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Morphology and Short-Term Changes of the Caleta Valdés Barrier Spit, Argentina

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ABSTRACT

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Caleta Valdés is an area constituted by a set of Holocene and Pleistocene gravel beach ridges, which form part of a barrier spit system. Longshore drift has been predominantly north to south for the last 5700 years. Evolution of the area has been monitored during the last 28 years. In this period, the northern spit has been growing southward, and its rate has increased from 25-meter per annum (1971–87), to 89-meter per annum (1987–96). During the 1996–9 time span, growth has increased up to 167-meter per annum. This growth rate implies an average movement of approximately 1400 metric tons of gravel a day during the last four years. The growth rate during the time span under study can be represented by a polynomial equation of the third order. Spit evolution can be predicted from this equation. It is thus possible to suggest that Caleta Valdés is likely to close by 2002 (±). Such a morphological change will cause drastic changes in hydrodynamics, and environmental conditions due to changes in both water salinity and temperature.

ADDITIONAL INDEX WORDS: *Argentine coast, barrier spit, Holocene evolution, littoral drift, rapid changes.*

INTRODUCTION

The Coastal evolution and geomorphology of the gravel barrier system of the Caleta Valdés area are presented as an initial step in developing a regional model of Patagonia's coast (Argentina).

Many examples of barrier beach evolution have been developed, but gravel barriers are less well known. The classic gravel study by STEERS (1962) on the growth of a gravel spit at Oxford Ness, UK (See KOMAR, 1998), CARTER and OXFORD (1984) described a range of longshore and onshore/offshore trends. SCHWARTZ (1972) and SCHWARTZ *et al.* (1989) studied the origin of spits, FITZGERALD *et al.* (1992) studied the evolution of a beach-ridge barrier at Buzzards Bay, Massachusetts, and FITZGERALD and VAN HETEREN (1999) studied paraglacial barrier systems.

COASTAL SETTING

Caleta Valdés is located in the Valdés Peninsula in the Province of Chubut, Patagonia (W 63° 36′, S 42° 12′–30′) (Figures 1, 2). Patagonia is a semiarid scrub plateau that covers nearly all of the southern portion of mainland Argentina. With an area of about 673,000 square kilometers, it constitutes a vast area of steppe and desert that extends from latitude 37° to 51° S. It is bounded, approximately, by the Patagonian Andes to the west, the Colorado River to the north, the Atlantic Ocean to the east, and the Strait of Magellan to the south, (Figure 1).

Geological studies at Caleta Valdés conducted by ROVERETO (1921), CODIGNOTTO (1983), and FASANO *et al.* (1983) have indicated that beach ridges dated from both the Pleistocene and the Holocene. CODIGNOTTO and KOKOT (1988) describe Caleta Valdés as a lagoon surrounded by a system of double spits, and identified a southward longshore drift direction.

CODIGNOTTO *et al.* (1995) determined the growth rate of the southward northern spit. ISLA and BUJALESKY (1995) pointed out that the mouth of Caleta Valdés includes complex spits, and mentioned a south-to-northward drift. MONTI (1997) characterized the sequence of Pleistocene and Holocene marine deposits on Caleta Valdés. KOKOT (1999) determined the erosion resistance of the Caleta Valdés coastal deposits.

Caleta Valdés is both a protected natural reserve and an international tourist attraction due to the abundance of marine life including seals, penguins and whales. Recent rapid shore changes may lead to a major habitat shift that would impact on wild life.

