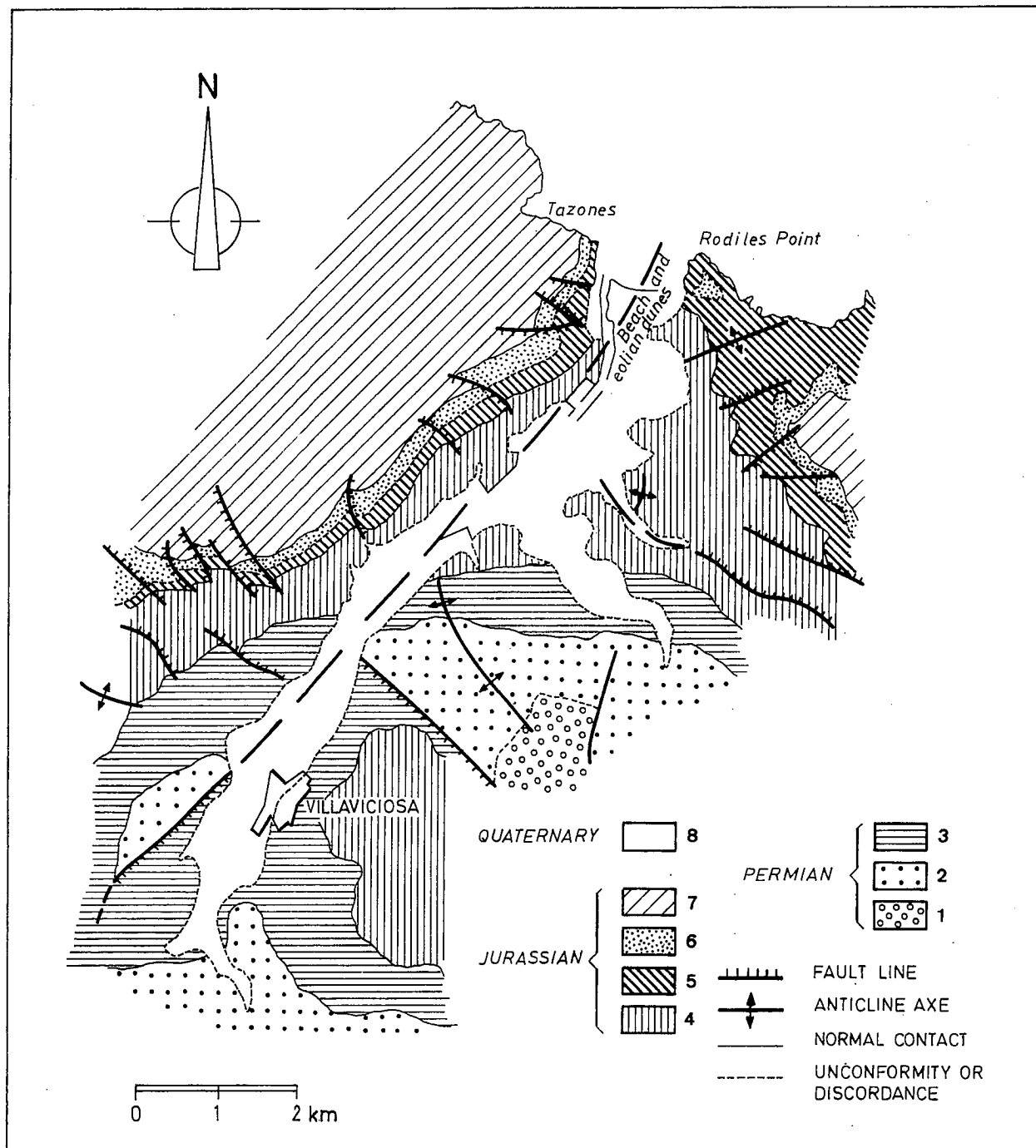
Several papers focused the attention on descriptions of modern estuarine deposits (Oomkens & Terwindt, 1960; de Raaf & Boersma, 1971; Barnes, 1974; Howard & Frey, 1975 a and b; King, 1980; Nichols *et al.*, 1991; Cooper, 1993), including biological distributions. Recent studies in estuaries are detailed on morphology, dynamics and sedimentology (facies models: Dalrymple *et al.*, 1992; estuarine lithosomes: Allen, 1993; and sequence stratigraphy: Allen & Posamentier, 1993), fundamentally correlated with other coastal environments and the application to fossil deposits. This paper has several objectives: 1) to

establish the longitudinal morphologic zonation, 2) to define the style of estuarine circulation according with sediment distribution, and 3) to characterize the high variety of surficial morphosedimentary units, including compositional patterns (siliciclastic/carbonate bioclastic ratio), textural properties, bioclastic and biological variety, and sedimentary structures of the active mesotidal estuary of Villaviciosa.

Our knowledge of this estuary is facilitated by a background of hydrodynamic and sedimentologic data (Vázquez-Argüelles, 1974; Flor *et al.*, 1992 b and c), and also detailed biological studies by Aedo (1986) about the estuarine vegetation and by Ortea (1975-76; 1977), Ortea & Llera (1974) about macrobenthos and fishes.

### Local setting

The estuary of Villaviciosa is located in the Asturian region (Gulf of Biscay, NW Spain) (Fig. 1). This is a cliffed coast containing several levels of raised abrasion platforms/cliffs (Mary, 1979; Flor, 1983;



**Figure 2.** Geological scheme modified from Gervilla *et al.* (1973) and Valenzuela *et al.* (1986). A great fault NE-SW affecting red Permian quartzite conglomerates (1), sandstones (2) and silts (3), and Jurassic dolomites (4) and limestones (5), and siliclastic sediments: quartzite conglomerates and sandstones (6) and sandstones and silts (7), was the passive control for fluvial widening of this estuary.

Mofino, 1986), distinguishing eight levels from 2-7 m to 220 m (Flor, 1992). Morphologically, is an entrenched funnel-shaped estuary after King (1980) and Allen (1993), orientated NE-SW and developing several lateral bays on the right side.

The estuary is 11 km long and 1.1 km wide, and is confined at its mouth by an beach/eolian dune system (Fig. 1). The upper saline limit is located near El Salín (B: about 10 km from the inlet) and the tidal wave has its upper limit in a small dam near the town of Villaviciosa (A: about 11 km from the inlet), for spring

tides during low fluvial discharge. The bayline (Posamentier & Vail, 1988; Allen, 1991) is located approximately 2 km upstream from the limit of tides.

The inlet was enlarged in 1934 by rubble-mound jetties and this promoted the progradation of the beach/eolian dune system about 175 m to the north side. Previously, wide tidal flat areas were reduced and reclaimed as agricultural lands. From approximately 1985, the boundary of the upper beach-outer eolian dune system has retreated more than 20 m (spectacular sand loss in the western side) due to natural causes.

The climate is humid-temperate, with an average precipitation of 1,100 mm/yr and the main temperatures range from 18.5 °C in summer to 9.5 °C in winter. There are two prevailing wind directions: westerly winds (75%), associated with storms, and from the northeast direction during anticyclonic conditions; the others, southerly and easterly components, are more intensive, all of them being very important during high tides because they generate inner refractive waves that are responsible for estuarine beaches on several sides. Tides are governed by the semidiurnal component  $M_2$ ; they are micro (1.0 m of minimum range), meso and macrotidal (4.2 m of maximum range), but frequencies calculated per year are 25.5, 73.0 and 1.5%, respectively. Therefore mesotidal ranges are the most important. Estuarine sediments outcrop almost entirely during spring low tides. Waves are normally from the north-northwest, with an annual average significant height of 1.0 m. A typical winter storm has 4 m significant wave height and significant wave periods range from 8 to 20 seconds (Losada *et al.*, 1989).

The catchment basin is 160 km<sup>2</sup>, and river discharges from the Valdediós and Ría coastal rivers (less than 20 km long), are very low with a seasonal and irregular character, a maximum in autumn and spring, and a minimum during summer. These small rivers does not at present introduce much sand and silt material; on the contrary, bioclastic sands penetrate into the outer estuarine area from the eroded shoreface retreat, mainly the outer dune belt. The main axis of the estuarine valley is located over an Alpidic fault trending NE-SW. The estuarine surface occupies a soft substrate of Permian silts and muds (Suárez-Rodríguez, 1988) flanked by Permian sandstones and gravels, and Jurassic limestones and dolomites from the Gijón Formation (Valenzuela *et al.*, 1986). The general valley shape with lateral bays is the result of these passive lithological and structural controls (Fig. 2), which allowed the incision of the main and tributary valleys during the last Würmian regression and later infilling during the Flandrian transgression to the actual.

### Morphological zonation

A great number of authors describe a tripartite longitudinal zonation for estuaries (Bird, 1967; Nichols & Biggs, 1985; Smith, 1988; Allen, 1991; Nichols *et al.*, 1991; Dalrymple *et al.*, 1992, Allen, 1993; Allen & Posamentier, 1993). However, it is very difficult to reproduce accurately this general scheme in the Villaviciosa estuary. Rather, it can be divided into four longitudinal segments (Fig. 3 a, b), as follows:

**Mouth complex.** An exposed beach/eolian dune system confines the estuary mouth and is crossed by a constricted inlet (outer main channel), that is scouring a channel which terminates seaward at a sandy mouth built on the offshore area of the exposed beach.

**Sandy bay.** The bay enlarges out upstream the inlet.

The main channel borders the bay at the western side and the secondary channel is located on the opposite side, enclosing a sandy shoal and minor channels. Several large bedforms are present similar to those described in detail by Hayes (1975) and Boothroyd & Hubbard (1975). Sandy flats, estuarine beaches and eolian dunes are especially well represented.

**Muddy flats.** The muddy tidal flats are closely vegetated (marshes) which develop a zoned disposition as the topography becomes higher, and are drained by meandering minor channels and tidal creeks during the ebb tide. The main channel is incised to the tidal flats and it acquires a certain degree of sinuosity, developing longitudinal and point bars, some of them with sandy and muddy composition. Generally, this is the broadest morphological zone, but in this case it has been reclaimed extensively as «porreo» (asturian word similar to «polder»).

**Upper channel.** Consists of muddy flats colonized by grass, almost fully reclaimed, and being active only the main channel, where the fluvial influence is more important. In this zone, the main channel displays a meandering feature and lies across the upper old tidal flats (formed during the Flandrian transgression), and which are now subject to fluvial floods, and spring tides.

