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Morphodynamics of a gravel-dominated macrotidal estuary: Rio Grande, Tierra del Fuego

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ABSTRACT. Rio Grande city (Tierra del Fuego) is located on two attached beach systems, one of Upper Pleistocene (Sangamonian) and the other of Holocene age. Both gravel spits grew from north to south modifying the inlet of the Rio Grande estuary. The present estuary is constrained by the modern and recurved spit Popper Spit. The main characteristic of this macrotidal estuary is that both margins and the bottom are mainly composed of rounded gravel. Expansion of the city is limited by oceanic and estuarine coasts, and is taking place towards salt marshes taking up more than 30 hectares in the last 20 years. The alteration of the tidal prism induced by marsh reclamation and the construction of a bridge may be affecting the inlet dynamics. The area of salt marsh and gravel banks were calculated by means of supervised classifications derived from a Landsat TM image. The inlet morphology changes in response to cycles dominated by longshore drift, wave refraction and ebb-tidal delta configuration. Oceanic beaches are characterised by large disc-shape boulders at the storm berm, spherical pebbles and sand runs at the foreshore, and fine sand on the low-tide terrace. Although tidal effects are very significant in the dynamics of the estuary, wind can prevail during some days or during slack water.

Key words: *Estuary, Macrotides, Marshes, Ebb-tidal Delta, Gravel*

RESUMEN. *Morfodinámica de un estuario macromareal dominado por gravas: Río Grande, Tierra del Fuego.* La ciudad de Río Grande (Tierra del Fuego) está ubicada sobre dos sistemas de playas adosadas, una del Pleistoceno superior (Sangamon) y la otra del Holoceno. Ambas espigas de grava crecieron de norte a sur condicionando la desembocadura del estuario del Río Grande, que a su vez está limitada por una espiga moderna y recurvada denominada Punta Popper. La característica de los ambientes estuarinos es el dominio de las gravas, tanto en los márgenes como en los bancos de fondo. El crecimiento de la ciudad, bordeada por costa de mar y de estuario, se está desarrollando hacia las marismas del estuario, ocupando más de 30 hectáreas en los últimos 20 años. La alteración del prisma de mareas inducida por la ocupación de marismas y la construcción de un puente puede estar afectando la dinámica de la boca. Las áreas ocupadas por marismas y bancos compuestos de grava fueron estimados mediante clasificaciones supervisadas derivadas de imágenes Landsat TM. La morfología de la boca de mareas cambia en relación con ciclos dominados por la deriva, la refracción de olas y la formación del delta de reflujo de mareas. Las playas oceánicas están caracterizadas por grandes clastos en el berma de tormenta, gravas redondeadas seleccionadas y tramos arenosos en la playa mesolitoral, y arena fina en la terraza baja. Aunque los efectos mareales son muy significativos en la dinámica del estuario, el viento puede ser dominante durante algunos días o durante las estoas de pleamar o bajamar.

Palabras clave: *Estuario, Macromareas, Marismas, Delta de reflujo, Gravas*

Introduction

There has been considerable interest in the last 20 years on the Quaternary Geology on Northern Tierra del Fuego where glacigenic and coastal deposits are overlapping (Rabassa *et al.* 1992; Mc Culloch and Bentley 1998). Codignotto and Malumián (1981) conducted a geological survey of the northern portion of the island, while Meglioli *et al.* (1990) distinguished between the different Quaternary units of glacial origin. Submerged moraine features were reported offshore San Sebastián Bay (Isla and Schnack 1995). Bujalesky (1997) characterised the dynamics of the macrotidal inlet taking into account both the historic variability of the minimum flow area and the wave effects. We described the evolution of different gravel beach plains of the eastern Tierra del Fuego (Isla and Bujalesky 2000), and Bujalesky *et al.* (2001) mapped the Quaternary units of glaciofluvial origin north of the Río Grande estuary. A geomorphological map of the submerged areas off the estuary identified a former discharge channel (Violante and Parker 2002).

The Río Grande flows from west to east, receiving tributaries from the south (de la Turba, Mc Lenan and Candelaria rivers) and from the north (Río Moneta). The estuary is crossed by two bridges: Route 3 bridge and a new bridge connecting Río Grande city with Margen Sur

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(location of our water sampling station). Before discharging into the Atlantic Ocean, the river makes a long bend to the south around gravel beach barriers on which the Río Grande is built (Fig. 1). The inlet is therefore constrained by gravel spits that have a significant morphologic variability (Bujalesky 1997).

In the present paper, we describe the morphology, sediment distribution, water dynamics and marsh distribution of the estuary. Reclamation processes that induced alteration of the estuary dynamics are critically analysed, and its evolution is discussed in terms of sea-level fluctuations during the Holocene, marsh evolution and the macrotidal regime.