The northeastern point of the Valdés peninsula is an approximately 50-km long gravel barrier beach. The gravel has a minor sand matrix and is composed of volcanic rock that

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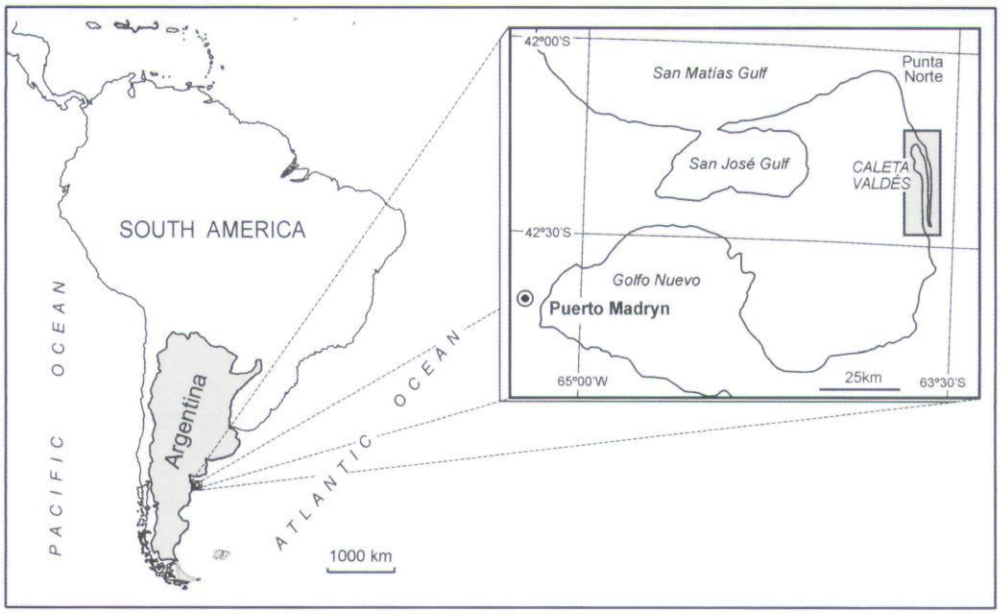

Figure 1. Location map. Caleta Valdés coastal area.

forms oblate and prolate clasts, the average size of which is 10 cm (b axis). The mass of the deposit averages 1.6 ton/m^3. The gravel is transported by longshore transport from an updrift source area. A relatively small new supply of sediment from inland source areas is introduced into the system by mass wasting. The height of the spit is about 4–5 m above the sea level.

The study area is a coastal lagoon between Punta Norte to the north, and Punta Cantor to the south. An approximately 33 km long barrier spit encloses the lagoon, parallel to the coastal line and attached to the main-land to the north. The width of the lagoon is variable and forms two main basins: a northern area 3000 m wide with several islands and a narrow southern area only 200 m wide (Figure 3). The lagoon is connected to the open sea through a 75-m wide tidal inlet at the southern end.

The barrier system is a 200-m wide spit composed of Holocene gravel deposits.

Figure 2. Oblique air view of Caleta Valdés (2000).