The sandy bay and muddy flats can be compared to the estuarine funnel and inner part of the estuary mouth of some authors (Allen, 1991; Nichols *et al.*, 1991; Allen & Posamentier, 1993), to the flood-tidal delta and washovers, and central basin, respectively (Dalrymple *et al.*, 1992), or to the central portion (Nichol, 1991), but in our case the proposed subdivision allows a better morphological, dynamic and sedimentological identification.

### Methodology

Hydrodynamics of the Villaviciosa estuary were measured by recording the surficial tidal waves, salinity and tidal currents in the water column at six sampling stations (Fig. 1) (0.5 m interval in depth), most of them simultaneously, with a frequency of fifteen minutes throughout almost a full tidal cycle for medium and spring tides and low river flow, which are the prevailing seasonal conditions.

Tidal currents (velocity and direction) and saline distributions through the whole water column were measured from a small boat at 12 cross sections in relation to the axis of the estuary valley. Cross sections were 500 to 1,000 m apart and at each one three recording points were used, one on each side of the channel and the third point in the middle. In the sandy bay, from half rising tide to half falling tide, radial profiles and more detailed records were made.

Salinities were recorded with a portable salinometer Ysi Model 33 S-C-T Meter, and speed and direction of current velocities with a current meter General Oceanic, Inc. Model 2035-MK III, being operative to

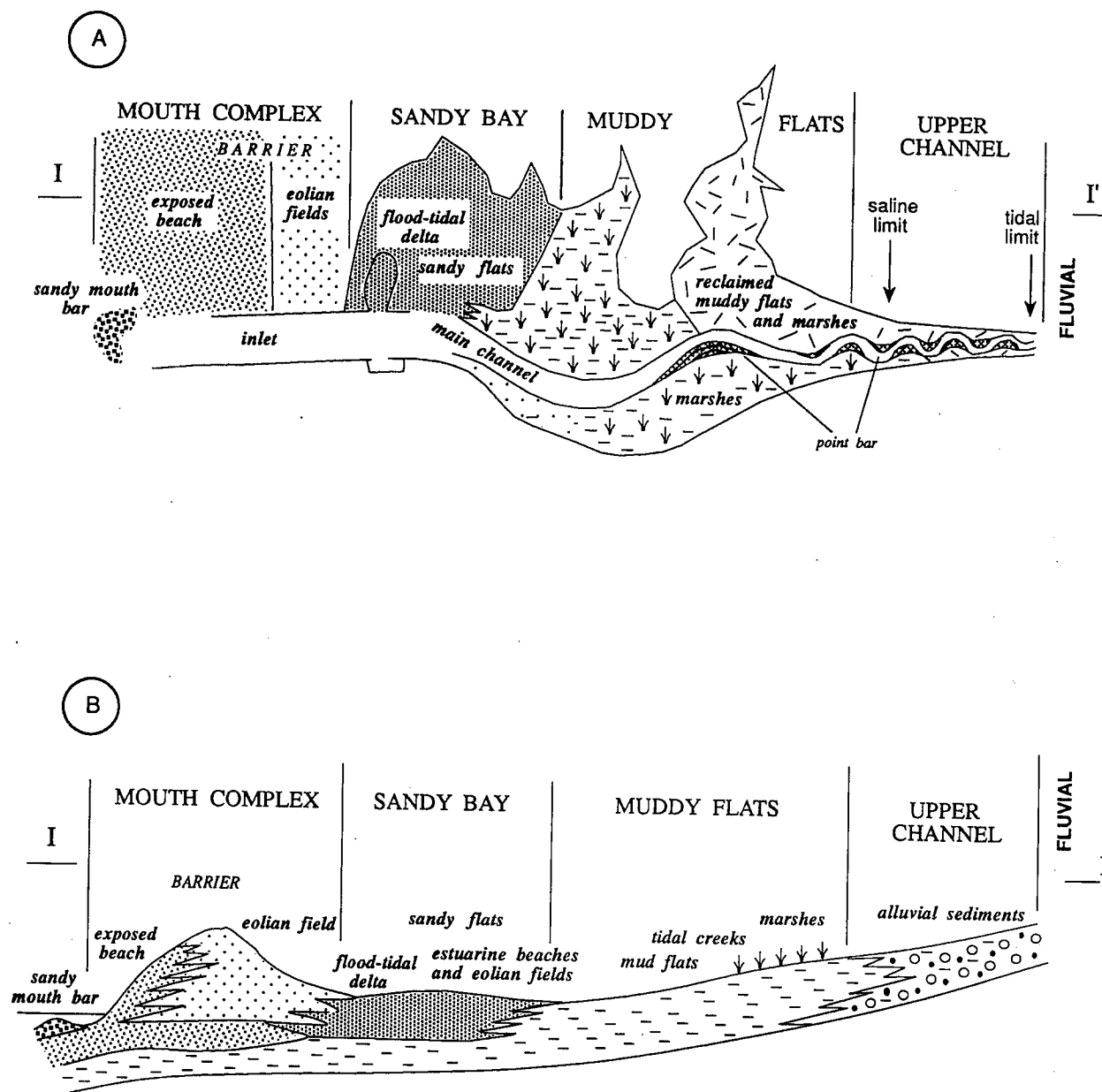


Figure 3. Longitudinal zonation of the estuary of Villaviciosa. A: morphological components in plan view, and B: main sedimentary facies in longitudinal section within an idealized confined mesotidal estuary (out of scale). Modified from Dalrymple *et al.* (1992), and adapted to the Villaviciosa estuary.

4.50 m of maximum depth.

A general circulation scheme was established from four intervals for spring and medium tides: high tide, half falling tide, low tide and half rising tide, each interval including about two hours, one hour before and one hour after.

A total of 222 sandy samples were collected from the surface, some of them by dredging (Petersen grab), supplemented by the results of 21 sandy and muddy samples collected by Vázquez-Argüelles (1974). Simultaneously, physical and organic sedimentary structures which represent the estuarine morpho-sedimentary units were described within the upper 40 cm of sediment. Sand samples were analysed by sieving at 0.50  $\phi$  intervals and granulometric parameters of Folk & Ward (1957) were obtained from cumulative weight

percentages curves on arithmetic probability graph paper. Bioclastic carbonate components were calculated by volumetric analysis (Bernard calcimeter).

River runoff is obtained theoretically from Álvarez (1971) because a gauging station did not exist. Fluvial and tidal water volumes were calculated during a tidal cycle (12 hours and 20 minutes, approximately), by measuring the complex surfaces of the estuarine sides covered by tides and applying the recorded tidal ranges.

Aerial photographs and geographic maps from the last century and recent years were consulted to differentiate the sandy beds, reclaimed flats and the position of major channels on the surface. Field verifications to define the morphosedimentary units, sedimentary structures, and vegetal and animal

identifications were necessary from 1990 to 1993. Vegetal cartography at a scale of 1:10,000 was established by Aedo (1986) and simplified in this paper.

### Hydrodynamics

Tides and fluvial discharge are the main dynamic agents controlling the mixing of waters and sedimentary distribution in this estuary. In addition, northwest winds act over some estuarine sandy point bars and sand flats, producing narrow and elongated dune fields. Refractive waves in the estuary, as a response to wind action during high tides, generate narrow sandy beaches only in the bay area and weak waves rework the sand flat surfaces resulting in symmetric or asymmetric and flattened ripples.

Fluvial discharge represents an average runoff of 795 mm/yr from a precipitation of 1,285 mm/yr, giving 102 mm/yr of potential groundwater (Álvarez, 1971). Autumn and spring seasons are the wettest (westerly winds) and winter and summer are relative dry periods, but highly variable. Tides are semidiurnal, ranging from 4.2 m during spring tides to 1.05 m during neap tides, giving tidal ranges between 2.0 m and 4.0 m for the 73.13% of the year; therefore these tides can be classified as mesotidal, after Davies (1964). Following Pritchard (1955), Vázquez-Argüelles (1974) calculated the ratio between fluvial ( $0.26 \times 10^6 \text{ m}^3$ ) and tidal volume ( $10.6 \times 10^6 \text{ m}^3$ ) per tidal cycle for the average surface runoff per year is 0.02. Thus the Villaviciosa estuary can be defined as a well-mixed estuary or weakly stratified (Jay & Smith, 1990), even during river flood conditions.

The tidal wave becomes slightly asymmetrical and its range decreases towards the upper meandering area upstream (hyposynchronous estuary, according to Le Floch, 1961). Salinity records during a tidal cycle from the surface to the bottom show the process of water mixing (Fig. 4). High values of surficial salinities reveal the strong marine influence in this estuary. A homogeneous water column is dominant at the mouth (station 1) and at the sandy bay (stations 2 and 3), where salinity decreases during the low tide but reaching maximum values after two hours. Upstream at stations 4, 5 and 6 from high tide to low tide, salinities are lower and decrease gradually to the bottom (partially mixed waters), but from low to high tide salinities become homogeneous, gradually increasing the absolute values. These are lower than the downstream areas, due to the river influence (Fig. 4).

Current velocities in mean tides recorded at the six gauging stations (Fig. 5) show the strong tidal power in the inlet, which is increased when spring tides occur. Resultant tidal curves are asymmetric and more irregular in the mouth, probably due to the superimposed wave effect, showing gradually decreasing tidal velocities from the surface to the bottom in the whole estuary. When low river flow and

medium tides occur, maximum velocities are about 0.60 m/s, recording values of up to 1.00 m/s in the inlet during spring tides. Maximum velocities appear at half tide (between low and high tide), being more important during the ebb interval, particularly in the upper meandering estuary. Minimum velocities occur during low tide, except in the channels that have a fluvial discharge component.

By including salinities and currents (velocity and direction records) in a dynamic scheme (Fig. 6) for medium tides on the surface, -1 m and -2 m deep (the remaining bottom waters have a similar behaviour to the last depth in this shallow estuary) the general circulation can be deduced during half rising tide, high tide and half falling tide, each one comprising about an interval of one hour before and after the culminating moment (a periodicity of three hours for these semidiurnal tides). Low tide reconstruction is excluded because the mixing and fresh waters simply travel through the channels.

*Half rising tide.* Salinities are high in the inlet and sandy bay, the salt water entering into the estuary, and mixing waters arriving to the inner estuary by the bottom. The main channel is the morphologic and dynamic distributor of marine water. Also, the tide promotes the constrained water entering through the seawall to the sandy bay, activating the flood-tidal delta. Surface salinity curves are oblique to the axis channel, decreasing toward the inner part, drawing curved lines upstream and slightly more saline downstream. Surface current velocities are maximum at the tidal inlet, sometimes 1.0 m/s in the outer area, decreasing as the estuary widens and in the meandering upper channel, and decrease progressively to the bottom. Currents are directed upstream when tidal influence is strong, even in the inner and narrow area of the upper estuarine channel. Channels are reworked by the flood tide, particularly the main channel and tidal delta; this tidal delta is active in the whole water column (Fig. 6 A).

