Holocene cuspate forelands in the Strait of Magellan, southern Chile

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ABSTRACT

The eastern inlet of the Strait of Magellan is characterised by the presence of two truncate cuspate forelands, typically high-energy accretionary morphologies. Both forelands, Punta Catalina on the Fuegian side and Punta Dungeness on the Patagonian side, show similar features and accretionary trends and could have been formed and developed at the same time during the late Holocene regressive phase. On the basis of air-photo interpretation, together with field survey, almost nine different accretionary phases of Punta Catalina spit can be recognised. Each phase is marked by an extensive beach-ridge system, and subsequent back-barrier mud-flat and marsh development. The coastal retreat and erosion processes along the Atlantic side are responsible for the shifting and morphological readjustment of the spit, which tends to prograde towards the opposite direction. The strong eolian modelling over ancient beach-ridge systems, is marked by deflation furrows, hollows and nikes and subsequent construction of elongate parabolic dunes. Despite the lack of datings, a reconstruction of the system evolution was attempted, allowed by the evidence of a strong similarity with the Dungeness foreland and considering the evolutionary framework of analogous accretionary coastal forms in South America during late Holocene.

Key words: Cuspate foreland, Beach ridges, Holocene, Tierra del Fuego, Chile.

RESUMEN

Puntas cuspidadas holocénicas en el Estrecho de Magallanes, sur de Chile. La boca oriental del Estrecho de Magallanes se caracteriza por la presencia de dos puntas cuspidadas truncadas, que son las morfologías típicas de un fuerte fenómeno de acreción litoral de alta energía. Ambos promontorios, Punta Catalina del lado de la Tierra del Fuego y Punta Dungeness del lado de la Patagonia, muestran la misma topografía y las mismas características de acreción, y podrían haberse formado y desarrollado al mismo tiempo durante la fase regresiva del Holoceno tardío. El análisis de fotografías aéreas junto con el trabajo de terreno han permitido a los autores distinguir nueve fases de acreción diferentes en Punta Catalina. Cada fase está marcada por un amplio sistema de bermas de playa y el consiguiente desarrollo de marismas detrás de la playa. La fuerte acción eólica sobre los antiguos sistemas de bermas se caracteriza por surcos y cuencas de deflación y por la presencia de un extenso campo de dunas parabólicas. Aunque faltan dataciones, se ha tratado de reconstruir la evolución del sistema, ya sea por la evidencia de una fuerte similitud con Punta Dungeness como por el contexto evolutivo holocénico de formas análogas costeras de acreción en Sudámerica.

Palabras claves: Puntas cuspidadas Bermas de playa, Holoceno, Tierra del Fuego, Chile.

Revista Geológica de Chile, Vol. 26, No. 2, p. 175-186, 3 Figs., December 1999.

INTRODUCTION

The first description and use of the term 'cuspate foreland' was given by Gulliver (1896, 1897). According to Johnson (1919), the cuspate forelands can be divided into three main forms: simple, truncate and complex, owing to the different accretionary/ retreating history.

Despite the evidence of existing cuspate forelands or recurved spits in southern South America (Codignotto and Aguirre, 1993; Isla and Bujalesky, 1993) detailed information about these structures is quite scarce, with the exception of the geomorphological investigation of Punta Dungeness (homonymous of the form in U.K.), which is located in the southernmost part of Patagonia, north of the eastern entrance of the Strait of Magellan (Uribe and Zamora, 1981).

During the 1991 'Magellan Project' expedition along the Strait of Magellan, a detailed geomorphological study of the coastal area was carried out (Brambati *et al.*, 1993; Simeoni *et al.*, 1997). Punta Catalina spit, located immediately south of Punta Dungeness, in the north-easternmost part of Tierra del Fuego, was surveyed and interpreted, using the aerial photos kindly furnished by the Instituto Hidrográfico de la Armada Argentina.

The authors have to highlight that the south-western limit of the structure is not covered by aerial photos, where the accretionary front of the spit is interrupted by the large tidal inlet that connects the mud flat of Punta Catalina with the open sea. On the western side of the inlet, the beach bordering the Bahía Lomas sand flat migrates northeastward, thus tending to close the triangular shape of the 'foreland'. This latter term is herein used as alternative to 'spit', indicating the opposite dynamics of beach migration on the margins of the inlet (see Yasso and Fairbridge, 1968 for further details).