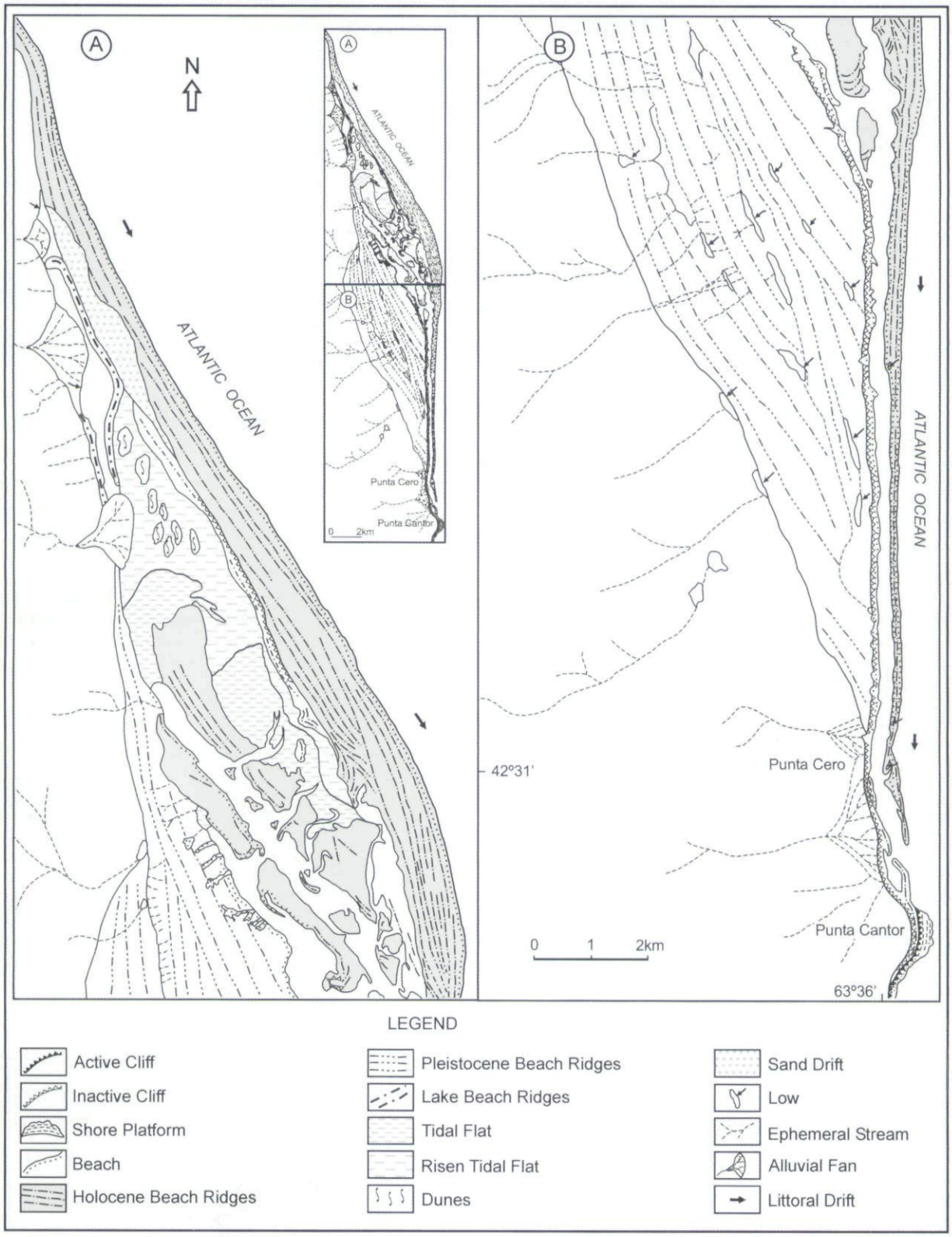

Figure 3. Geomorphologic map of Caleta Valdés.

Figure 4. Inactive cliff in Pleistocene outcrops and cuspate spit in Caleta Valdés.

West of the lagoon, an approximately 10-kilometer long area, between 15 and 20 m above sea level, is composed of Pleistocene gravel beach ridges. The beach barrier system is adjacent to the Puerto Madryn Formation (HALLER, 1979), which is a Tertiary friable sandstone. It outcrops south of the lagoon at Punta Cantor, and west of Pleistocene deposits. The maximum age of the modern barrier has been calculated to be 5700 years old (CODIGNOTTO and KOKOT, 1988).

Tides are semidiurnal, with a 3.08-meter average amplitude (SERVICIO DE HIDROGRAFÍA NAVAL, 1997). Tidal currents are parallel to the coast and their speed range is almost 7.5-meter/s in practically the whole area. In the inlet throat of Caleta Valdés, current speed ranges are between 7.5- to 11 m/s, where flood heads W–E, and ebb heads E–W (SERVICIO DE HIDROGRAFÍA NAVAL, 1962).

With regard to the city of Rawson, harbor located 80 km from Caleta Valdés, to the south, POUSA *et al.* (1995) have measured significant wave heights up to 2 m, and the highest breakers were observed during the winter season. Predominant wind directions are from the west and southwest. Winds can cause steep seas—especially when blowing against the current. The area is a semibarren region, which is part of the Patagonian steppe. Rainfall is scarce, only reaching 150 mm per annum.