Geological, Climatic and Oceanographic Setting

The studied area is close to the boundary between the South American Plate and the Scotia Plate; the exact limit is assigned to the Río Irigoyen Fault Zone and Lake Fagnano. Several Tertiary formations have been described in the northeastern part of the Isla Grande (Doello Jurado 1922; Codignotto and Malumián 1981; Buatois and Camacho 1993; Olivero *et al.* 1998). Recently, the dispersed outcrops were reinterpreted as three main forming sedimentary cycles:

1. The Palaeocene transgression arrived from the west (Río Claro Formation; Bautois and Camacho 1993) and ended during the Eocene (La Despedida Formation; Doello Jurado 1922).
2. The second transgression came from the Atlantic Ocean and comprises the Cabo Inés strata (informal stratigraphic unit) assumed to be Oligocene and correlated to the Cabo Peña Formation (Buatois and Camacho 1993).
3. The third transgression (Miocene) affected only the northern part of the island; its deposits begin with the Cerro Águila Conglomerate, and pass up into the deltaic sediments of the Carmen Silva, and Castillo formations (Codignotto and Malumián 1981).

There was a fourth transgression of little duration and extension (Punta Basílica Sandstone) correlated with the Filaret formation from Chile, and assigned to the Upper Miocene – Lower Pliocene (Codignotto and Malumián 1981). These transgressions have similar counterparts within the same Austral Basin in the Santa Cruz sector (Russo *et al.* 1980; Codignotto and Malumián 1981).

Different Pleistocene units overlie the Tertiary sediments of different ages and palaeoenvironments (Meglioli *et al.* 1990; Coronato *et al.* 1999; Bujalesky *et al.* 2001). In most cases, the Quaternary and modern beaches rest on an abrasion platform cut into Tertiary rocks. As these Tertiary rocks are close to the Cordillera, they are much affected by faulting. The southern beaches of Tierra del Fuego are located between capes controlled by transform fault zones and subject to frequent earthquakes.

The climate of Tierra del Fuego is dominated by the prevailing westerly winds, with Pacific cyclones moving eastwards but not far from the Antarctic ice (Tuhkanen 1992). The Cordillera de Los Andes causes a climatic step from west to east, and from south to north. Rainfall is subject to these topographic effects. Rio Grande and Ushuaia have similar mean annual temperatures of 5-6° C. Rainfall at Ushuaia is 534.7 mm/year diminishing to the north; in Rio Grande, it is only 340 mm/year (Bujalesky 1998). Prevailing winds are also affected by topographic effects: in the region of the Magellan Strait they blow from west and north west; in Rio Grande city they prevail from the west, and in Ushuaia they are from the south west. Spring and summer are the most windy seasons (Bujalesky, 1998).

The mean tidal range in Río Grande outer estuary is 4.16 m. Wave climate is relatively mild along the Atlantic coast due to the prevalence of the strong westerly winds. Reports from the British Meteorological Office (covering a sea area from the coast to 65° W, and between 50° and 55° S, from the period 1949-1968; Compagnie de Recherches et D'etudes Oceanographiques- Geomatter 1985) indicate:

(a) the frequency of wave heights higher than 3.5 m is very low;

(b) around 20% of waves are less than 1 m in height on average throughout the year;

(c) long-period waves are relatively uncommon; and waves with periods greater than 10 s come from the east and north east;

(d) gales of 41-47 knots from any direction between north and ESE (with a return period of 50 years) are estimated to generate an extreme wave height of 12 m and a period of 11.5 s in a water depth of 50 m (referred to spring tide level);

(e) this estimated extreme wave would break in a water depth of 15 m (chart depth + tidal height above chart datum + storm surge), and would be near the breaking point in 10 m depth even at spring high water. In summer, the strong winds blow silt from the dried ponds located west of Río Grande city.

A regional north to south longshore drift has been deduced from coastal features and sediment transport experiments (Codignotto and Malumián 1981; Isla *et al.* 1991). However, beach heavy minerals suggest that present longshore transport is from south to north (Gomez Peral and Martínez 1997). Based on old aerial photographs, Bujalesky (1997) described the evolution of the recurved Popper Spit (Rio Grande Inlet) in response to a local drift from south to north. Refraction diagrams explain how this local drift is caused by the refraction of waves induced by the Gusano and Exterior rocky reefs (Fig. 1) (Isla and Bujalesky 2000).