The geomorphological setting of Punta Catalina is herein presented, together with a proposal of its possible origin and development, in an effort to understand the evolutive trend of the accretionary systems during the Holocene regressive phase in southernmost South America.

STUDY AREA

The eastern part of the Strait of Magellan (Fig. 1) has a 27 km wide entrance, delimited by Punta Dungeness foreland in the north, and Punta Catalina in the south. Westwards, the Strait consists of a series of wide basins connected by two narrows (Primera and Segunda Angostura). The sea-bottom morphology and the bathymetric contours show an eastern inlet oriented northwest-southeast due to the accretion of a submerged sandy bank, called Banco Sarmiento, which connects to Punta Dungeness. On the Fuegian side, Punta Catalina represents the eastern limit of Bahìa Lomas, which is the widest tidal flat of the Strait of Magellan.

The eastern side of the Strait of Magellan is tide-dominated (semi-diurnal). A macrotidal regime affects particularly the first embayment, in the west of the Atlantic entrance, with a mean range of 7.1 m and a spring range reaching up to 9 m (Medeiros and Kjerfve, 1988). Currents are very strong, reaching 2.5 m/s in the Atlantic entrance and up to 4.5 m/s and 3 m/s in the Primera and Segunda Angostura, respectively. Shallow depths and strong currents are the main features of the eastern part of the Strait; they induce erosion and resuspension phenomena in the coastal and sea-bottom material (Brambati *et al.*, 1991; Fontolan and Panella, 1991).

The climate of the eastern Strait is a modified middle latitudinal steppe type (BSR-SMIK) by the Köppen's classification, with low rainfall, ranging from 250 to 350 mm/y in the Patagonic Pampa region, and low mean temperatures (6-7°C: Huber, 1977a, 1977b).

Winds in the Magellanic region are particularly strong, flowing from west in the 60% of cases, and from northwest and southwest in the 20%. Their average speed is 7 m/s, but it can often exceed 25 m/s, particularly during winter and spring, when the Antarctic cold air masses flow northwards (M. Zamora and A. Santana, 1981)[1].

[1] 1981. Características climáticas del área central de la Provincia de Magallanes, XII Región (Unpublished), *Instituto de la Patagonia*, Informe Final, 100 p. Punta Arenas.