METHODOLOGY

The geomorphological evolution of Caleta Valdés has been studied on several scales of imagery: 1:20,000 scale aerial photography; 1:100,000 and 1:250,000 scale satellite images; and 1:100,000 scale topographic maps. Aerial photographs of year 1971 were obtained from the Argentine Navy Hydrographic Service, and those corresponding to years 1987, 1996 and 1999 were taken by the authors, have been corrected and put to orthogonal projection at an identical scale. Comparison of images has allowed us to detect morphological changes over a 28-year period, and direct measurements taken during a field study over the last 12 years. Similar methods have been used in other parts of the world. For example, SMITH and FITZGERALD (1994) have studied the morphological changes that have occurred in the tidal mouth of the Essex River from 1943 to 1985. FOX *et al.* (1995) in Penouille spit, Gaspé Bay, Canada, determined erosion and deposition rates between 1765 and 1981 by comparing beach ridge maps and aerial photographs. EITNER (1996) studied sediment changes occuring over a 30-year time span at the Otzumer Balje tidal inlet between the East Frisian Islands, using topographic maps, topographic surveys, and aerial interpretations. BINDERUP (1997) studied the evolution of a spit on Vejro Island, Denmark by analyzing aerial photographs taken over a 34-year time span thus determining changes in the coastal profile. MASON *et al.* (1997) studied the Late Holocene evolution of the Cape Espenberg spit, Alaska, showing four evolution phases that took place between 5000 and 1000 BP.

GEOMORPHOLOGY

The marine erosion landforms in the area include active and inactive cliffs (Figure 4), and shore platforms on Tertiary sedimentary rock. The active cliffs are located in Punta Cantor and Punta Norte and at the western sector of the lagoon facing the tidal inlet (Figures 1, 3).

Small channels are found on the shore platforms, almost perpendicularly to the coastline, sometimes covered with thin gravel deposits forming ephemeral beaches. Accumulation forms include Pleistocene and Holocene beach ridges and beaches.

A sector located to the west of the lagoon is composed of

Figure 5. Gravel cuspate spit and intertidal transverse bar.

Pleistocene beach ridges 15 m above sea level, forming four subparallel ridges with a general NW–SE orientation. This group of beach ridges is connected to an inactive cliff to the west.

The sector of marine accumulation between Punta Norte and Punta Cantor is a barrier spit formed by Holocene beach ridges (Figure 2). This barrier spit, which is about 33 km long and is located 8 meters above sea level, is a compound spit with at least 10 examples of hook-shaped spits, each one showing an eroded end linked, with a small lagoon. The oldest beach ridges have a plant layer consisting of *Schinus polygamus* and *Lycium chilensis* bushy steppe. Plant zonation along the ridges reflects variations in elevation and salinity.

Some cuspate spits—both symmetrical (Figure 4) and asymmetric, can be observed. Some of them have intertidal transverse bars at their ends (Figure 5). In general, at both sides of the cuspate spits there are erosional bays similar to those described by ZENKOVICH (1967). A Barrier spit is flanked by beaches on both sides and is composed of coarse and very coarse gravel with a small sandy matrix and shells. Beaches continue laterally with variable slopes, especially on oceanic beaches. Cuspate spits, affected by both waves and tidal currents, are found in the narrowest sector of the lagoon. Inside the lagoon, waves are generated by predominantly N and SW winds. Opposing currents with different intensities shape asymmetric cuspate spits.

Tidal action dominates the northern area of the lagoon whereas tidal plains and tidal channels are evident in the island sector. Silt and clay are the prevailing sediments deposited in low energy settings of the lagoon. There are tidal deltas among islands associated with former inlets with coarser sediment.