Methods

Urban colonisation of the salt marshes was estimated comparing photographs of 1970 and 1991. Gravel beach plains of Pleistocene and Holocene ages were recognised by means of these aerial photographs and a Landsat 5 TM

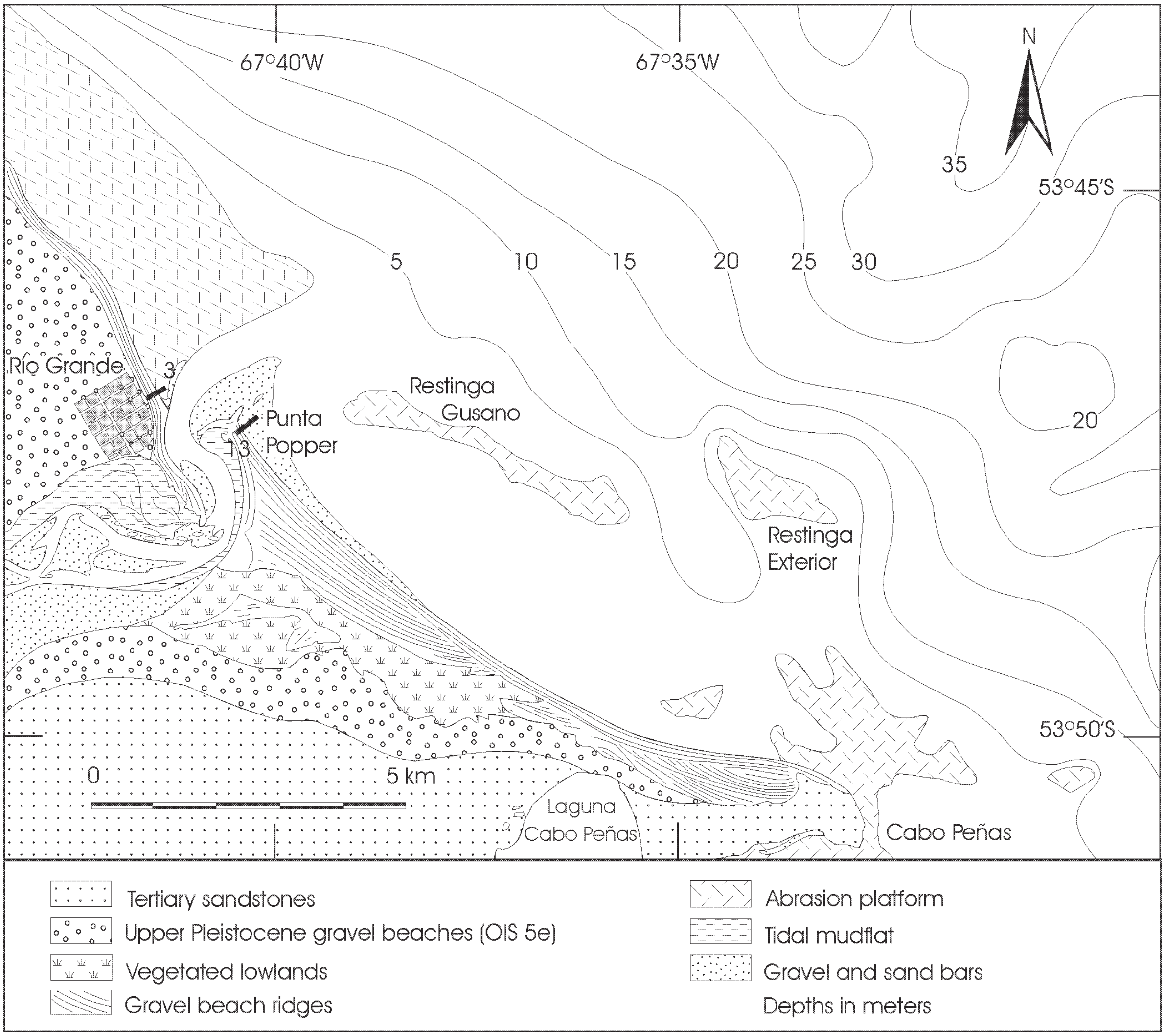

Figura 1: Geomorphological map of Río Grande estuary and surrounding area, with surface tracks of profiles 3 and 13.

image. A supervised classification (maximum likelihood method assigning probabilities) was performed on an image taken on April 21, 1999. The units considered as training sites were: coastal areas, urban areas, lagoons (ponds), marshes, praire, gravel banks and beach-ridge plains. Afterwards, the areas (in hectares) of these units were calculated. Twenty five beach profiles were surveyed using a theodolite during low tide. The profiles spanned from the Atlantic beaches to the inner estuary beaches (Fig. 1). Popper Spit was surveyed in detail. Beaches and beach plains were positioned using hand-held GPS equipment. The minimum flow area of the inlet was estimated from aerial photographs considering that the bottom of the channel is restricted to the submerged Tertiary rocks. Grain-size sampling was conducted according to morphodynamic criteria. In the laboratory, the 124 sediment samples were sieved at a 0.5 phi-unit interval. By means of an Horiba (U 10) water quality checker, six water parameters were tested at the bridge between Río Grande and Margen Sur. The ranges and accuracies are shown in Table 1.