*High tide.* Salt water continues to enter at all depths, the waters being very salty and brackish (25‰) near the point of maximum saline wave, but this flood continues until two hours after the high tide, upstream of the meandering upper channel. Current velocities are maximum at the inlet, decreasing with depth and upstream. Now, in the upper body of water (1 m) affecting the sandy bay, a levogyre horizontal current is originated due probably to the Coriolis force, strongest at the southern side and more intensive in the lower boundary at the northwestern side, activating a small spillover lobe (speeds under 0.3 m/s). This levogyre current has also been deduced in the Eo estuary in the sandy bay area (Flor *et al.*, 1992 a). In contrast, the dynamics of tidal delta have ceased at this time. When the flood-tidal delta ceases its activity, the secondary channel downstream ends in a spillover lobe and water flow is extruded to the main channel. This counterclockwise current promotes the formation of a smooth channel, here denominating the

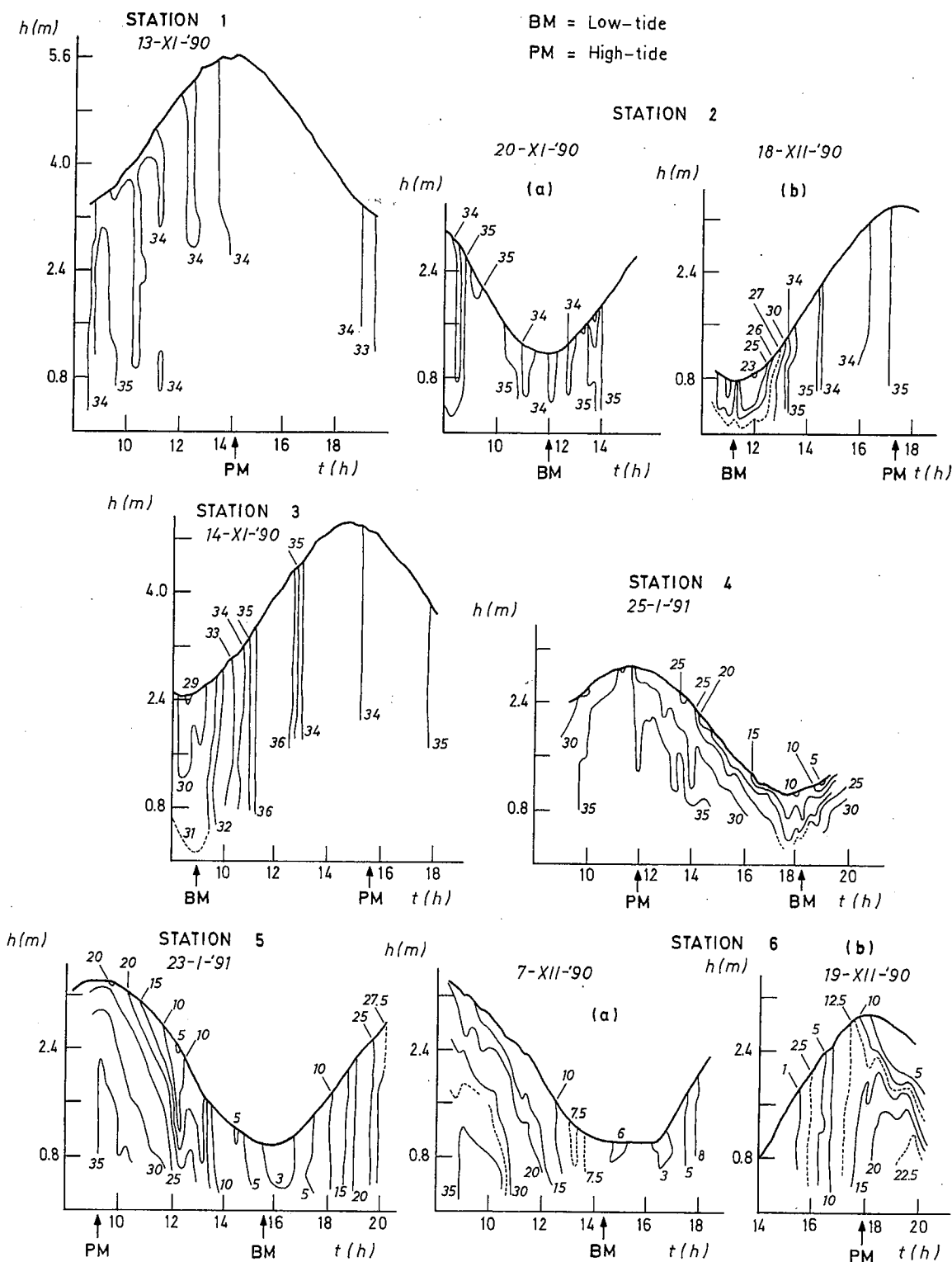


Figure 4. Surficial tidal and vertical salinity distributions for medium tides during low water discharge. Note the vertically homogeneous dominant mixing waters from about low tide to after the high tide at almost all stations, and lateral mixing between high tide and low tide in the inner half estuary.

secondary channel, that in many places is partially scoured at low tide by a deeper and broader draining large areas. This great gyre originates the sedimentation build up of the sandy shoal in the bay which supports a variety of morphosedimentary units (Fig. 6 B).

*Half falling tide.* One or two hours after high tide,

ebb tide currents move downstream through the whole water column, recording the strongest current velocities during the full tidal cycle in the main channel and neighbouring areas. All channel types begin their activity as fluvial channels according to their hierarchy. Salinity decreases upstream on the surface, but a broad

lens of brackish water is recorded in the boundary between the inner mud flats and the meandering upper channel. (Fig. 6 C). This characteristic allows us to assimilate this estuary to a laterally homogeneous one (Dyer, 1973).

### Morphosedimentary units

Surficial sediment distribution in Villaviciosa estuary shows a great variety of morphosedimentary units (Fig. 7). They are characterized by their shape and size, position, physical sedimentary structures, animal and vegetal colonization, textural parameters and composition: siliciclastic and carbonate components (Figs. 8 and 9).

#### *Mouth complex*

*Sandy mouth bar.* This bar is almost entirely submerged except during spring low tides. It has not been included in our field works but its geometry and situation was studied with detailed aerial photographs. Generally, it displays an asymmetric triangular shape and its main crest is oblique (NW-SE) to the channel due to the wave incidence; the bar is about 400 m long, 240 m on the southern side and an average of 120 m wide seaward; when the bar crest emerges it can be studied allowing us to conclude that it is approximately similar to that described by Wright (1977) as wave-dominated crescentic bars with oblique wave incidence. Due to seasonal river discharge and tidal dominance, the mouth bar may be temporarily broken.

*Beach/eolian dune system.* The exposed mesotidal beach is a sandy pocket beach that can be divided into backshore, foreshore and offshore areas. The beach-dune system is elongated normal to the main channel with a W-E direction, the foreshore gently arcuate and the offshore sharper, both with the concavity seaward. It is 900 m long, and the width is variable from 760 m in the western area, where the sandy mouth bar is situated, to 360 m in the eastern area. The backshore represents a narrow transition zone (70 m wide) to the dune field with a gentle seaward slope; the inner boundary is erosive, generating a sharp step in the foredune (1-2 m high); eolian sand ripples are the main features of this surface. The intertidal zone is divided into a seaward inclined surface with a belt of rill marks at its base, developing romboidal ripples, swash marks and crescent marks in the upper part. During swell waves it generates an equilibrium bar with a small berm and beach cusps at its front; the broadest lower area is a low tide terrace with several longshore bar and trough systems aligned alongshore. Several asymmetrical megaripples, some of them with top flat surfaces and wave and current ripples, can be generated on the trough floor, and romboid ripples and primary current lineation are the current structures on the bar face. Sinuous millimetric tracks with irregular but sinuosity

tendency of Mysidaceans (*Paramysis helleri*) and wandering polychaetes are abundant in the low tide terrace.

The eolian dunes can be separated into two dune fields as a response to the evolution of the estuary mouth; the inner dune field is the oldest and was active before the sidewall construction in 1934. This inner field is almost entirely reclaimed, with a surface of 83,040 m<sup>2</sup>, an average width of 230 m and about 460 m length, represented in three disconnected areas: a) the western field is the widest and it is represented by three smooth ridge dunes (less than 1 m high); b) the central outcrop is a small climbing dune over an old beach cliff (about 7,785 m<sup>2</sup> of surface), and 3) a high simple and smooth foredune ridge closing a small blind valley. The outer dune field is 1,115 m long, and has variable width, from 500 m in the western area to 86 m in the eastern side, with a surface of 133,210 m<sup>2</sup>. It is composed of several smooth foredune between flat surfaces; near the beach, the lee side of a ridge (relief of 1 m) is still conserved, the stoss side being eroded; minor dunes with tongue-like topographies (its axis is transverse to the dune/beach boundary) and reactivation embryonic dunes are the actual eolian sedimentation.

*Inlet.* This is the most energetic morphosedimentary unit of the estuary. The main sandy channel is limited by sidewalls (120 m wide), so it is artificially increased in length up to 600 m; the most important bedforms are plane beds and accessory hydraulic dunes and small sand waves, and current ripples are superimposed. Only typically marine algae (*Fucus spiralis*, *Anemonia sulcata*) and animals (the gastropod *Nassarius reticulatus*, the crab *Carcinus maenas*, and the fish *Blennius* spp.) are present in this area.

#### *Sandy bay*

This broad area is developed at the right side of the main channel and its inner border, defined by two small lateral bays (previously as marshes), has been reclaimed. Several morphosedimentary units can be differentiated, most of them as portions of a continuous sandy shoal.