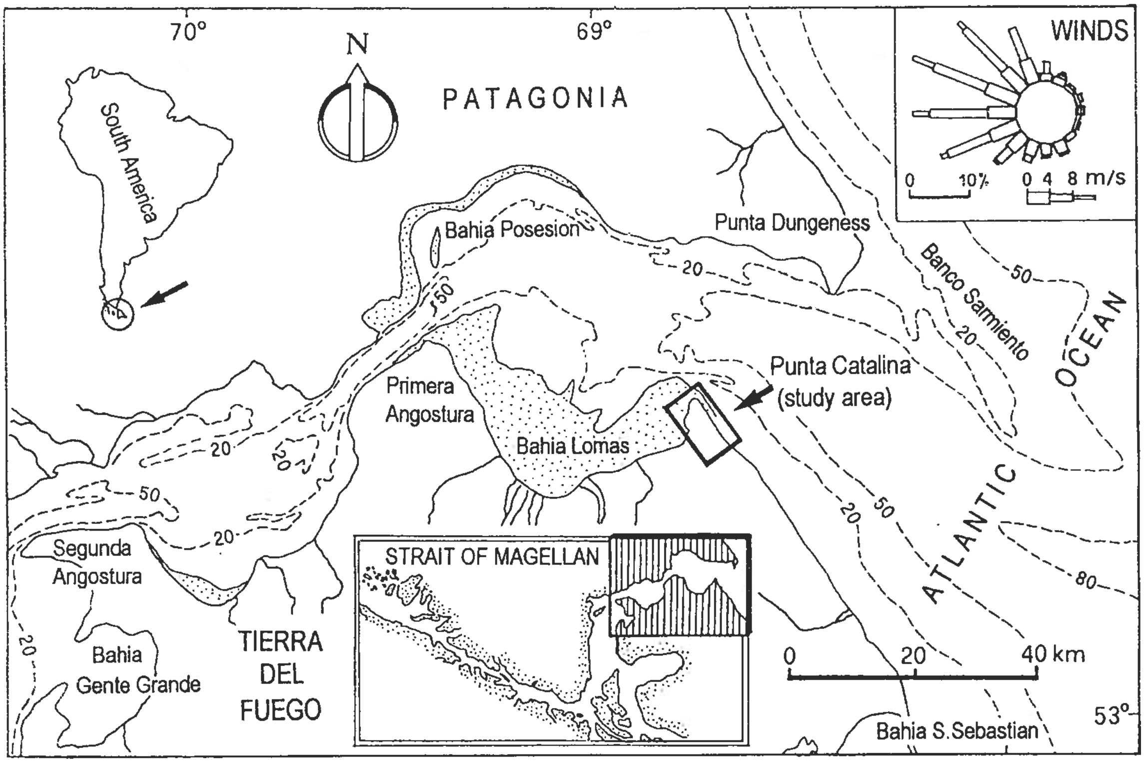

FIG. 1. Location map of northeasternmost Strait of Magellan. The study area is also reported, together with wind data (after Zamora and Santana, 1981). Depths in meters.

QUATERNARY GEOLOGY

During Quaternary, the whole Pampa region of southern Patagonia and Tierra del Fuego were strongly molded, particularly during the oldest and largest glaciation (Caldenius, 1932; Clapperton, 1993), whose acme occurred during Early Pleistocene about 1.0-1.2 Ma BP (Mercer, 1976). During that period glaciers advanced up to 200 km east of the Cordillera, reaching the Atlantic continental shelf along wide and deep valleys represented by the present Strait of Magellan, Bahía Inútil, Bahía San Sebastián, Fagnano Lake and Beagle channel (Caldenius, 1932; Raedeke, 1978; Isla *et al.*, 1991).

Following Clapperton *et al.* (1995) last glaciation in the central Strait of Magellan is testified by five glacier advances, >42 ka BP (advance A, uncertain), 28-24 ka B P (advance B and event C), *ca.* 17 ka BP (advance D: last glacial maximum) and *ca.* 12 ka BP (advance E).

The insular condition of Tierra del Fuego, with the final opening of the Strait of Magellan was completed not before 11 ka BP (Clapperton *et al.*, 1995; Rabassa *et al.*, 1989). Sea level reached its maximum (*ca.* +3.5 m above present m.s.l.) about 5.0-6.0 ka BP (Porter *et al.*, 1984).

During the Holocene regressive phase the Strait of Magellan underwent a strong moulding of the coastal area, where the presence of a thick cover of unconsolidated glacial and glacio-fluvial sediments enhanced the erosion, subsequent transport and selective deposition phenomena. Nowadays, it is possible to recognize erosional (submergence) coasts, testified by different orders of probably marine terraces, or accretionary (emergence) coasts, formed by wide tidal flats and curved spits, mainly on the Atlantic side (Simeoni *et al.*, 1997; Brambati *et al.*, 1993; Isla *et al.*, 1991).

GEOMORPHOLOGY OF PUNTA CATALINA

In figure 2 a detailed morphology of the Catalina foreland is reported. The identified, landforms, deposits and responsible processes will be indicated below.

GLACIAL AND PERIGLACIAL DEPOSITS

Glacial deposits lie in the southern part of the studied area, as sharp landforms more than 20 m high. They are formed by till deposits, stratified in various units, interbedded with glacifluvial mud-supported conglomerates and glacio-lacustrine deposits; in many cases aeolian cross-bedded sands and loess cover the till and the periglacial deposits.

The sequence, often incomplete or not well exposed can be observed along the Atlantic cliff, in the southern limit of the spit. These deposits can be ascribed to the system of terminal moraines which regressed progressively since mid-Pleistocene, and to the periglacial moulding related to the glacier retreat.

FLUVIAL PROCESSES

The Patagonic Atlantic area is covered by highly permeable conglomerate deposits. Therefore, the drainage network has an ephemeral character due to scarce rainfall, easily absorbed by the soil. In the studied area two talwegs were distinguished, lying into elongate ancient glacifluvial valleys. The hydrographic network inside the valleys is often irregular and apparently ends near the Atlantic in lakes or ponds. The scarce evidence of scouring traces and the lack of small deltas towards the Atlantic indicate the limited discharge and erosion capacity, mainly due to the water retained by the small depressions of glacial origin (present lakes).