Results

Salt marsh colonisation and reclamation

As expected for a regressive coast, where the sea level has been dropping for the last 6000 years, the Río Grande estuary is colonised by salt marshes. The net vertical accretion of the marsh surface (NVA) relates to the arithmetic sum between the vertical balance on the marsh surface (deposition or erosion), plant production or decomposition below ground, and compaction or subsidence (Delaune and Pezeshki 1994; Reed 1995). Comparing photographs from 1970 and 1991, it is clear that salt marshes subject to periodic floods became isolated from the tidal excursion following the construction of two bridges, at the headlands and close to the inlet of the estuary. In approximately 20 years more than 30 hectares of salt marsh were converted into urban lots (Fig. 2). This process continues today.

The supervised classification resulted in an estimate of 650 hectares covered by salt marshes and 220 hectares of

Figura 2: Comparison of aerial photographs of the Rio Grande estuary (1970 and 1991). More than 30 hectares of salt marshes have been urbanized.

Table 1: Ranges and accuracy of the water-quality parameters.

Parameter	Range	Accuracy	Units
pH	0-14	0,01	Adimensional
Conductivity	0-1	0,001	MS/cm
Turbidity	0-800	1	NTU
Dissolved oxygen	0-19,9	0,1	mg/l
Temperature	0-50	0,1	ºC
Salinity	0-4	0,1	%

the estuary covered by sand (gravel and sand) banks or sand flats (Fig. 3).

Ebb-tidal delta dynamics and tidal-inlet stability model

Popper Spit grows from the southern coast of the Río Grande estuary, away from the Upper Pleistocene and Holocene spits (where the city is located). The behaviour of the spit depends on:

a) the bathymetry governed by Tertiary rocks forming reefs offshore the inlet (Exterior and Gusano reefs),

b) the local longshore drift from south to north,

c) the energy of the ebb-oriented tidal currents.

Bujalesky (1997) compiled in detail the morphological changes that took place at the inlet between 1945 and 1995. He noted that the Gusano Reef could induce a local drift in the opposite direction to the regional drift, considering the model proposed by Lynch-Blosse and Kumar (1976). He concluded that there is a clockwise coastal sediment circulation pattern: offshore induced by ebb currents, alongshore conditioned by oblique waves (longshore currents) and onshore transported by waves (refracted by the outer reefs). The recent evolution of the inlet involves cycles of several years and is dominated by longshore growth, landward retreat (wave refraction) and ebb-tidal delta growth (Fig. 4; Bujalesky 1997).

Longshore growth is mainly the result of sediment transport and erosion of the backbarrier beach. Wind waves develop in the estuary during high tide and induce the initiation of sediment motion. Littoral drift on the sea side of the spit has a secondary role. Overwash phenomena provide sediment to the backbarrier beach causing its landward migration. When the spit reaches its maximum possible length, the sediment supply becomes scarce to compensate the volume eroded from the backbarrier. The landward migration rate of the shoreface can become faster than that of the backbarrier. As the sediment on the bottom of the inlet rests directly onto bedrock, it does not migrate significantly, and becomes unstable at the minimum flow area reduction. These facts cause the breakdown of the spit barrier. A transverse bar fixed to the shoreface of the spit forms as a consequence of the reduction of the minimum flow area (Ac), where strong ebb tidal currents meet the waves. After the spit barrier breakdown, the minimum flow area increases, ebb-tide current velocities diminish and waves recycle the transverse bar sediments (Bujalesky 1997). The morphology of the inlet is governed by the availability of gravel over the abrasion platforms and the rocky reefs.

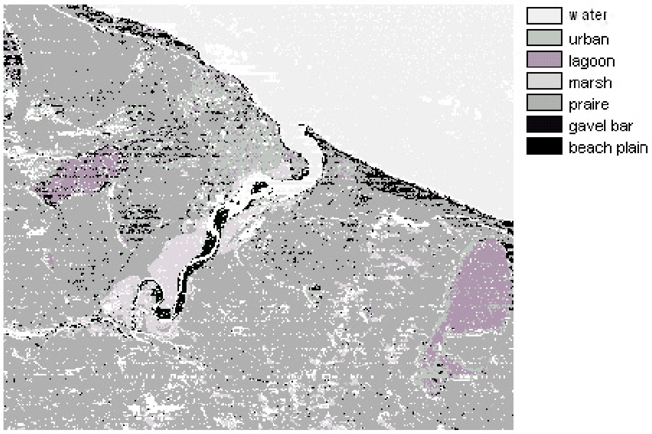

Figura 3: Supervised-classification (maximum likelihood method) results of Rio Grande surroundings.

Three dominant phases were envisaged as influencing the minimum inlet area (Ac):

a) During the longshore-drift phase, Ac is at its maximum operative function and width (Fig. 4);

b) During a period of wave-refraction phase, Ac becomes narrower as the point of the spit is closer to the Rio Grande city coast, and

c) During the ebb-tidal delta configuration phase, Ac reduces to its minimum width (Fig. 4).