*Main channel.* This channel links the inlet with the fluvial channel and crosses the sandy bay with a low sinuosity (radius about 700 m); it is only confined on the northern side, but its width is similar to the unconfined southern side; it frequently develops sand waves at the left convex bank and a point bar with superimposed hydraulic dunes and current ripples on the opposite right bank; plane beds can be present in the most active areas; channel talus are gently to moderately sharp, in the first case with a narrow belt of incised rill marks and in the last case with current ripples where filter bivalves are the characteristic infauna: *Solen marginatus*, *Cerastoderma edule*, *Tellina incarnata*, and the echinoid *Echinocardium cordatum* in sandy substratum, and *Phollas dactylus* in hard muddy substrate. Debris of bivalves *Cerastoderma*



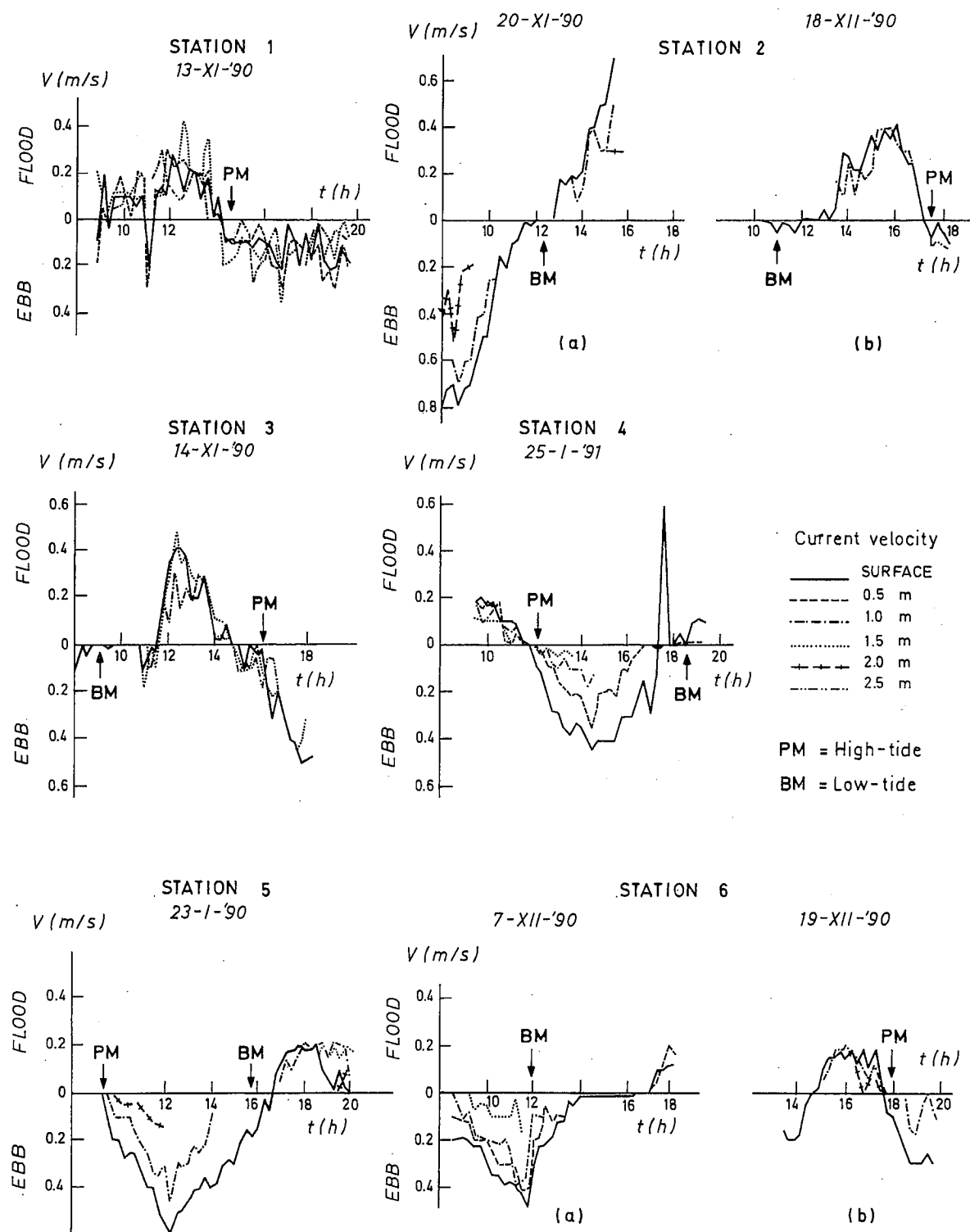


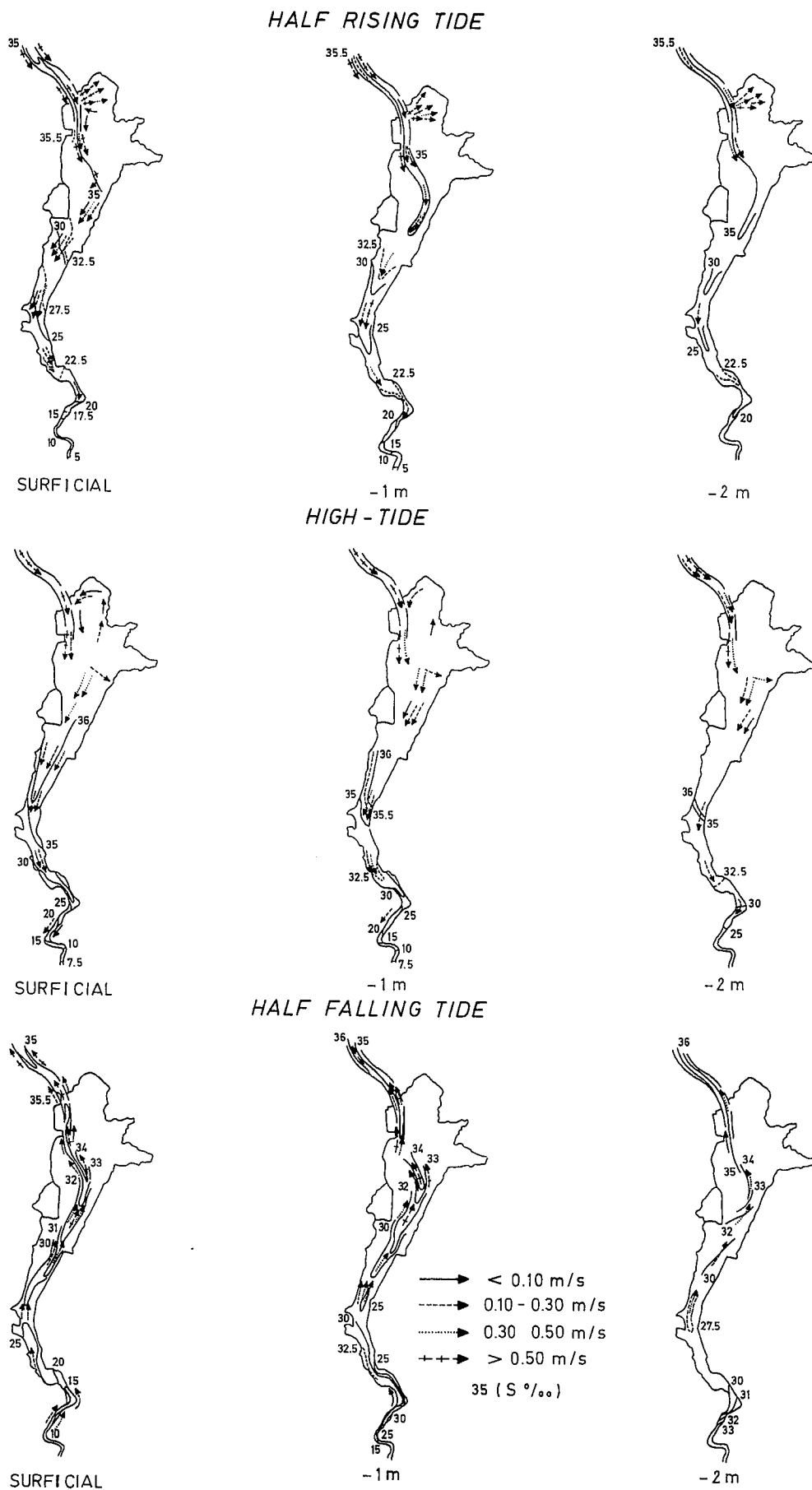
Figure 5. Velocity distributions in depths for medium tides (see text).

*edule*, *Mytilus edulis* and *Ostraea edulis*, and Carcinidae are very common and there are mud balls in the sediment.

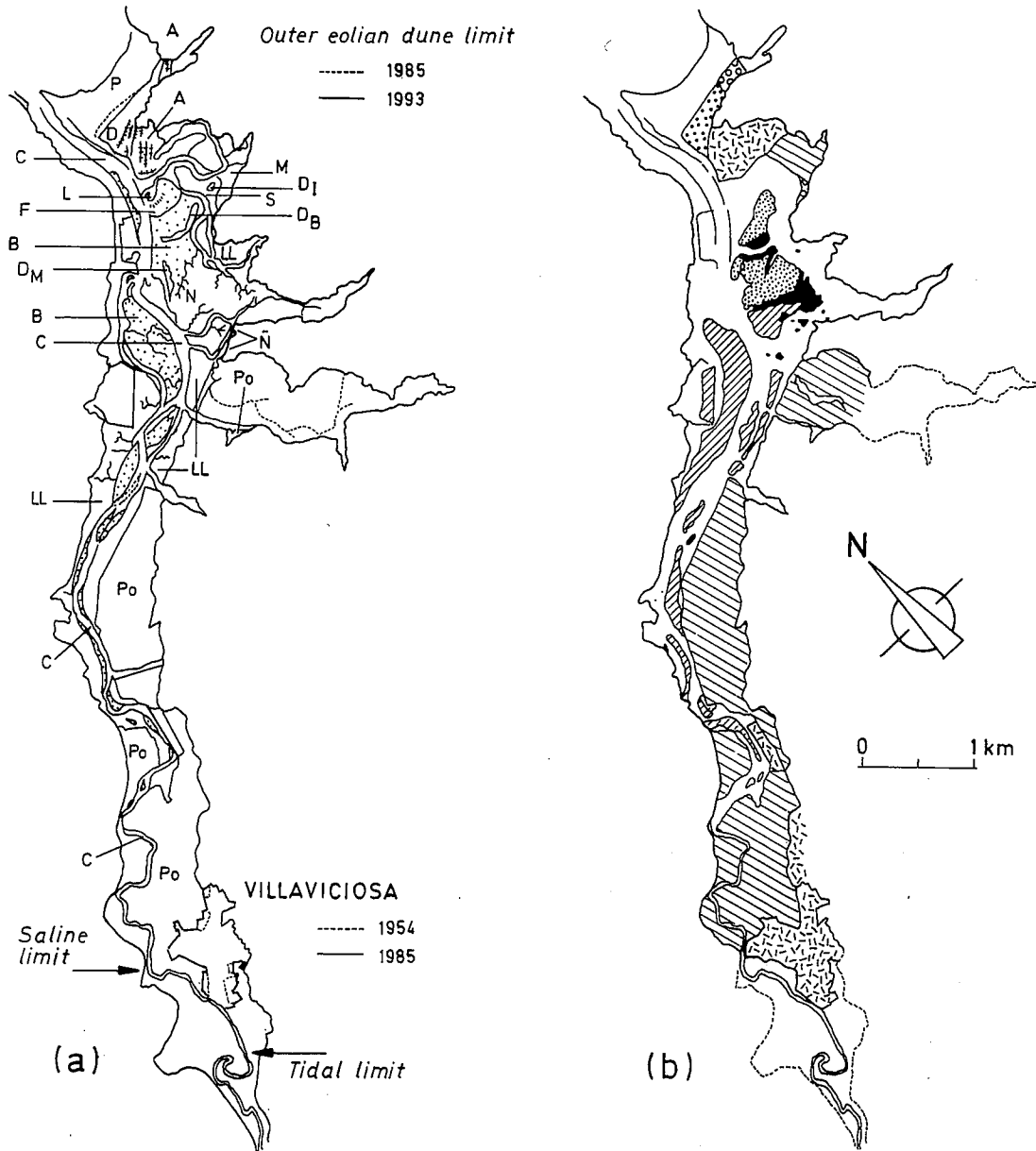
**Secondary channel.** It is defined in this and other Asturian estuaries (Flor and Camblor, 1989; Flor *et al.*, 1992 a) as a minor channel generated beyond the main channel and the sandy shoal, being active approximately from the rising to descending half tides