AEOLIAN DEPOSITS AND PROCESSES

Aeolian processes hold a very important role on landscape moulding in the southern Patagonia, since the westerly winds blow regularly and strongly during the year. In the Catalina foreland, the wind effect is well marked by deflation surfaces, furrows and hollows, roughly perpendicular to the Atlantic coast. The wind action is amplified by the morphologic contrast between tidal flat and paleo-beach ridges, together with the obstacle given by southern moraine landforms. Therefore, deflation acts immediately downdrift to the marsh-beach ridge boundary, whose different morphological level represents the first obstacle to the wind force. Locally, the strong wind action can erode the superficial deposit, thus permitting the ancient marsh deposits to crop out. In some cases, well developed elongate parabolic dunes (Pye, 1993) lie transgressively over the ancient beach ridge systems. The abrupt ends of some longitudinal crests and aeolian corridor traces along the Atlantic coast indicate that these forms originated after the ancient beach ridge systems construction. Although nowadays the transgressive process of parabolic dune construction seems to be reduced by the progradation and migration of the present beach ridge system (thus limiting the wind fetch efficiency), the evidence of younger parabolic forms and blowouts in the southern part of the deflation sheet could indicate the effectiveness of winds blowing from the Strait over the widest part of the present tidal flat and marsh, without significant morphological obstacles.

In the southern part of the foreland, close to the highest glacial landforms, the effect of morphological contrast gave rise to the deposition of a big layer of sands and loess, with typical aeolian sedimentary structures, whose thickness can range from some tens of meters to 3-4 meters. Inside the northernmost valley, closed between two moraine sand-covered plateau, further aeolian deposits lie, often reworked or with superimposed streams.

The orientation of the aeolian forms follows the trend of the whole aeolian surfaces recognized in the Strait of Magellan by Brambati *et al.* (1993), as well as the analogous deposits of Punta Dungeness (Uribe and Zamora, 1981), thus confirming the very limited directional variability of strong Patagonian winds.

MARINE LAND FORMS AND PROCESSES

Marine forms are well represented in the studied area, since the origin of the foreland is basically due to the contrast of erosional and accretionary effect of currents and waves. The different mapped land forms are detailed below.