Beach morphology and sediment distribution

In a general way, the beach profiles indicate same morphology as that described in previous works on the region (Isla and Bujalesky 2000). Upper foreshores are dominated by gravel, and oblate clasts dominate at the storm berms. At the foreshore, sand runs may be common. Seepage is present at the toe of the foreshore. The low-tide terrace is composed of sand, except in areas close to the estuary where gravel banks form veneers of anorbital gravel ripples. As expected, banks are a common feature of this macrotidal estuary, although in this case they are mainly composed of gravel.

The profiles sampled within the estuary as well as those attached to the macrotidal inlet are dominated by fine gravel. Gravel banks were located in front of some beaches close to the estuary. Only at the profile immediately north of the inlet (profile 3) fine sand was recognised in the intertidal sectors (Fig. 5a). The beaches to the south of the inlet have a reflective profile (Fig. 5b). At the end and at Popper Spit (profiles PP1 to PP4) very coarse sand and granule gravel were sampled (Fig. 6). Larger clasts (over 2 mm) are only located at the toe of the Atlantic beach, on top of the storm berm and on some places of the backshore spit slope. This latter portion of the spit facing to the estuary with larger clasts indicates

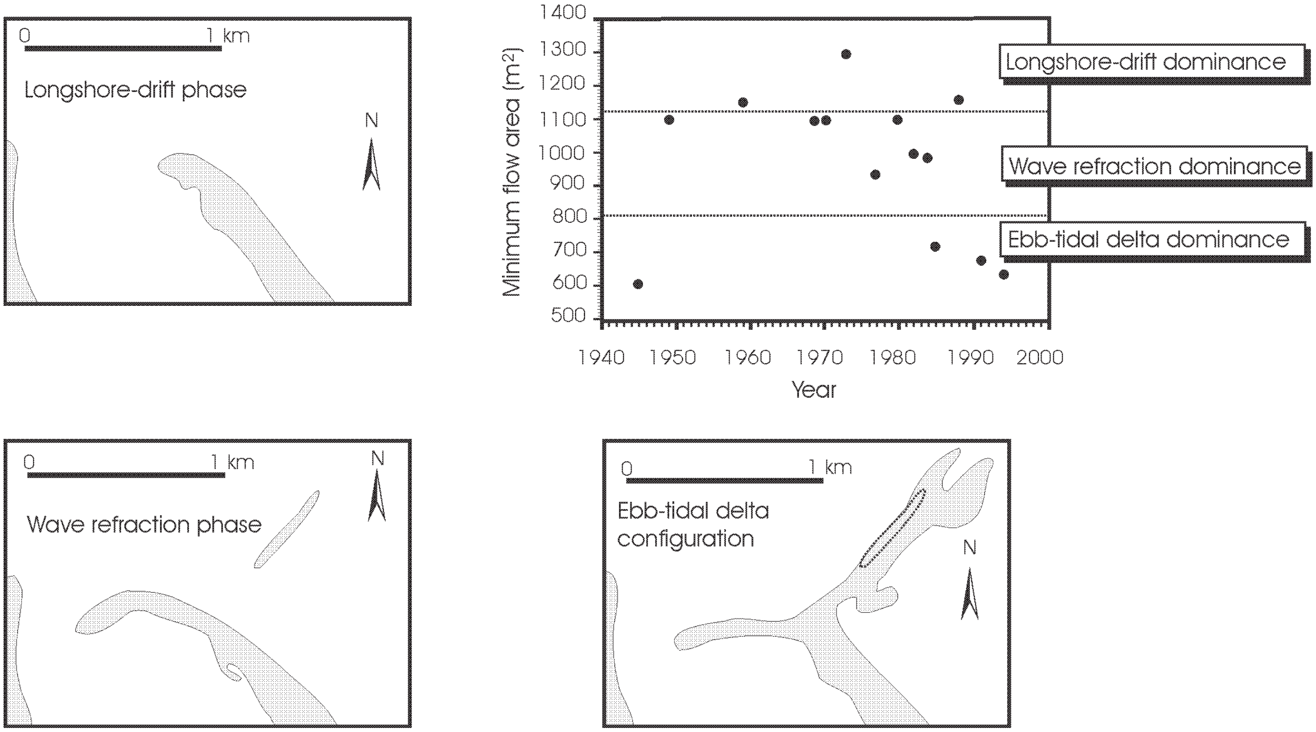

Figure 4: Evolutionary phases of Punta Popper spit cycles (modified from Bujalesky 1997). Minimum flow areas (cross-section areas below the mean tide level) were calculated from soundings performed by the Servicio de Hidrografía Naval, and assuming a direct response of the area to variations of the width of the inlet.

that the spit is a transgressive one: it rolls landwards and in this process gravel beach deposits become exhumed.