due to a horizontal current and reworked during low tides as a fluvial channel. In this estuary, it is located on the right side of the sandy bay and it is linked with a minor channel draining a lateral bay (mixed and muddy flats and marshes).

When it appears in isolation it is a smooth channel with current ripples covering the bed, but when linked with a minor channel it develops the characteristics of



**Figure 6.** Circulatory scheme during half rising tide, high tide and half falling tide for spring and medium tides during low water discharge in the surface, at 1 and 2 m depth. Also are included isohalines and current vectors.



**MORPHOSEDIMENTARY UNITS**

EMERGED BEACH	P	
EOLIAN SANDY FIELDS	RODILES	OLD DUNES A
		ACTIVE DUNES D
	MISIEGO	M y D <sub>I</sub>
	SHOAL	D <sub>B</sub> / POINT-BAR D <sub>M</sub>
MAIN CHANNEL	C	
SANDY SHOAL	B	
FLOOD-TIDAL DELTA	F	
SPILLOVER LOBE	L	
SECONDARY CHANNEL	S	
MINOR CHANNEL	N̄	
TIDAL CREEKS	N	
MUD FLATS	LL	
RECLAIMED TIDAL FLATS	Po	

**VEGETATION AREAS**

	HYDROPHYTIC VEGETATION (EOLIAN DUNES)
	PINUS AND EUCALIPTUS (EOLIAN DUNES)
	ZOSTERA
	SPARTINA
	HALOPHYTIC SHRUB
	SUBHALOPHYTIC GRASS
	URBANIZED AREA

Figure 7. Surficial distributions of morphosedimentary units (a), including the emerged exposed beach and its related eolian system that enclose the estuary of Villaviciosa, and the vegetation areas (b). This last scheme modified from Aedo (1986).

sandy longitudinal and point bars with hydraulic dunes near the outlet and superimposed current ripples (crescentic and lingoid shaped). The sandy bed is bioturbated by tubicolous annelids (*Owenia fusiformis*, *Arenicola marina* and more scarcely *Aricia foetida*, and *Lanice conchilega*), scarce *Tellina incarnata*, *Cerastoderma edule*, *Echinocardium cordatum*, *Arenicola marina* and burrows of the ghost shrimp *Upogebia pusilla*. Tracks and nests of Carcinidae, fin impressions of small fishes (Callionymidae, Gobidae and Blennidae), and grooves generated by algae and wood fragments can be drawn on the surface. Belts of rill marks at the base of slopes and tension fissures at the top are also important structures. Debris of bivalves *Cerastoderma edule*, *Venerupis decussatus*, *Scrobicularia plana* are very common and there are mud balls in the sediment. Smooth slopes of the channel are inhabited by *Aricia foetida*, *Arenicola marina*, and burrows of the ghost shrimp *Upogebia pusilla*.

Sandy point bars have variable lengths at decametric scale and widths between 5 and 6 m, with lingoid-shaped small ripples whose troughs are covered by muddy films and on the lee-sides by organic debris. Bordering sandy flats, a narrow belt of rill marks is developed with microdeltas at their ends; grooves and floating vegetation as *Zostera noltii*, *Enteromorpha* sp., *Laminaria* sp., etc; tracks of Carcinidae, crawling and browsing traces made by *Nereis diversicolor* and pellets of *Arenicola marina* are other biogenic structures.

Minor channels. Also denominated as large tidal creeks, they incise sandy, mixed and muddy flats and marshes and drain lateral muddy embayments promoting a typical fluvial sedimentation during low tide, and several tidal creeks empty through them. They have a sinuous tracing (maximum radius of 120 m in the lower segment) even more accentuated than the main and secondary channels but less than the tidal creeks, and average widths of 40 m. Their heads are not well defined with the upper drainage flowing to different channels.

When a minor channel is active, its lithology is sandy and locally muddy and sandy. Point bars and longitudinal bars are the most important sedimentary morphologies, and current ripples are the minor bedforms occupying the sandy beds. Tubicolous annelids (*Owenia fusiformis*), *Audouinia tentacullata*, *Glycera tessellata*, and locally *Arenicola marina* and the bivalve *Scrobicularia plana* are the bioturbating organisms in the bed, the latter in muddy sediments; on the bottom, resting traces and trails of the small shrimp *Crangon crangon* are frequent. In the sandy channel talus the sipunculid *Golfingia elongata* is very common. In some places, hydraulic dunes can be important. Abandoned minor channels are infilled by fining-upward sediment.

Where channels erode a mud flat, the walls are sharp and Carcinidae caves are profuse. Fish fin marks, and traces of Isopodes and Carcinidae can be important

on the sandy bed. Mud balls are a significant sedimentary component derived from eroded flats, that are formerly incorporated at the talus base as faulted blocks and into the sediment.

*Sandy shoal*. This is defined as the sandy body located between the main and secondary channels originated by the building-up of sedimentation during high tides due to the Coriolis effect in the sandy bay which creates a horizontal levogyre circulation with a resultant accretion (corkscrew effect). During low tides it is reworked by both channels that have a fluvial behaviour; also the inner water waves acting over sand flats and wind deflation over dry surfaces complete the complex dynamics in this area.

It can be differentiated five morphosedimentary units:

a) Sandy flats are subplane surfaces, gently dipping to the channels in this estuary, and are characterized by current ripples, and in some places wave and capped ripples, with muddy films settled on the troughs. A subsurface sponge-like texture is a very common sedimentary structure. In some locations, bioturbation by polychaetes (*Arenicola marina* and its cylindrical pellets with radius of 1-3 mm, *Terebella lapidaria*, *Lanice conchilega* and *Nereis diversicolor*), *Cerastoderma edule* and *Upogebia pusilla* can be important. The inner sandy flats tend to be colonized from *Enteromorpha* algae to *Spartina maritima*, *Salicornia europea* and *Halimione portulacoides*.

b) Flood-tidal delta generated from a broken sidewall growing normally to the right margin of the main channel over a surface of 53,200 m<sup>2</sup>. Its shape is like-tongue in plan, slightly curved to the NE (deviation due to the Coriolis force) with a maximum length of 325 m and a width of 135 m near the flood ramp and of 205 in the outer areas. It develops an incised ramp linked outwards with a smooth channel and a broad assymetric fan marked by sand waves and current ripples.

The flood ramp surface, due to the strong flows, is a planar bed. On the flood channel, megaripples with irregular crests are frequent, and superimposed lingoid ripples with oblique crests occur near the flood ramp. Megaripples acquire dimensions (h = 0.3 m, l = 2,7 m) with undulatory crests, evolving downstream to arcuate crests (h = 0.2 m, l = 2,0 m). In the outer area, the sand waves are smooth (h = 0.2 m, l = 4-5 m) with bifurcating crests and superimposed lingoid and crescentic ripples. Smooth grooves of the green algae *Ulva lactuca* are frequent. The polychaetes *Owenia fusiformis*, *Nephtys hombergi* and *Ophelia* sp. also inhabits this area, together with the bivalve *Cerastoderma edule*, the echinoid *Echinocardium cordatum* and the crab *Carcinus maenas*. The same organisms are also present in the next unit.

c) Ebb-tidal spillover lobe is linked with the flood-tidal delta dynamic system, because it acts in the contrary direction during the ebb tide. It has an acute and assymetric V shape with the apex situated