Islands located north of Caleta Valdés are separated by tidal straits (Figure 3), and consist of two groups dividing the lagoon longitudinally. The islands are NW–SE oriented, and are formed from beach ridges and uplifted tidal plains partially covered by wind deposits and some vegetation. Pleistocene beach ridges are partly dissected by a low density surface drainage with a trellis pattern. Even though rainfall is scarce, Quaternary deposits located to the west of the lagoon are cut by trenches formed by ephemeral runoff. Ephemeral river action is also evidenced by the presence of alluvial fans located among Tertiary outcrops and Quaternary deposits corresponding to Pleistocene beach ridges. Aeolian landforms are closely linked to uplifted tidal plains. Three different types of accumulations have been found: a) N to S-oriented longitudinal dunes to the northern sector of the lagoon; b) barchan-type dunes, and c) sand sheets that are found within the beach ridge area to the NW of lagoon.

GEOMORPHOLOGICAL EVOLUTION

There exists a 50-kilometer long, 150-meter wide gravel deposit in the coastal area located between Punta Norte and Punta Cantor (Figure 1). Offshore gravel deposits were detected during a survey performed by the authors on board the ocean survey vessel El Austral (formerly Atlantis) in 1991. To determine bottom characteristics samples were extracted and a bathymetric and seismic measurements were made during the survey. There is no evidence, however, of any offshore-onshore transport. Morphological evidence suggests predominant longshore gravel movement. Gravel deposits are scarce to the south of Punta Cantor, where the coast includes active cliffs on Tertiary sedimentary rock.

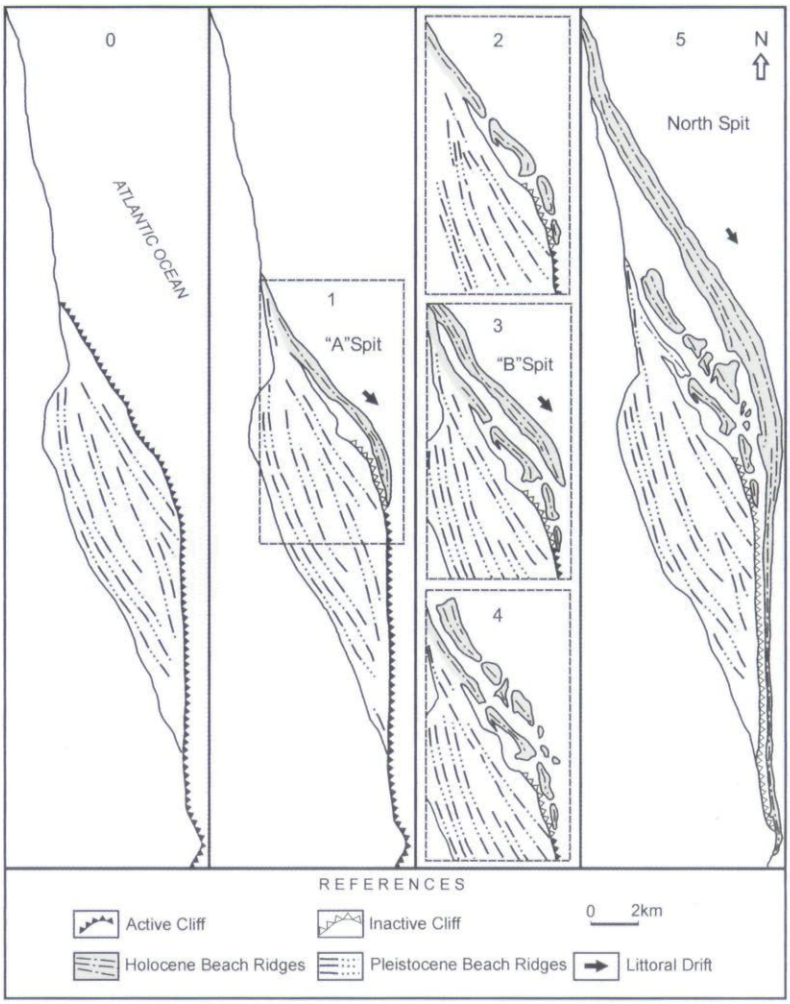

Figure 6. Evolutionary stages of the Caleta Valdés coastal area.