Water quality variations

In order to qualify the dynamics of this macrotidal estuary a water-quality monitoring was performed at the bridge closer to the estuary (53° 48.354'S; 67° 41.162'W). During that windy day on March 9, 2002, high tide was expected at 04.59 hours and at 18.06 hours (6.2 and 6.5 m over datum respectively); low tide at midday (11.30 hours and 2.1 m height). A delay of 20 minutes is expected between the outer estuary and the bridge station. During that morning, water temperature increased from 7 to 9º C, and decreased back to 7º C at the noon (Fig 7a). Salinity decreased slowly until 14.00 hours, dropping and rising significantly before and after the low tide (15.00 hours). It became stable again after 17.00 hours (Fig 7b). This behaviour undoubtedly reflects the effects of wind on the tidal excursion. Turbidity decreased rapidly and significantly during the falling tide. After a minimum that lasted about two hours, turbidity began to increase but slowly (Fig 7c).

Discussion

The effects of the strong westerly winds were also recognised on the tidal flats of San Sebastián Bay, where wave heights are higher within the bay than at the Atlantic coast (Isla *et al*., 1991). These wind effects are evident in Río Grande during some specially dry summers. Silt from the lagoons located to the west of Río Grande are deflated toward the coast.

The evolution of macrotidal estuaries is not well understood (Dalrymple *et al*. 1992). Sedimentary models from the Northern Hemisphere can not be applied to estuaries from the Southern Hemisphere, in the sense that these estuaries evolved in relation to a sea–level fluctuation (Isla 1998).The transgressive phase is recognised as flood-oriented; during the regressive phases the estuaries became ebb oriented, when marshes or mangroves colonised the former tidal flats. In the evolution of macrotidal estuaries, the increase or decrease of the tidal prism is also important.

The estuarine area of Cobequid Bay-Salmon River (Bay of Fundy, Canada) is similar to the Rio Grande estuary in the sense that sand flats and sand bars, dominated by gravel and sand, occupy more than 80% of the area, while marshes are scarce and restricted to the distal sectors. At the same time, the geological history of the Bay of Fundy is similar to that of eastern Tierra del Fuego: the regressive phase in this Canadian example is not of Holocene glacioeustatic origin but induced by a glacioisostatic uplift (Dalrymple *et al.* 1990). However, in that area the tidal effects are significantly larger (16.3 m). It is assumed that tidal effects also varied in response to the relative sea level movements of tectonic origin (Dalrymple *et al.* 1990).

Lessa and Masselink (1995) studied the evolution of a

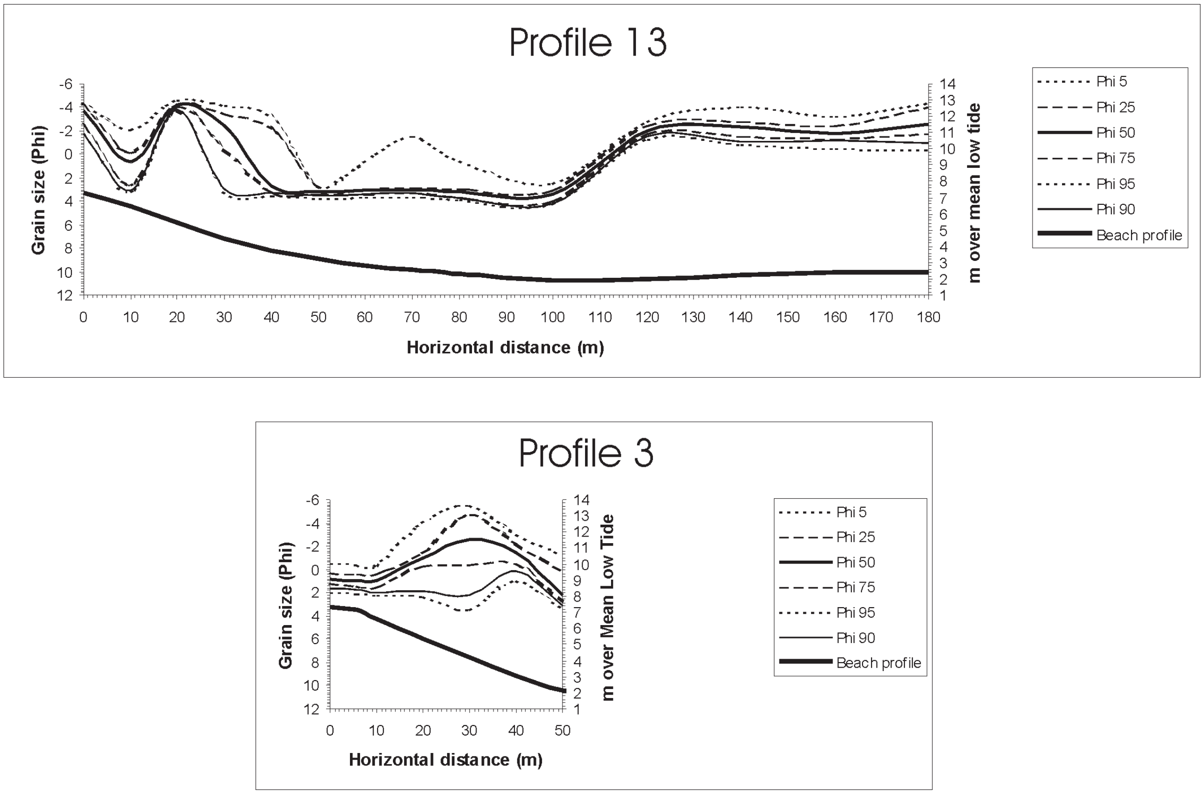

Figura 5: a) Topography and sediment at a beach located north of the inlet (profile 3, location in fig. 1). **b)** Topography and sediment at a beach located south of the inlet. (profile 13).