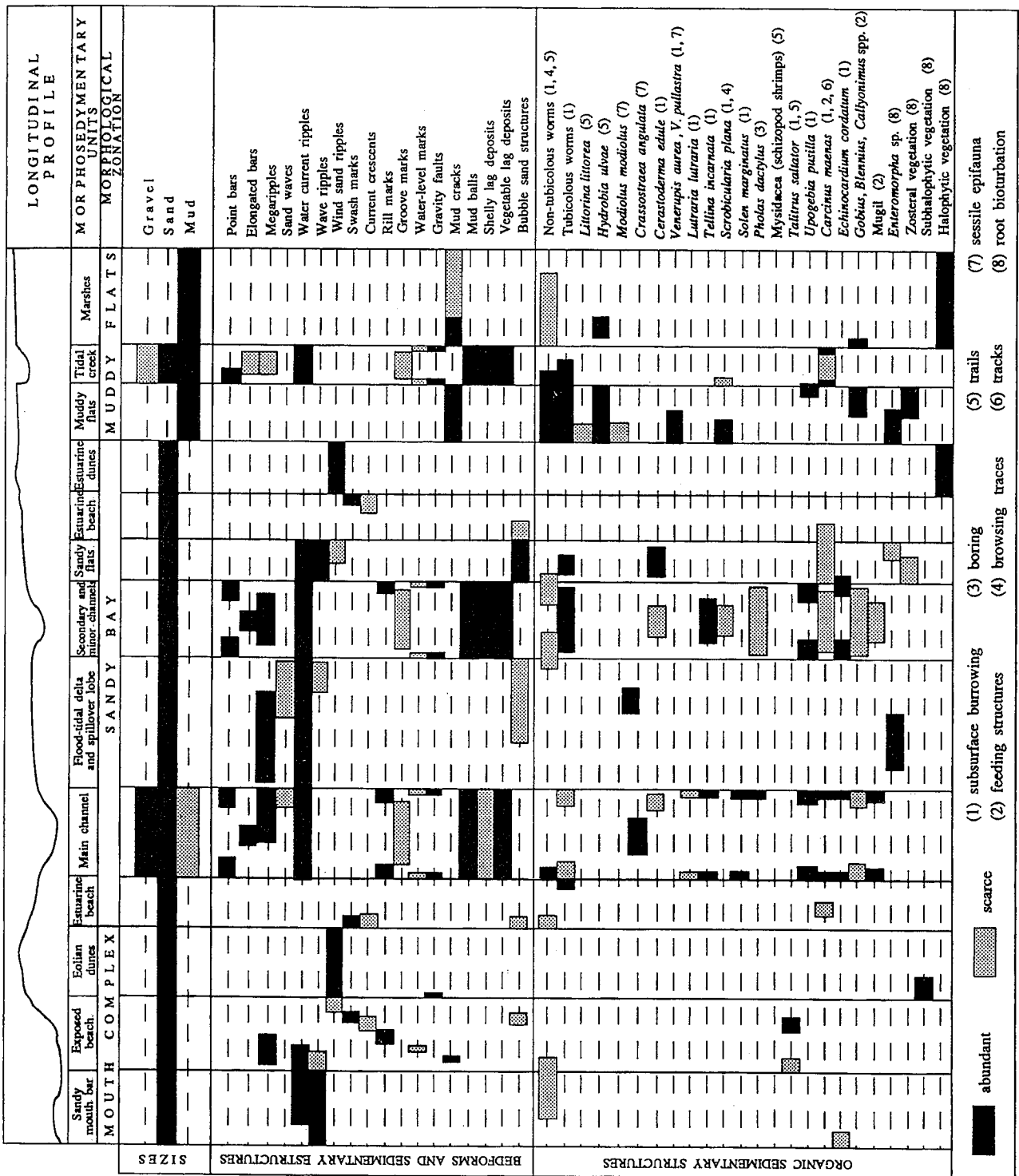


Figure 8. Schematic distribution of the main bedforms and sedimentary structures in the estuary.

downstream and the arms between 25-30 m long, generating megaripples and current ripples on the stoss side. During low tide the secondary channel, now as a minor drainage channel, borders this unit and substitutes the spillover lobe activity.

d) Estuarine beaches are narrow sandy belts (15-20 m wide) in the upper intertidal area, that gradually extend to the secondary channel talus. Swash marks, crescent marks and subsurface sponge-like texture are

the most important structures. This kind of structure almost completely lacks fauna.

e) Estuarine eolian fields occupy the marginal belt outward of the sand flat area and the surface beyond the sandy point bar. They originated by deflation of sands from northwestern winds and were reworked by other less important wind components (NE and SW). They draw an arcuate shape in plan with 455 m length and a more or less constant width of 45 m. The first

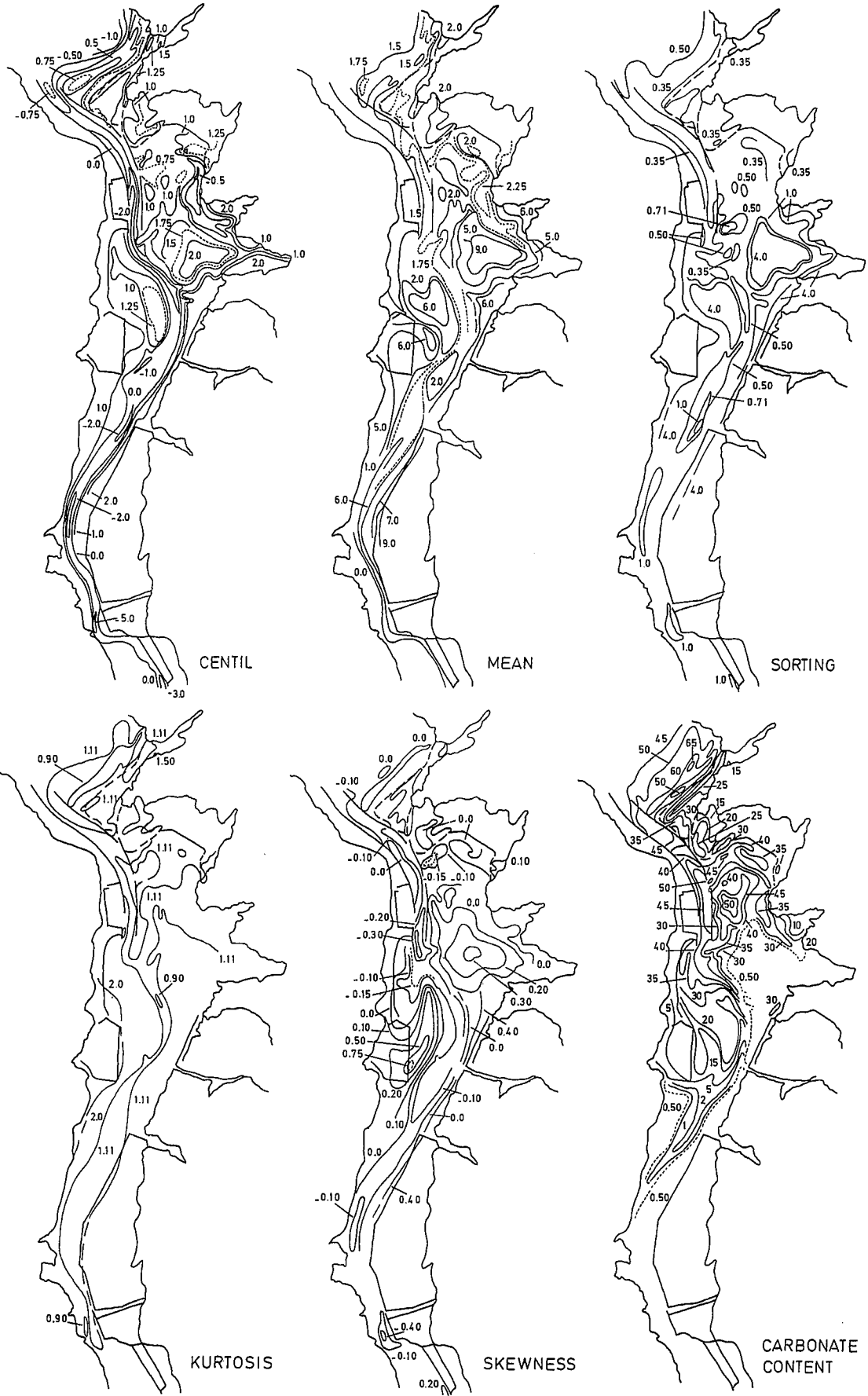


Figure 9. Surficial isolines distributions of the textural parameter: centil, mean, sorting, skewness and kurtosis, as well as the percent bioclastic carbonate content.

eolian field is represented by two parallel ridges, the inner higher, and the outer constructed of sparse eolian mounds and irregularly colonized by *Salicornia europea*, both elongated normally to prevailing winds. The last eolian field is smaller and the only ridge is sinuous due to the formation of eolian dunes such as small parabolic ones. Both eolian fields are almost entirely colonized by halophytic vegetation (*Salicornia europea* in the outer ridge and *Halimione portulacoides*). The other dune field, now fossilized, occurs in the inner area beyond the secondary channel as hummocky dunes over a surface of 34,600 m<sup>2</sup>, generated by deflation (NW winds) of the small sandy flats.

#### Mixed and muddy flats

The main channel crosses these broad flats with a radius in the outer segment of 700 m, like in the sandy bay. Active mixed and muddy flats are drained by minor channel and tidal creeks, but most of the area has been reclaimed.

*Mixed flats.* These are located between the sandy bay and muddy flats, occupying an asymmetric belt (300 m width in the western side, and 100 m in the eastern side) and obliquely aligned to the general axis due to the marine and fluvial influence, respectively.

Their surface is colonized by a green algae, *Enteromorpha* sp., locally by the brown algae *Ascophyllum nodosum*, and the herbaceous *Zostera noltii* in the left side, which during low tide tend to orientate downflow, and in some places it is invaded by sandy blankets developing current ripples. Pellets and fecal mounds of *Arenicola marina* are very scattered. The right side is colonized by the *Zostera noltii* with the bivalves *Venerupis pullastra*, *Venerupis aurea*, *Cerastoderma edule* and *Modiolus modiolus* fixed to the substratum and *Littorina littorea*, a relict gastropod from the Upper Pleistocene in this coast; also the worms *Audouinia tentacullata*, *Glycera tesellata*, *Owenia fusiformis* and *Nereis diversicolor* occur at a high density.

*Muddy flats.* This unit can be divided in several areas:

a) Unvegetated muddy flats that extend and occupy small surfaces near the channels with the infauna of *Nereis diversicolor*, *Terebella lapidaria* and *Scrobicularia plana* as the most representative, and less frequently *Lanice conchilega*. Sedimentation is active but with a slow rate, the surface having copious traces of pectoral fin marks of fish (*Gobius* sp. and *Blennius* sp.), and crawling and dendritic browsing traces of *Nereis diversicolor*, and star-shaped browsing traces of *Scrobicularia plana*. Millimetric pellets are numerous near the animal cavities.

b) Zosteral flats: *Zostera noltii* is the dominant species, but brown (*Fucus vesiculosus*) and green (*Enteromorpha* sp.) algae are also present. This vegetal colonization allows the presence of the bivalve *Modiolus modiolus*, and the gastropods *Hydrobia ulvae*

and *Littorina littorea* on the surface, and an abundant infauna of polychaete worms (*Glycera tessellata*, *Nephtys hombergi*, *Melinna palmata* and *Audouinia tentacullata*). Locally, *Ascophyllum* flats colonizing sandy substrates contain abundant gastropods *Littorina obtusata* and large amphipods.

c) Marshes: Occupy the higher topographic and less energetic areas, where the vegetation is zoned according to the differential subaerial exposure; the main vegetation is represented by *Spartina maritima* and *Fucus spiralis*, *Halimione portulacoides*, *Juncus maritimus* and other species: *Glaux maritima*. Before the reclamation, these were the broadest areas of the estuary.

d) Ponds: Abandoned tidal creeks that work as discontinuous enlarged pools, occasionally maintaining the sinuous tracing; on the plants and on the bed near them, are numerous small gastropod *Hydrobia ulvae*, and occasional *Nereis diversicolor* reside in these ponds.