Morphological changes that have taken place at Caleta Valdés are noteworthy among spits. These have been analyzed through the study landforms dating back 5700 years using 28 years of aerial photographs. Figure 6 illustrates the different stages as interpreted on the basis of the aerial photographs. Time "0" shows a coast shaped by Pleistocene beach ridges that are currently at 15 meters above sea level. These raised beach ridges were subject to erosion forming a cliff that has been active for some time.

Starting from a longshore gravel supply from the North, a barrier spit (Spit "A") grew and formed a small lagoon (Time "1"). The open end of the spit eventually joined the coast, closing the lagoon. The spit broke into segments, thereby forming three barrier islands (Time "2") while the area linked to dry land remained as a small spit. At a later stage, Spit "B" (Time "3") grew southward to the east of Spit "A". Spit "B" also broke into segments forming a new barrier island system parallel to the former system (Time "4"). A new stage commenced place with the growth of the barrier spit called North Spit (Time "5"). This is a compound spit where old hook-shaped ends with linked lagoons can be identified (ZENKOVICH, 1967). The spit has been formed by a north-southward longshore transport generated by prevailing waves, and currents from the NE (KOKOT, 1999). In 1971, the end of North Spit was 2400 m from Punta Cantor. From Table 1, the spit growth rates are presented, based on dates and the position of the free end of the spit between 1971 and 1999. These data indicate a clear acceleration of the growth rate of the spit (Figures 7, 8, 9). The spit cross section is approximately 2000 m^2—which means that for each advance of one meter, 2000 m^3 of gravel has been deposited. Taking into ac-

Table 1. *North spit growth rate.*

Year	Period (years)	Growth (km)	Velocity (m/year)	Volume (m^3)	Weight (ton)	(ton/day)
1971	0	0	0	0	0	0
1987	16	0.4	25	800,000	1,280,000	220
1996	9	0.8	89	1,600,000	2,560,000	780
1999	3	0.5	167	1,000,000	1,600,000	1,460