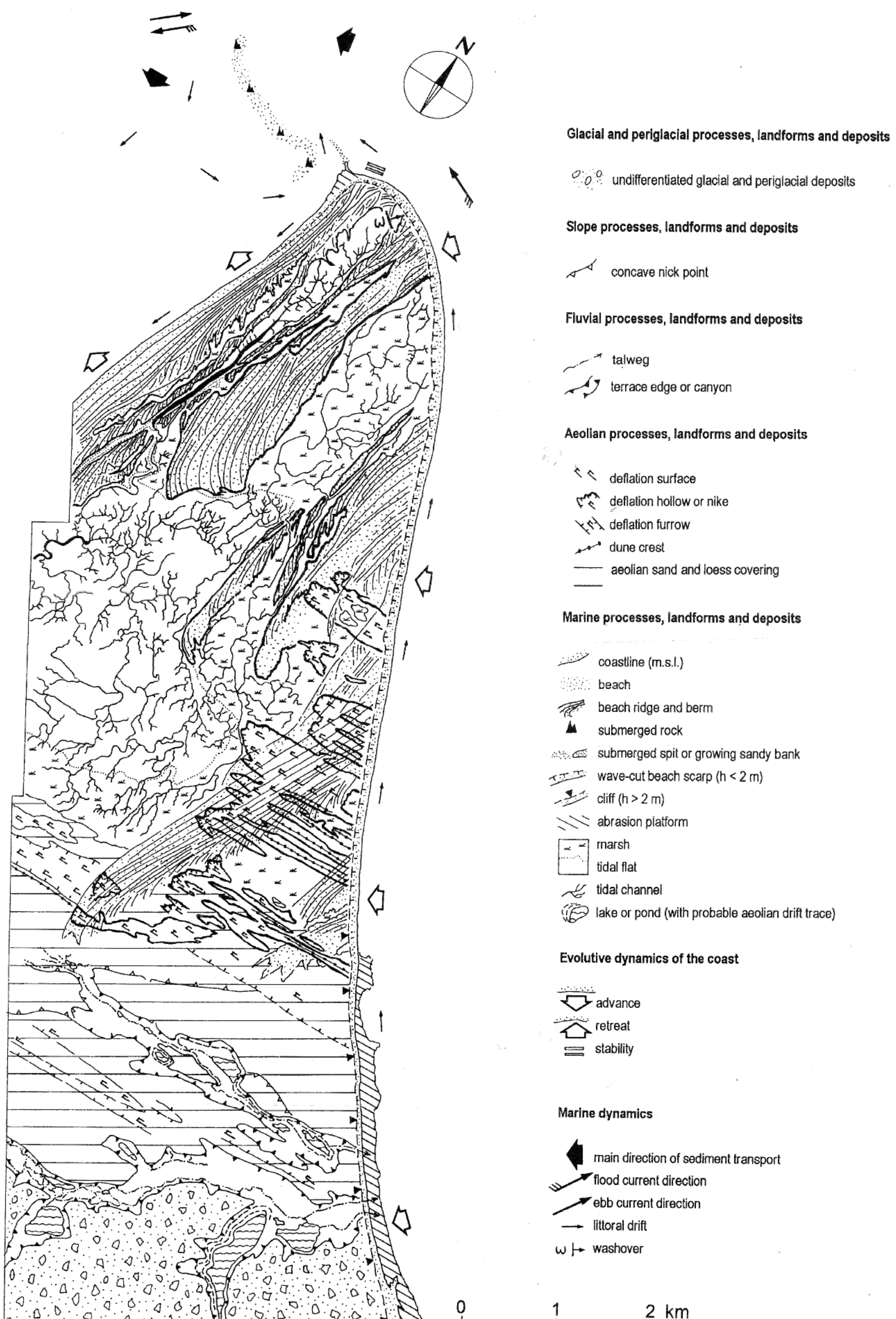

FIG. 2. Geomorphological map of the Catalina foreland strait of Magellan

TIDAL FLAT

There are two types of flat, according to the position, referred to the shoreline and to the main grain-size type: a gravel-sand flat is located seaward, in front of the present beach ridge while a mud-flat lies behind the beach:

a- gravel-sand flat: it is the inter-tidal area facing the present beaches. The exposition to waves and tide-induced currents permits the deposition and re-mobilization of a big amount of gravel and sand material; locally, pelitic lenses and several moraines and glacifluvial residual cobbles can be found.

Since the tidal range varies from 6 to 8 m in the Atlantic entrance of the Strait, the tidal flat has its maximum width (10-15 km) at Bahía Lomas, limited eastwards by Punta Catalina. The gravel-sand flat width decreases progressively eastwards, up to some tens of meters along the eastern coast of the foreland. Since the aerial-photos refer to mean marigraphic condition, the exact outer flat limit cannot be drawn. However, other marine forms can be recognized on the photos, as submerged sand banks, whose presence is testified by breaking and sediment plumes, with a pale grey color standing out against the dark background of the sea.

b- mud flat and marsh: they represent the typical depositional areas of a macrotidal environment, in protected or sheltered zones. Generally, a mud flat is well developed inside a cuspate foreland, when the communication with open sea is allowed by a single tidal inlet located between two accretionary opposite spits. In the Strait of Magellan, all the cuspate forelands and curved spits have a mud flat dividing the beach from the mainland, both for the wide tidal range and for the high angle which divides the spit from the original coast. In other cases, a mud flat develops without or with scarce frontal protection in an accretionary bay, and represents the transition from an outer gravel-sand flat, thus indicating the energy decrease towards the inner part of a deposition area (*i.e.*, Bahía San Sebastian: Isla *et al.*, 1991). The morphology of a mud flat is due both to the fluctuation and range of the tidal prism. The outer active sector (mud flat) can be distinguished from the inner quite-inactive one (salt marsh), delimited by the mean high tide level. The mud flat has a well developed interlacing drainage pattern, with creeks and channels converging seawards in a single main channel. This latter connects directly with the inlet, delimiting westwards the frontal spit.