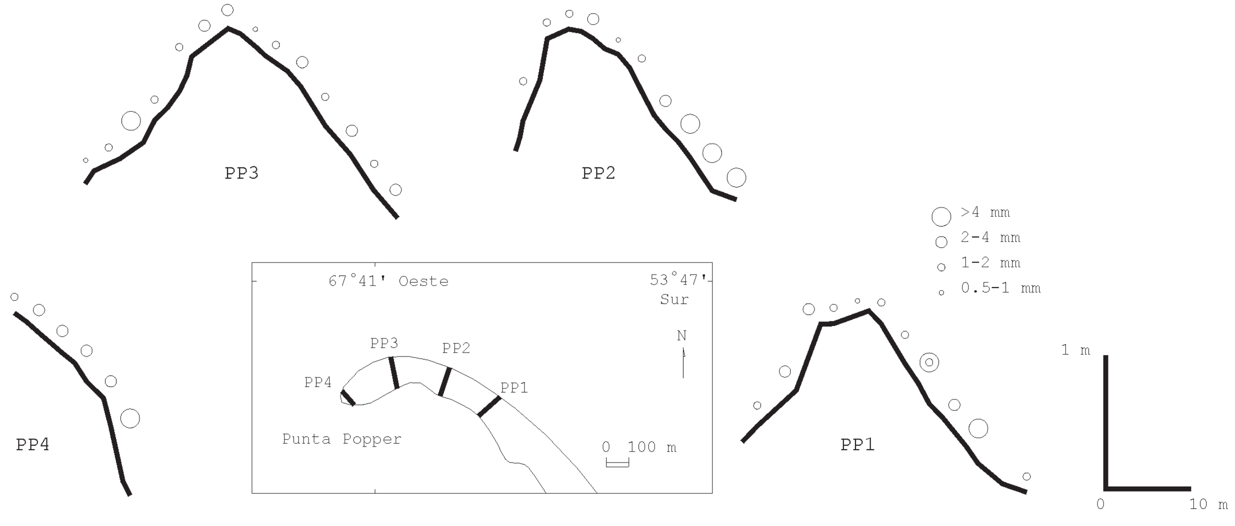

Figura 6: Morphologic profiles across Popper Spit indicating gravel-size variations

macrotidal barrier estuary in Eastern Australia. Assuming a deposition rate of 0.5 mm/year, the calculated rise in sea level of 4 mm/year significantly exceeded the sedimentation rate. However, during the mid-Holocene, a drop in sea level of 1.5 m between 6500 and 4000 years BP, maintained the estuarine area although the intertidal areas were seldom flooded. This caused the formation of hypersaline supratidal areas. Dispite this drop in sea level, the tidal prism was not severely affected. The inlet cross area was reduced and the barrier expanded laterally under the influence of littoral drift. This expansion favoured mangrove colonisation of the former intertidal areas. Similar processes occurred in the Río Grande, although marshes rather than mangrove swamps are the environments under expansion.

On the microtidal coast of Huelva (SE Spain), the estuary of the Piedras River evolved from a maximum sea-level highstand that occurred about 4000-3500 years BP