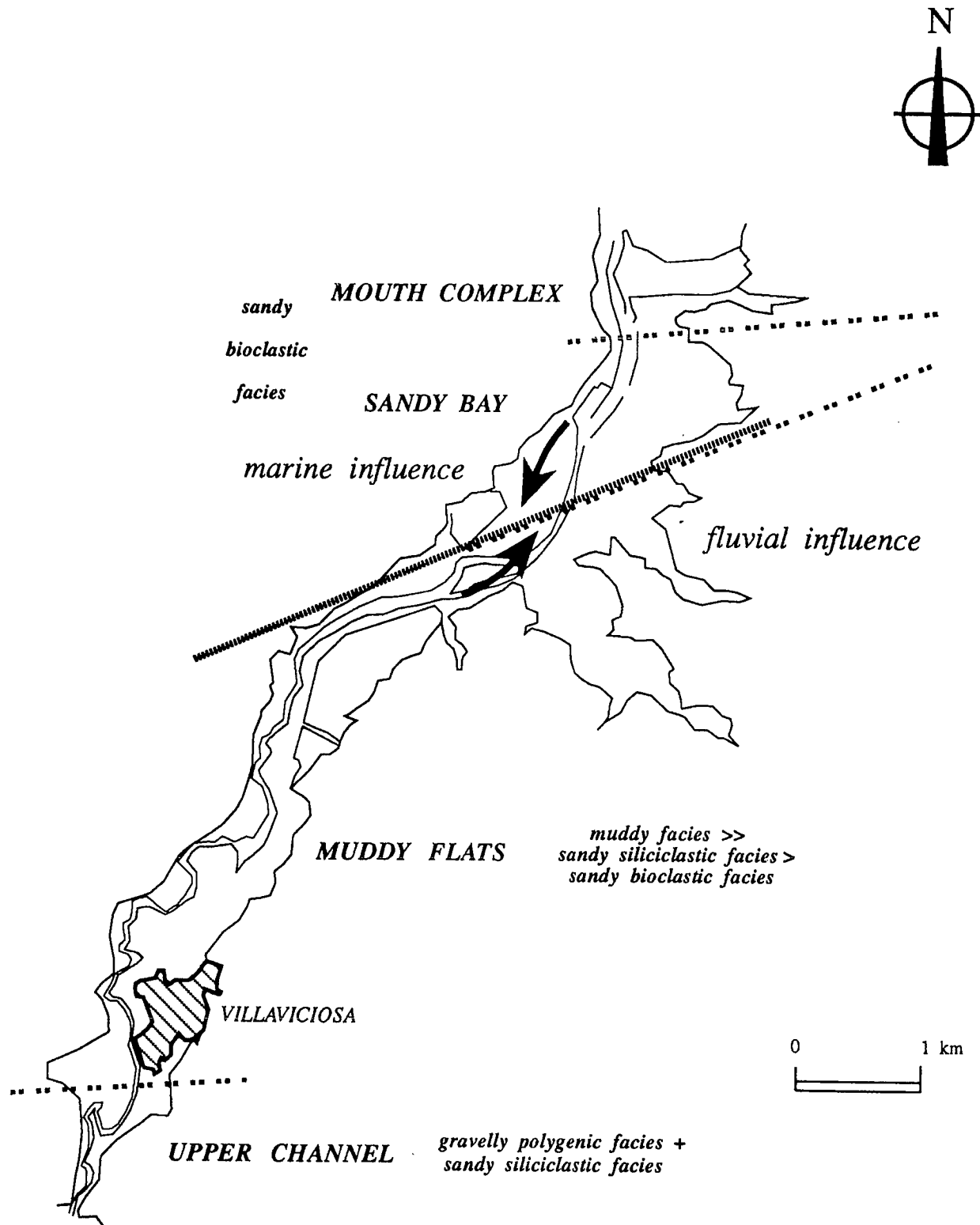
e) Minor channels: These channels with maximum lengths of 1 km, average width of 35 m, and a height/width ratio from 0.02 to 0.10, vary their traces from straight to sinuous with vertical walls due to eroding processes where the caves of *Carcinus maenas* are dispersed and faulted blocks supply mud balls to the channel bed. Longitudinal and point bars, some of them with several scroll bars and swales of sand and mud with superimposed current ripples are developed, and lag deposits in beds are significant, as are mud balls incorporated into the beds. Tubicolous anelids (*Owenia fusiformis*), *Arenicola marina*, *Nereis diversicolor*, and *Scrobicularia plana* in the muddy and soft beds are locally abundant.

f) Tidal creeks: Drain tidal flats and empty into a minor channel with a sinuous geometry and show the dendritic drainage pattern typical of muddy intertidal flats; the heads are not well organized, having a muddy lithology, but downstream their incision is greater and the bed is sandier with lag deposits of biogenic fragments of *Scrobicularia plana*, *Bittium reticulatum* and *Hydrobia ulvae*, and sinuosity generates points bars. Mud balls are integrated into the sandy beds. Lengths are not more than 115 m with variable width of 1-3 m, an average altitude of 2 m, and height/width ratios between 0.17 and 0.04.

*Main channel.* This has a high sinuosity (radius of 700-800 m) that evolves upstream to a sharp sinuosity, developing some smooth point and elongated bars of sand and mud sediments. Lags of *Scrobicularia plana*, *Hydrobia ulvae*, scarce terrestrial snails (*Helix* sp.), and continental organic debris (chestnut, oak, eucalyptus...) can be in the bed covered by muddy films. Some clasts are colonized by *Fucus* and *Ulva* algae.

#### Upper channel

The upper meandering channel is narrow, with an average radius of 80 m, and sharply incised into the muddy flats, here reclaimed. Gravelly and sandy beds,



**Figure 10.** Marine and fluvial influences deduced from both correlated geomorphologic zonation and facies distributions. Surficial distributions of the textural parameter centil and mean, and the percent carbonate content are particularly useful in this assignment. Note that in the left side, sandy bioclastic facies enter from the outer estuary due to the Coriolis effect in the Northern Hemisphere.

point bars and lags of *Scrobicularia plana* and terrestrial gastropods (*Helix* sp.) and leaves, branches and seeds of several trees (eucaliptus, oak, chestnut, hazel, etc) are present. Only *Scrobicularia plana* and *Nereis diversicolor* inhabit the outer area.

#### Textural and carbonate percent distributions

Sediments are constituted by sand, mud and scarce gravel. The surficial distribution shows a clear gradation, the outer sediments sandier than the inner



BEACH	CENTIL		MEAN		SORTING $\phi$	SKEWNESS	KURTOSIS	BIOGENIC CARBONATE %
	$\phi$	mm	$\phi$	mm				
Foreshore								
Low-tide terrace (n=18)	0.53	0.69	1.66	0.32	0.42	-0.05	0.98	50.52
Upper talus (n=4)	0.21	0.86	1.56	0.34	0.46	-0.02	0.94	56.88
Backshore (n=7)	0.65	0.64	1.61	0.33	0.38	-0.03	0.92	52.55
Transition area (n=4)	1.09	0.47	1.90	0.27	0.33	-0.03	1.05	33.51
Outer dunes (n=22)	1.05	0.48	1.92	0.26	0.33	-0.07	1.09	27.51
Eastern inner dunes (n=8)	1.13	0.46	2.05	0.24	0.33	0.00	1.22	20.47
Climbing dunes (n=3)	1.09	0.47	2.06	0.24	0.31	0.00	1.20	26.48
Western inner dunes (n=15)	1.09	0.47	2.00	0.25	0.31	-0.03	1.21	22.36
Inlet (n=7)	0.25	0.84	1.70	0.31	0.37	-0.07	1.09	42.85
Medium (n=17)	0.48	0.72	1.78	0.29	0.37	-0.18	1.11	37.68
Inner (n=22)	-1.07	2.10	1.60	0.33	0.76	-0.16	1.11	13.58
SECONDARY CHANNEL (n=7)	0.75	0.59	1.81	0.28	0.34	-0.11	1.09	42.55
MINOR CHANNEL (n=24)	-0.28	1.21	2.13	0.23	0.55	-0.07	1.43	29.56
Tidal delta (n=19)	0.99	0.50	1.76	0.29	0.34	-0.07	1.04	44.03
Spillover lobe (n=11)	1.00	0.50	1.85	0.28	0.33	-0.09	1.11	40.64
SANDY SHOAL								
Sandy flat (n=16)	0.94	0.52	1.91	0.27	0.38	-0.04	1.14	40.49
Eolian dunes (n=20)	0.97	0.51	1.95	0.26	0.41	0.00	1.22	44.49
Left margin (n=11)	0.98	0.51	1.88	0.27	0.31	-0.08	1.25	35.67
OTHER SANDY FLATS								
Rigth margin (n=6)	0.91	0.53	2.10	0.23	0.35	0.02	1.07	35.95
Secondary channel (n=6)	1.15	0.45	2.06	0.24	0.37	0.26	0.90	34.62
ESTUARINE BEACHES								
Point bar (n=4)	1.18	0.44	2.06	0.24	0.39	0.14	1.16	27.96
Mixed flats (n=3)	1.19	0.44	6.26	0.01	4.52	0.39	1.20	16.81
Muddy flats (n=8)	1.90	0.27	6.46	0.01	3.19	0.40	1.35	3.31
MUDDY FLATS								
Tidal creek (n=8)	0.76	0.59	2.27	0.21	0.39	0.08	1.17	27.49

Table I. Average values of textural parameters and percent bioclast carbonate composition of the main representative morphosedimentary units of the estuary of Villaviciosa.

ones, due to the coastal proximity (more energetic areas). Sands are distributed in the outer part (mouth complex and bay) and in the minor channel beds. Muds occupy the inner flats and lateral bays. Gravels of river basin origin are linked to the upper meandering channel; a low biogenic content comes from estuarine and coastal bivalves and gastropods.

Surficial granulometric distributions of statistical parameters: centil, mean, sorting, skewness and kurtosis, and also the percent carbonate content, are illustrated in Fig. 9, and average values of the distinguishing morphosedimentary units are synthesized in Table I. On the exposed beach and eolian dunes, isolines are parallel to the water line but on the main channel they are adapted to the general axis of the main channel. Over the sandy shoals and mixed and muddy flats, the isolines display concentric shapes where minor channels and tidal creeks act as sharp boundaries.