The salt marsh represents the vegetated inner part of the flat. The marsh is the last stage of an over-nourished flat in an accretionary system. Therefore, the relative landward migration of the flat reduce flooding and sedimentation, thus allowing rapid growth of a halophytes carpet. The drainage pattern is less dense, and more interlacing than that of the mud flat.

In the northernmost part of the foreland an ancient abandoned channel and an active channel immediately to the south, both lying parallel to the beach ridges, can be recognized. The former is a relict form, swiftly occluded in the western part by the prograding hooks of the beach; the latter is well incised over an isolated portion of flat which ends eastward with a washover. The connection with the tidal channels was possible by means of a capture process, which involves the cut-off of the westernmost part of the channel during the accretion and hooking of the beach, analogously with the former relict stream.

It is clear, therefore, that these morphologies are extremely unstable, and that abandoned channels or isolated spit and ancient beach ridge portions are the result of the continuous variation between tidal prism expansion, wind forcing and littoral currents, causing either erosion or deposition outside and inside the flat.

PRESENT BEACH

Punta Catalina has two types of beach related to the different evolutive trend involving both sides of the foreland. The Strait-facing beach is the easternmost edge of the prograding system of Bahía Lomas, and presents a gentle slope together with a width varying from 150 to 250 m. The backshore consists of a series of shingle beach ridges testifying the progressive accretion of the beach and the pulsating action of wave run-up during different tidal conditions. The beach is often delimited landward by a barren dune crest, while spit hooks and curved ridges indicate the main direction of progradation and sediment transport. The eastern gravel beach facing the Atlantic Ocean is narrow, few tens of meters wide, with a steep slope. It closes landwards with a wave-cut beach scarp. This latter progressively elevates going towards the southern landforms, thus becoming a cliff (h>2 m). All the features of the Atlantic coast indicate a well pronounced erosion.

BEACH RIDGES

A beach ridge complex represents one of the most important morphologies of the spit. The sequence of ancient beaches, testified by beach ridge alignment, marks the progradation stages of the foreland. The accretionary hooked spits and ridges indicate also the northwest migration of the forms. The ancient beaches, in sequencial form or separated by marshes consist of many gravel-sand ridges lying roughly parallel with the present Strait-facing beach. They always end with a more or less curved hook, indicating the direction of growth. Nine different phases of growth can be distinguished, marked by eight paleo-systems and by the present beach ridge system. All beach ridges are truncate in the Atlantic side, thus indicating that the growth of the foreland involves a progradation towards the northwest, as response to the retreating of the Atlantic beaches. The widest part of the two more recent beach-ridge systems, in which each individual crest can be easily recognized, extends for about 900 m each. Ridges elevate for 0.5-1.0 m while the mean spacing is *ca.* 15 m. Consequently, each system is given by *ca.* 60 crests. Despite the difficulty of recognizing the forms both on the ground and by means of the air-photos, the same geometries and spacing rate seem to characterize also the ancient sets.

CLIFF

This form marks the face of the southern landforms abruptly eroded by sea-action. Cliffs consist of sub-vertical faces different in height, composed by stratified moraine and glacifluvial deposits, with aeolian sands or loess covering. Northwards the cliff decreases in height and forms a beach scarp, due to the erosion of lower (beach and marsh) deposits. The cliff has a narrow beach in front of it, and only along the southern part of the studied area a wide abrasion platform outcrops.

ABRASION PLATFORM

It is a flat erosional surface reworked by wave motion, consisting of consolidated material (probably marine sediment of Cenozoic age). It crops out only along the southernmost cliffed coast, where the strong erosional processes along the Atlantic coast involved also the Tertiary basement, below the glacial and periglacial sequence.

Evidences of other outcrops of consolidated material or discontinuities on the sea bottom can be seen near the top of the cuspate foreland. The abrupt curve of the sediment plume is, in fact, intercepted by a submerged form, marked by breakers.

ORIGIN AND EVOLUTION OF THE CUSPATE FORELAND

A wide literature exists about beach-ridge systems and related accretionary trends (Johnson, 1919; Zenkovich, 1967; Tanner, 1995; Taylor and Stone, 1996), whereas the growth stages and ridge periodicity seem to vary too much for being related to possible astronomical or climatic cycles (cf. Tanner, 1995 and references therein).

