Beach-morphodynamic changes conditioned by the Holocene sea-level fluctuation: Mesotidal beaches of Northern Patagonia

Cambios morfodinámicos de las playas condicionadas por la fluctuación holocena del nivel del mar: Playas mesomareales del Norte de la Patagonia

ABSTRACT

Beach morphodynamics are stated as depending on wave climate, tidal range and grain size. Sediment availability is a conditioning factor biased to inheritance factors. Seven natural beaches from Northern Patagonia: 4 from Southern Buenos Aires and 3 from Eastern Rio Negro Province were surveyed during several years. La Chiquita Beach is characterised by an abundance of fine sand supplied by the Colorado River delta. Pocitos Beach is rather stable although it is changing due to colonisation by the invasive reef-building oyster Crassostrea virginica. Faro Segunda Barranca is an open-ocean beach, very affected by extratropical storms coming from the SE. The beach of Villa Siete de Marzo has a very active dynamics affected by the embankments of the Negro River outlet, and episodic storms. The beach of Balneario El Cóndor is very wide with an intense strong longshore drift from west to east. The beach in front of the San Matías Lighthouse (Villarino Peninsula) is controlled by an abrasion platform close to the low-tide limit. Las Grutas beach is also controlled by


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an abrasion platform but the sand abundance is related to the ebb-tidal delta of the San Antonio Gulf. Open-ocean beaches in Buenos Aires province are very affected by a drift towards the north delivered by South Atlantic waves. On the other hand, Río Negro beaches are affected by the strong westerly winds blowing alongshore.

**Keywords** — Morfodynamics, wave-dominated beaches, tide-dominated beaches, San Matías Gulf.

**INTRODUCTION**

Beaches of northern Patagonia are being demanded in the last years since the pandemic 2020-2021 forced claiming of new touristic resorts without urban agglomerations. However, most of these young touristic villages lack some services or could not afford the hole summer season. For example, the most popular beach of the region, Las Grutas, has environmental problems that are increasing (Genchi et al., 2011; Fucks et al., 2011; Bonuceli and Navarte, 2017; Isla and Isla, 2020). At the same time, the morphological changes of these beaches are very significant implying different tidal ranges and wave regimes according to their configuration in relation to the dominant winds.

Beach morphology varies in response to wave height, wave period and tidal range, although grain size is another conditioning factor (Short and Wright, 1984;
Masselink and Short, 1993). In bimodal beaches, grain-size segregation is the determinant conditioning factor (Isla et al., 2006).

In Southern Patagonia, gravel can be segregated in a way that macrotidal beaches have reflective conditions close to high tide and dissipative ones during low tide (Isla et al., 2005, 2006). In Northern Patagonia, beaches with different tidal ranges can be discriminated (Isla and Bértola, 2003); their dynamics depend on the inherited gravel availability. These beaches were surveyed and sampled seasonally (summer and winter) in order to record their morphological variations. In this manuscript, these beaches are described in their grain-size composition and sediment availability, morphological changes and therefore their morphodynamics parameters. Changes in the tidal ranges during the Holocene were finally analyzed, in order to explain the evolution of those parameters.

**SETTING**

Most of the sea cliffs in Northern Patagonia are composed of the sandstones of the Rio Negro Formation (Andreis, 1975; Schillizzi et al., 2010), locally interfingered with the “Enterrriense” marine transgression (Isla and Rivero D’Andrea, 1993; Zavala and Freije, 2005); towards the west, by the Bajo del Gualicho Formation (also called “Patagoniense” Fucks et al., 2012). These cliffs are topped with the Tehuelche Gravels in several places (Darwin, 1846; Zavala and Freije, 2005) which constitute the supply of gravels to some of the beaches. The marine highstands that affected this region, during the Upper Pleistocene (OIS 5e) and the Middle Holocene, were reported either at the Colorado River delta (Weiler, 2000) and at the San Antonio Bay (Angulo et al., 1978). Sand dunes have climbed to these cliffs to form cliff-top barriers (Isla, 2017) and to migrate towards the east (Toffani, 2020; Toffani et al., 2020). The provenance for these sands was reported discriminating sources and processes (Toffani and Isla, 2022).

Low-lying areas were subject to the flooding by the sea, either during the Upper Pleistocene (Rutter et al., 1989; Weiler, 2000; Charó, 2013) or during the Late Holocene. The Holocene transgression affected several low-lying environments: the Colorado Delta (Weiler, 1983; Fayó et al., 2018), San Blas Bay (Espinosa and Isla, 2011), the Río Negro estuary (Escandell et al., 2009), Caleta Los Loros (Sander et al., 2018), Bajo La Quinta (Favier-Dubois and Kokot, 2011) and San Antonio Bay (Rutter et al., 1989).

The climate of northern Patagonia is temperate semiarid to arid (Coronato et al., 2008). San Matías Gulf is located within the planetary belt of the westerly winds that in Patagonia are fed from the high-pressure center from the South Pacific, the anticyclone of the South Atlantic, and the low-pressure subpolar channel (del Valle et al., 2008). As a consequence, the dominant wind blows from the WSW with an increment from the south components during the summer (Agosta et al., 2019). According to measurements performed in 1957 and 1958 (International Geophysical Year), more intense winds occur between 40° and 60° S (Loon, 1967).