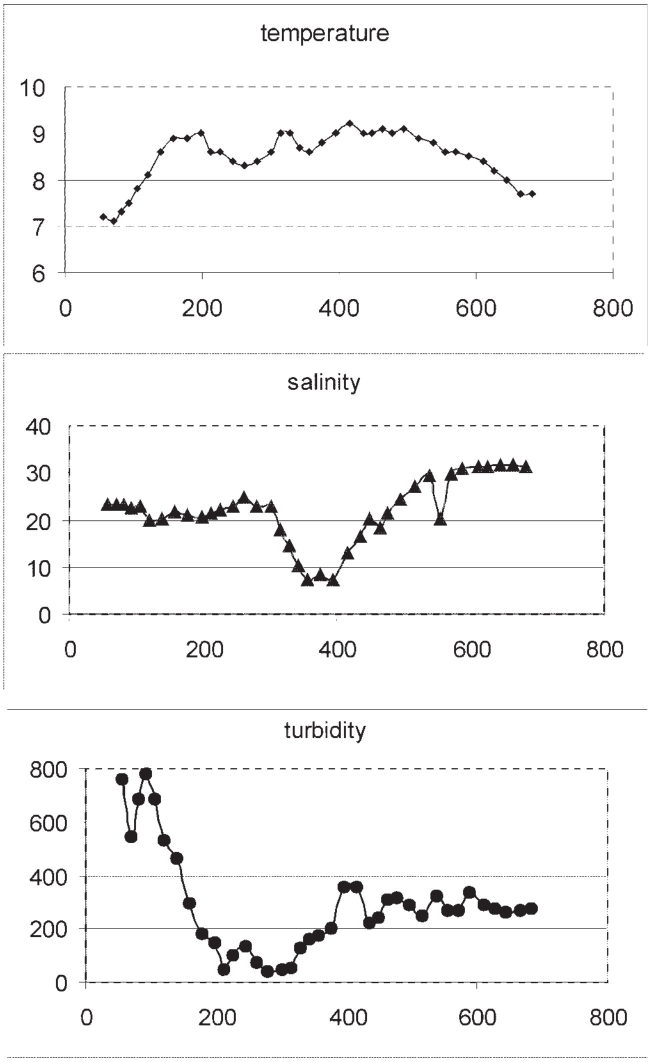

Figura 7: Water-quality data collected at the estuary on March 9, 2002. **a)** Water temperature vs. Minutes after 09.00 hours. **b)** Salinity (in practical salinity units) vs. Minutes after 09.00 hours., and **c)** Turbidity (in nephelometric turbidity units) vs. Minutes after 09.00 hours.

(Borrego *et al.* 1993). A barrier island developed from east to west, and in modern times an elongated spit grew from west to east. In this case of evolution of an estuary the reduction of the tidal prism was assigned to an increase of the infilling rate or modern dam constructions.

In the macrotidal estuary of the River Tamar (England), the turbidity maximum fluctuates according to the tide and the monthly variations of the tidal range. During neap tides, the maximum concentration is about 20 ppm, but increases an order of magnitude during spring tides. (Uncles and Stephens 1989). This maximum concentration is related to the fresh -saltwater interphase, although it is occasionally located at the headlands of this interphase. According to the data collected at the Río Grande estuary, the maximum turbidity occurs during the falling tide, about 3 hours before the minimum salinity (Fig. 7).

For the macrotidal coast of Canada, sedimentation within the salt marsh fluctuates between minerogenic and organogenic modes according to two factors whose effects are not necessarily predictable: sea level variation and barrier spit dynamics (Jennings *et al.*1995). Although it is normally accepted that marsh maturity (with a probable lag of 100 to 1000 years) is coincident with the development of the upper marsh, some changes in the composition (mineral or organic) can be triggered by eustatic changes or variations in sediment dynamics (sediment availability). Salt marshes are not considered as the best indicators of sea-level variations as they are strongly influenced by accretion processes (Jennings *et al.* 1995). For example, the East Friesian Islands (West Germany) changed their surface due to empoldering of marshes and tidal flats (30% reduction), and this effect caused variations of the mesotidal inlets (narrowing and reduction of the tidal prisms; Fitzgerald *et al.* 1984). Variations of the inlet throat of Price Inlet (South Carolina, USA) between 1974 and 1977 were explained by wave energy, sediment-supply rate and periodic fluctuations (astronomical and meteorological) of the sea level (Fitzgerald and Nummedal 1983).

Salt marshes were commonly used to evaluate sea level rise (French 1994) or their stability in response to sea level rise (Chmura *et al.* 1992). In the Mississippi delta area, the measurements of the vertical accretion rates in different areas was used to discern the apparent (local) water level rise (Delaune *et al.* 1992). The apparent intercalation between salt marshes and mudflats in response to sea-level behaviour has been used to estimate fluctuations within the Flandrian transgression (Allen 1995). However, in modern times, most of the impacts on coastal marshes are induced by human activities (Kennish 2001). The Río Grande salt marshes are also being modified by human activities, but within a general trend of progradation induced by the post-Flandrian regression.

Conclusions

1. Rio Grande city is located on beach systems of Upper Pleistocene and Holocene ages that constrained the northern margin of the estuary. In historic times, Popper Spit controlled the minimum flow area of this gravel-dominated estuary.
2. Salt marshes colonised the estuarine environments preferentially where sand and silt was deposited over the gravel. Today they are threatened by the increasing rate of urbanisation.
3. The morphology of this macrotidal inlet varies in relation to longshore-drift, wave-refraction and ebb-tidal delta accumulation phases.
4. The composition of the oceanic beaches is characterised by large discoidal pebbles at the storm berm, sorted rounded pebbles and sand runs at the foreshore, and fine sand at the low-tide terrace.
5. Estuarine dynamics (temperature, salinity, turbidity) fluctuates in relation to the tide but the wind effect is very important during some days and during slack water.

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