Considering the geometry and spacing of the ridges, and their strong analogies with the Dungeness foreland (Uribe and Zamora, 1981), the almost quite regular elevation of the forms supports the hypotesis that progradation or depositional regression occurred rather than aggradation (Curray, 1964; Swift, 1975; Thompson and Baedke, 1995). The Curray's (1964) model considers the above two cases of coastal responses as a result of relative steady or falling sea-level. Owing to the lack of datings for Punta Catalina, the measured beach accretion rates for the present Punta Dungeness ridges system could be used to give some indications about the age of the foreland. Considering the linear equation of Uribe and Zamora (1981) as the accretion rate and the total width of the Catalina beach-ridge systems, an estimate of *ca.* 6,500 years has been found. Although this time does not take into account the periods of marsh development (stages between adjacent beach ridge systems), it can be easily supposed that these environments have been generated during the growth and development of a new detatched spit arm. This phenomenon unavoidably involves an acceleration of the accretion rates during the different migration stages, and therefore the 6,500 years age is likely to be overestimated. In any case, Punta Catalina is a truncate cuspate spit formed during the late Holocene.

An uncertainty exists about the relative sea-level changes occurred during Holocene along the southern Atlantic coasts of South America, as summarized by Pirazzoli (1991, p. 174-176). Among the different interpretations the 3.5 m highstand at 5-6 ka BP seems to be the most accepted for the Strait of Magellan and the northern Tierra del Fuego (Porter *et al.*, 1984, Isla *et al.*, 1991). Nevertheless, considering only the evidence of terraces both along the Strait of Magellan (Auer, 1970; Brambati *et al.*, 1993), and along the southernmost Argentine Patagonian coast (*i.e.*, the area near Puerto Deseado), together with the observation made by Uribe and Zamora (1981) on the formation of Punta Dungeness, an almost continuous erosional level lies about 8-10 m above the present sea level (Clapperton, 1993, and references therein) and can be related to the Holocene highstand. Despite the disagreement about the elevation, probably due to differential isostatic uplift responses, or to possibly unorthodox elevation positioning of dated levels, the emergence is the main response for the last 5-7 ky. The only submergence hypothesis, based on the glacio-isostatic model of Clark and Bloom (1979) is not confirmed by both morphological evidences and Holocene dated raised marine deposits.

At the beginning of the sea drop, the Strait of Magellan was already flooded by the sea. The eastern entrance of the Strait was delimited by lateral moraine and glacio-fluvial deposits, that could be subjected to erosion and winnowing by wave motion and strong drift current. Following the model by Scott *et al.* (1987), this phase of reworking of unconsolidated moraine or glacio-fluvial deposits permits the formation of several littoral accretionary forms, connected with ancient glacier limits or deposits. Among these morphologies, the formation of spits, cuspate forelands, barrier islands or coastal lagoons, is likely mainly where a strong irregularity of coastal and sea-bottom morphology exists.

The development of the two cuspate forelands in both sides of the Atlantic entrance could be, therefore, related to the same evolutive phase, as proposed by Scott *et al.* (1987). In this perspective, the 4.2 ka BP date for Punta Dungeness formation (Uribe and Zamora, 1981), the inferred mid-Holocene earlier growth phase of El Páramo spit (Isla *et al.*, 1991) and the major coastal evolution as barrier spits or barrier islands which began 6,000 years ago along the northeastern Argentine coast (Codignotto and Aguirre, 1993), agree well with this hypothesis.

In figure 3 an evolutive scheme of Punta Catalina is proposed, based on the location and orientation of beach ridges and marshes. Although the early evolutive stages of the spit were not observed