The principal interchange of fluvial and marine sediments is produced through the main channel. Tidal floods allow the movement sandy bioclastic sediment, a higher percent in the west side of the outer estuary; in the sandy bay, currents are intense, promoting the distribution of sands into the flood-tidal delta and ebb-tidal spillover lobe; lateral sand flats and effective deflation by winds during low tides generating several dune fields complete the main dynamics with the fluvial or ebb action of channels.

Coarse sands ( $Mz < 0.0 \phi$ ) are very scarce, occurring only locally along the upper meandering channel. Medium sands ( $1.0 < Mz < 2.0 \phi$ ) are represented in the most energetic areas: exposed beach, inlet, main and secondary channel, flood and ebb-tidal deltas, sandy flats and some of the tidal bars and spillover lobes. Fine sands ( $2.0 < Mz < 3.0 \phi$ ) are characteristic of the eolian dunes, some minor channels and tidal creeks, sandy flats and estuarine beaches. Very fine sands and muds ( $Mz > 3.0 \phi$ ) are restricted to the mixed and muddy flats.

Sands are generally well sorted; the best sorting is in the eolian dunes, tidal delta and spillover lobe, some sandy flats, and the secondary channel (very well sorted); well sorted sands also appear in the exposed beach, inlet and main channel in the sandy bay, some sandy flats and estuarine eolian dunes and beaches, the minor channel and tidal creeks. Very poorly sorted sands are present in the mixed and muddy flats.

Skewness is negative in the more energetic areas: exposed beach, several types of channels, flood-tidal deltas and spillover lobes, and some eolian dunes. It is positive in areas with dominant settling processes: mixed and muddy flats, estuarine beaches and some sandy flats and eolian dunes. Kurtosis is not considered a good parameter for the interpretation of grain size distribution (McLaren, 1981) in sandy and muddy sediments; these values vary between platykurtic and leptokurtic.

Percent carbonate content is maximum in the most energetic areas: the exposed beach (averages up to 50 %, higher in the intertidal talus) and in the nucleus of

the sandy bay area (40-45 %), decreasing from the source areas of the dune fields, and sharply toward the inner mixed and muddy flats when marine sedimentation is reduced and fluvial influence is strong. It decreases towards the inner part of the estuary, being higher on the western side.

An asymmetric surficial distribution of centil, mean and carbonate content with regard to the estuarine axis or the main channel shows the marine influence, represented by the bioclastic sands. So, the western side from the inlet displays the greater sizes and higher carbonate contents (Fig. 9), and an hypothetically line with an oblique trend can be drawn (Fig. 10). This broken line separates the sandy facies (marine influence) from the muddy ones (fluvial influence), and the Coriolis effect can be deduced from the asymmetric distributions of the statistical size parameters and carbonate percent.

Biological groups in this carbonate component are mainly from the intertidal rocks: barnacles, calcareous algae and worms as well as bivalves, gastropods and echinoderms. The main biological groups: bivalves, gastropods and balanus exceed 50% when marine influence is strong (exposed beach and associated dunes, and sandy bay area). Flood tidal delta, estuarine eolian dunes and sandy flats show a high variety of microbiological groups that are dominant toward the inner areas (Flor *et al.*, 1992 b).

## Discussion

The four morphosedimentary and dynamic zones are a consistent feature in the Villaviciosa estuary and other studied cantabrian ones (Fig. 3 a, b). The mouth complex and sandy bay has been included by some authors as a simple unit (Nichol, 1991, designated barrier/inlet zone; Dalrymple *et al.*, 1992, as a marine sand body) which belongs to the outer zone from a tripartite distribution of lithofacies (coarse-fine-coarse), corresponding with the general pattern of net bedload transport. Our division is more accurate under the geomorphological point of view because it reflects different dynamic units and sedimentary facies. Even in other estuaries, some zone can be incompletely represented, particularly the mouth complex (for example: Eo, Niembro, Tinamayor, Tinamenor, and Pasajes shallow estuaries in the norwestern coast of Spain, near Villaviciosa) when barrier is a minor unit being substituted by a narrow rocky inlet; so, wave influence in those estuaries is not a main dynamic pattern. But in the inner estuary (sandy bay, muddy flats and upper channel) the longitudinal zonation, dynamics and surficial sediment distribution is the same as the proposed Villaviciosa estuary. Contrary to the ideas of Dalrymple *et al.* (1992), wave-dominated estuaries is not a correct division; they state that tidal influence is small, and waves with any tidal currents cause sediment to move alongshore and onshore, the barrier preventing the wave energy from entering the

estuary. These contradictory arguments and the previous considerations allow us to assert that, consequently, tidal power (more than 1 m/s of registered current velocity in the outer area of the Villaviciosa inlet) is the more important energetic agent in the confined estuary, and it is enough evidence to separate the outer morphological zone into the mouth complex and the sandy bay.

The mouth complex is a large sandy structure constructed by the waves in the outer side (exposed beach) and winds (eolian fields) with a sandy mouth bar reworked both by ebb tides and waves, and inlet mainly feeling tidal currents. Sandy bay is developed by flood and ebb tidal currents and surficial gyres during high tides, better when spring tides, and in the shallow borders, inner waves generate narrow estuarine beaches and winds deflating broad sandy flats some estuarine dune fields. In the Villaviciosa estuary, a flood-tidal delta, sandy flats, main and secondary channels and estuarine beaches and eolian dunes are the main sedimentary facies. Mud flats in the inner estuary reflect the lowest energetic areas with a main channel crossing them and displaying numerous tidal creeks, increasing upstream the fluvial influence. The upper meandering channel shows an almost exclusive fluvial influence, with broad, lateral reclaimed marshes.

Under the compositional and textural points of view, the Villaviciosa estuary shows a tripartite distribution of facies which can be correlated with the morphological zonation (Fig. 10): 1) sandy bioclastic facies including the mouth complex and the sandy bay where the marine influence is dominant; 2) muddy facies much more important than the sandy siliciclastic and bioclastic facies (muddy flats); and 3) gravelly polygenic facies and sandy siliciclastic facies (upper channel). These last facies 2 and 3 experience a prevailing fluvial influence.

### Summary and conclusions

The Villaviciosa estuary is a small mesotidal and almost full filled estuary in a cliffed coast developing a longitudinal morphological zonation from the mouth to the fluvial system comprising: *mouth complex* which confines the estuary, *sandy bay* with a strong marine influence, *mixed and muddy flats* colonized by Algae, gramineous and halophytic vegetation (marshes mainly reclaimed) dominated by fluvial dynamics and a poorly developed *upper channel* that links with the fluvial channel.

The estuary is predominantly vertically homogeneous even during river floods. Tidal waves travel into the estuary with scarce deformation, only decreasing gradually through the upper meandering channel. Maximum velocities are recorded in the inlet (more than 1.0 m/s) and during half tides (rising and falling events), having stronger flood currents in the outer estuary (station 1) than in the inner side (remaining

stations). Flood currents (marine waters) enter by the western side and under the surficial mixing waters through the main channel and other minor channels draining the flats. Ebb currents flow out by the opposite side, being in general the extruding processes through the channels during low tides; during medium and principally spring high tides, from half rising to half falling tides, horizontal gyres of the surficial waters in the bay area are formed. Under these waters strong currents flow independently, one of flood trajectory generating the tidal delta, and the other of the opposite direction activating the spillover lobe. The main channel directs flooding waters to the western side and the secondary channels moves the ebb waters in the eastern side of this complex eddy. After the half falling tide, a minor channel has fluvial dynamics and it is substituted by the secondary channel which doesn't coincide with the former and reworks the previous morphology.

The mouth complex is principally constructed by waves and since there is a sandy excess in this coastal segment, winds transport sediment to the associated eolian dunes in the back areas. Channels direct water and sediments, playing the main dynamics during floods with a marine control, and ebb tides as fluvial one. The flood-tidal delta has a compound behaviour: strong bottom flows are the main currents that elongate it to a pear-shaped body as well as surficial horizontal currents both acting during high tides, and those due to the main and secondary channels that rework it during low tides. The ebb-tidal spillover lobe has the simple dynamics of extrusion between rising and falling half tides. Sandy flats are generated by lateral currents from the channels and are reworked by estuarine small waves as well as the estuarine beaches. Estuarine eolian fields grow by sands deflated (NW winds) from the sandy point bars, sandy flats and estuarine beaches. Mixed and tidal flats are developed in sheltered areas that bind to the main channel under a strong fluvial influence.

The main morphosedimentary units of the Villaviciosa estuary are: mouth complex (exposed pocket beach and associated eolian dunes, that enclose the estuary, a mouth sandy bar generated in the offshore area, and the inlet), sandy bay (including lateral sandy flats, a sandy shoal bordered by the main, minor and secondary channels, developing a flood-tidal delta and an ebb spillover lobe, and estuarine beaches and eolian dune fields), tidal flats (unvegetated muddy flats, Enteromorpha flats when there is a strong marine influence, Zosterid flats when there is mixing waters and by halophytic vegetation in the upper parts, mainly reclaimed, crossed by the main channel, minor channels and tidal creeks), and the upper channel (main meandering channel, and reclaimed marshes and tidal creeks).

General and local circulation are responsible for the distribution and appearance of all the distinguished morphosedimentary units. The outer estuary (marine influence) is sandier than the inner (fluvial influence)

as can be deduced from the morphological zonation, due to the coastal proximity and lack of fluvial supply, which is extruded onto the coast, particularly during flood conditions. From the main channel, that represents the most energetic morphodynamic unit in the estuary, sediment sizes decrease sharply when it erodes or gradually when it develops a point bar or mixed or muddy flats. In the inner main channel almost all the entire lithological types are present: sand, mud and even fluvial siliciclastic and carbonate gravel with low or null contents of actual bioclastic component. Medium and fine sands are the most important represented sizes and very fine sands and muds reach the marginal flats. The majority of sands are well sorted, being located in the marine and eolian (the best values) influenced areas while poorly sorted sands represent fluvial or minor marine influence. Skewness is negative in the more energetic areas and positive (less important) in areas with dominant settling processes and in transitional areas (eolian dunes, estuarine beaches, some sand flats and mixed and muddy flats).

Percent carbonate content (bioclasts) is important in the outer estuary due to the strong marine influence, decreasing toward the inner areas; maximum values are correlated with more energetic areas (exposed beaches, inlet and sandy bay area), and minimum ones are reached when marine sedimentation is reduced (mixed and muddy flats), being substituted by fluvial influence. Bivalves, gastropods, barnacles, algae and echinoderms, which are the most important biological groups, are found about the exposed rocky areas, in the nearby cliffed environments.

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