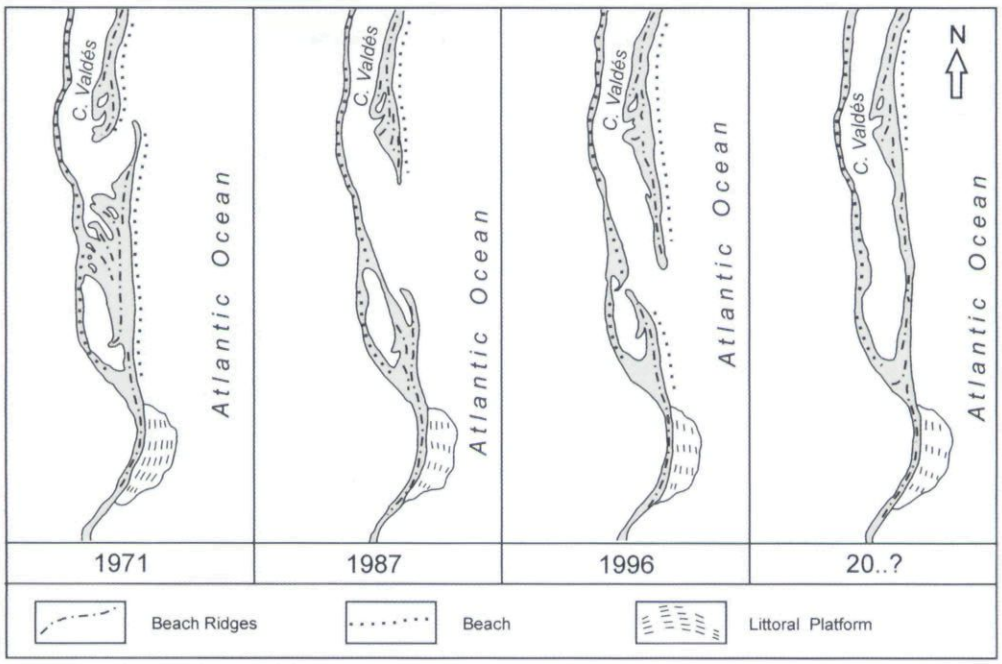

Figure 7. Map of the Caleta Valdés mouth and past & future evolutionary.

count the present growth rate of the spit, this is equivalent to a 1460-ton gravel accumulation per day. So, on the basis of the spit growth rate during the last 28 years, approximately 5,400,000-tons of gravel have accumulated. From Figure 7, the evolution stage for each date can be seen. Between 1971 and 1996 a South-North oriented spit, the South Spit, was formed. Currently, that spit has been eroded away while the northern spit developed. Both the dynamics and migration of tidal inlets bring several variables into play, including, tidal currents, longshore currents, and sediment inflow.

Figure 8. Aerial photograph, Argentine Navy Hydrographic Agency (1968). Caleta Valdés mouth, North spit, South spit and the shore platform in Punta Cantor.

Figure 9. Oblique aerial photograph of Caleta Valdés mouth, 1996. Note the changes in spit progradation.

These processes have been discussed by LEATHERMAN (1980), as part of the evolution of barrier islands.

TESSLER and DE MAHIQUES (1993), suggested that the growth rate of spits in the southern coastal region of the State of São Paulo, Brazil, is not only linked to the shore drift process but also to an interaction of inlet and lagoon dynamics. LEVIN (1993) showed that morphological changes of a tidal inlet in the Mississippi Delta are due to time-related changes within the tidal prism, and sediment inflow. BORREGO *et al.* (1993) documented the growth of the Piedras spit in Huelva, Spain. They showed that infill of a lagoon is related to tidal currents and longshore currents. OERTEL and FOYLE (1995) have also studied the migration of inlets and the growth of spits in the Cheseapeake bay.

Similarly, in Caleta Valdés, morphological changes depend not only on the littoral drift but also on the tide dynamics and strong currents in the lagoon.

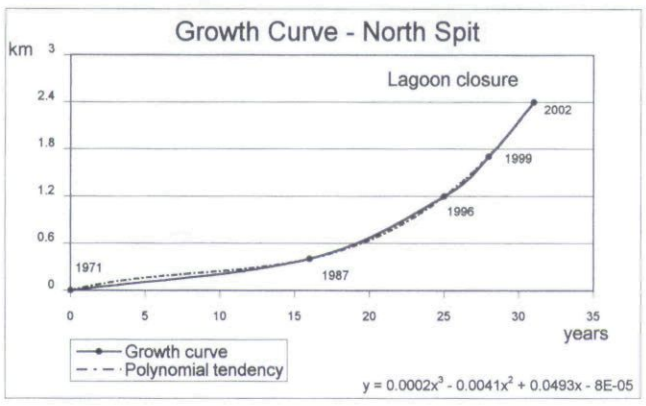

Figure 10. Evolutive and predictive curve of barrier spit progradation.

There is acceleration in the growth rate of the spit at Caleta Valdés (Figure 10). The trend can be described as a third order polynomial. This can be used to predict when spit will cover the remaining distance to Cantor Point, thus closing Caleta Valdés.

According to both Figure 7, and the above-mentioned tendency, the lagoon will be closed by 2002. Such a prediction simplifies all the processes in the coastal evolution of the area. FENSTER *et al.* (1993) have developed a coastline position prediction method based on historical data. It is these authors' contention that any coastal movement over time can be seen as linear, non-linear, cyclical, and even chaotic processes. At Caleta Valdés, changes in the coastline position have a non linear trend. Changes occur over a wide range of time scales. Coastlines change in response to sea level eustatic changes, and tectonics. Movements, however, may also be due to constant fluctuations in tide and wave interactions. The destruction of the southern spit is a result of a combination of the tidal inlet dynamics and the prevailing north-south longshore transport.