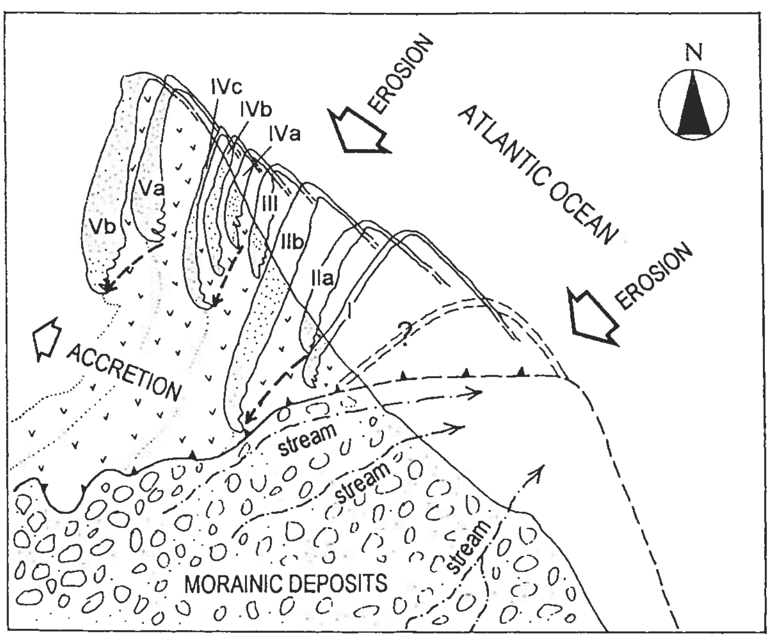

FIG. 3. Reconstruction of late Holocene evolutive phases of Punta Catalina foreland. See text for explanations.

because of the concomitance of obliterating erosional processes along the Atlantic coast and deflation effects, nine phases of growth, the last one representing the present stage, can be recognized.

Among them, the accretionary stages can be regrouped into 5 main pulsating events. The first one (**I**) is given by an almost completely hidden hooked beach, because of the thick covering of aeolian deposits lying on the whole southern sector of the investigated area. A little portion of ancient marsh separates this first beach ridge complex from a second feeble growth stage (**IIa**). A sediment supply stasis, marked by a wide ancient marsh, preceded a well marked growth phase, which originates the longest beach ridge system of Punta Catalina (**IIb**). It is a wide spit, partly reworked and covered by aeolian deposits, which did not affect the identification of ridge alignment.

Northwards, a little developed beach ridge system (**III**) is amalgamated to the previous one, more important, but it is easily recognizable as a different event for its shortening and strong discordance. A limited portion of a marsh, which cropped out after a strong deflation, separates the system **III** from the system **IV**. The latter is composed by three (**IVa**, **IVb**, **IVc**) well distinct superimposed phases. The IVc phase could represent either a separate progradation stage with respect to the **IVb** one, owing to its pronounced southwest elongation, or a frontal portion of a single phase (**IVb+IVc**), isolated by ingression effect of the present marsh. The last accretionary phase is given by two systems: a wide hooked fossil beach (**Va**) and the present accretionary beach ridge system (**Vb**). The former can be easily recognized, since it lies as an isolated spit, surrounded by the terminal (inner) fingering of the wide mud flat (tidal flat northward, and marsh southward). The latter represents the youngest spit arm whose length and well pronounced hooked form testifies a present phase with a large amount of sediment supply.

At the beginning of the Holocene regression, the abrupt irregularity of the coast, and the large amount of transported sediment from the south, gave rise to the accretion of a spit, swiftly growing westwards as a curved hooked form because of wave refraction. As the beach ridge system prograded, the erosional effect on the Atlantic side caused the WNW migration, together with the truncation of the curved beaches, producing a typical truncate cuspate form. On the opposite side of the Strait, an analogous process gave rise to the formation of Punta Dungeness, in which 8 accretionary stages can be observed. The present foreland landscape is the product of both the ingression processes by the intertidal muddy area and the superimposition of deflation effect. In fact, the expansion of the tidal prism involved a partial fragmentation of the beach ridges, as testified by the presence of relict tidal channels, which in some cases, gave rise to capture processes. Wind effect has already been discussed. It is enough to remember that the whole southern studied area is at present covered by aeolian sediments, which obliterated all pre-existing morphologies.

ACKNOWLEDGEMENTS

This work was conducted as a part of the 'Magellan Project', which was founded by the Italian National Program for the Antarctic Research (PNRA). The authors wish to thank the student L. Fiorencis (University of Trieste, Italy) for her helpful support in the photo-interpretation. Professor A. Brambati (University of Trieste, Italy), Professor R. Paskoff (University Lumière de Lyon, France), Dr. J. Araya (Universidad de Chile) and other two anonymous referees are gratefully acknowledged for their useful suggestions and critical review of the manuscript. Many thanks also to Dr. E. Colizza (University of Trieste, Italy) who provided assistance during the surveys.

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Manuscript received: June 10, 1999; accepted: October 26, 1999.