The important inflow of sediments from the north at the mouth of Caleta Valdés forces a southward migration of the tidal inlet. Owing to the strong flood-ebb tidal currents, inlet migration has occurred at the expense of the southern spit that no longer exists.

Whenever Caleta Valdés is closed, any future access of fauna, such as fish and whales will be prevented; and any influx of water will be restricted to flow through the gravel barrier. When shore dynamics within the lagoon are changed, cuspate spit growth will increase (CODIGNOTTO and KOKOT, 1988), leading to segmentation of the lagoon (ZENKOVICH, 1967).

Changes in the environmental conditions due to variations in the physical and chemical parameters of the water, and changes in sedimentation processes will most likely occur.

DISCUSSION

Three spits were created and developed southward at Caleta Valdés during the Holocene. Two spits were segmented, and, later isolated from waves due to the growth of a third spit. A dominant southward longshore transport system is responsible for the formation of the three spits. Another, smaller spit grew northward. Currently, there is no evidence of any northward longshore transport. The spit, which no longer exists, was 2300 m long by 1971. Its origin could have been due to the effects caused by SE storms that are both violent and short-lived in addition to being quite common along the Patagonian coasts. Since there is no gravel south of Punta Cantor that could have contributed to the formation of the southern spit, gravel is likely to have originated from erosion of the North spit. Evidence of such a process can be seen in the 1971 photograph where hook-shaped beach ridges appear—a fact directing our attention to the old hook-shaped ends near Punta Cantor. Thus we hypothesize that, when the cove is eventually closed, storm breaching could cause a reopening of Caleta Valdés.

CONCLUSIONS

Caleta Valdés is an area composed of a set of Holocene and Pleistocene gravel beach ridges, which form part of a barrier spit system. A predominantly north-south longshore transport has existed during the last 5700 years. The northern spit has been subject to an accelerated growing rate. The growth rate has increased from 25-meter per annum to 167-meter per annum over the last 28 years. Based on this tendency, the lagoon will close by 2002. The advance of the northern spit during the last 28 years has involved the movement of more than 5,000,000 tons of gravel. The predicted lagoon closing in progress at Caleta Valdés is bound to cause environmental changes due to modifications in water salinity, temperature, and hydrodynamics.

In March 2003, the spit was already about to close, only 20 m from Punta Cantor. At present morphological changes are continued and depend on the strong currents at the inlet.

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□ RESUMEN □

La Caleta Valdés es una albufera semicerrada por un sistema de espigas de barrera. Estas espigas están constituidas por una asociación de crestas de playa de grava, originadas durante el Pleistoceno y el Holoceno. Durante los últimos 28 años se monitoreó la evolución del área, comprobando que la Espiga Norte creció hacia el sur a una velocidad que pasó de 25 m/año (1971–1987), a 89 m/año (1987–1996) y a 167 m/año (1996–1999). Este aumento en la velocidad de crecimiento, implicó el transporte promedio durante los últimos cuatro años, de aproximadamente 1400 ton de grava por día. En el período estudiado, el crecimiento indica una tendencia que puede representarse por una curva polinomial de tercer orden. A partir de la extrapolación de la curva polinomial se puede predecir la evolución, donde el crecimiento de la misma conducirá al cierre de la Caleta Valdés aproximadamente en el año 2002. Este cambio morfológico implica cambios drásticos en la hidrodinámica así como en las condiciones ecológicas por modificaciones en la salinidad y temperatura del agua. A partir de la interpretación geomorfológica del área, donde se encontraron restos de espigas en gancho, que fueron datadas por el método de 14C, se determinó que el sentido predominante de la deriva litoral fue de norte a sur durante los últimos 5700 años.