The region possesses several depressions (salt pans) of tectonic origin, which are emerged but below present sea level (Bajo del Gualicho, Gran Bajo Valdés).
Tides at the shelf are semidiurnal from 41°S to the south, and mixed towards the north (Perillo et al., 2006). Tidal ranges increase towards the gulfs and embayments, as the widths of the continental shelves increase (Cram, 1978). This is the case for the Bahía Blanca embayment and the San Matías Gulf (Fig. 1) in Northern Patagonia (Isla and Bujalesky, 1995; Isla and Bértola, 2003). Within the Bahia Blanca embayment, bathymetric conditions produce an increase of water temperature and salinity (Lucas et al., 2005). In relation to the continental shelf width, and different embayment configurations, some beaches are subject to microtidal regimes while others are macrotidal (Isla and Bujalesky, 1995; Fig. 1). In this sense, mean tidal ranges show an increment from 0.6 m at Pocitos to 6.73 m at the San Antonio harbor (Table 1) in less than 200 km. This increase in tidal ranges conditions the extended banks flanking tidal inlets (Kana et al., 2013). Tidal dynamics within the gulf is characterized based on observations and models (Moreira et al., 2009). According to measurements performed and referred to the high tide at Punta Colorada harbour, maximum currents occur at the inlet of the gulf either at the north and south (Vara and Mazio, 1983). The gulf becomes intensively stratified between 40 and 100 m since the beginning of the spring to the beginning of the winter (Piola and Scasso, 1988).

Some of the surveyed beaches are subject to open-ocean waves (La Chiquita, Faro Segunda Barranca, Siete de Marzo, El Cóndor) while others are located within bays or gulfs (Pocitos, Baliza San Matías and Las Grutas). According to simulations of deep-water waves (1981-2012 interval), waves from the west dominate (44.5%; 15.2% from the SW, 16.7% from the W and 12.6% from the NW; Worner et al., 2019). Offshore wave height increases from 0.72 m in front of Anegada Bay to 1.26 m offshore Segunda Barranca. South of this lighthouse waves decrease to 0.48 m.
La Chiquita es una playa muy ancha entre dos canales distributarios del Delta del Colorado (Fig. 1). Se relaciona con el más reciente banco de los cuatro bancos de arena reconocidos en el avance deltaico (Fayó et al., 2018).

Pocitos Beach, ubicado dentro de la Bahía de Anegada (Fig. 1), está colonizado por Spartina y Sarcocornia (Isla et al., 2010; Fig. 2). En los últimos años, esta playa fue muy afectada por la introducción de un molusco constructor de arrecifes, Crassostrea virginica (Escapa et al., 2004). El original playón de arena está cambiando debido a la extensión de los arrecifes intermareales. Un modelo de transporte Lagrangiano fue aplicado para explicar su dinámica, y la exportación de larvas durante la temporada de verano (Alvarez et al., 2001; Sepúlveda y Olivares, 2013). Segunda Barranca es una playa estrecha de mar abierto.
Fig. 2. Photographs of the beaches surveyed. La Chiquita is characterized by the presence of ancient tidal flats related to the Colorado River delta migration. Pocitos beach possesses a sand flat colonized by marshes and recently by reef-building oysters. The beach at Segunda Barranca lighthouse is located in front of a low cliff subject to storms arriving from the South Atlantic Ocean. Siete de Marzo is a resort village, very influenced by the effects of northward-migrating banks transported from the Negro River outlet. El Condor beach is located at the southern spit that limited the Negro outlet from the south. The beach in front of Baliza San Matías is composed of fine sand and conditioned by intertidal rocky outcrops. The beach of Las Grutas is rather wide with scattered outcrops.
beach in front of a low cliff composed of Tertiary rocks, covered by foredunes. The monitored beach is located at the foot of the lighthouse.

7 de Marzo is a wide beach, very close to the northern coast of the Rio Negro inlet. Wide channels containing megaripples, which are very stable and subject to a significant coarse-grained transport, are the main features.

The complex sand spit that enclosed the Rio Negro outlet (Del Rio et al., 1991) has a wide beach where the El Cóndor Village is settled.

The Baliza San Matías beach is located in front of the lighthouse. The width of this macrotidal beach is limited by an abrasion platform composed by conglomerates formed during a former marine highstand.

Located at the north of San Matías Gulf (Fig. 1), Las Grutas, the most popular beach resort of Rio Negro, is macrotidal and located at the foot of the cliffs where the village is settled. The extension of this beach is conditioned by the Reparo Bank flanking the San Antonio Oeste tidal inlet (ebb-tidal delta) and beach rock outcrops dominating to the west of the village. The cliffs have been receding at a rate of 0.07 m/yr (Kokot and Chomnalez, 2012). Most of the dynamics of the beach was altered with the construction of canyons and gullies to drain the anthropogenic increase in groundwater levels (Genchi et al., 2010, 2011).

METHODS

Beach profiles were surveyed during the early summer (December 2013) and winter (August 2014) times. Topographic surveys of those years (2013-2014) were referred to fixed points (stairs, cemented floors, paved routes) marked with painting devices. Volumes of eroded or accumulated sand between different surveys were analyzed in terms of m$^3$ per m of profile. Sediment samples collected, were dried and analyzed sieving at 0.5 phi intervals. Morphodynamic parameters were collected from several surveys at these beaches, spanning from micro to macrotidal regimes in relatively short distances (Table 1). Digital elevation models (DEM) were downloaded from the srtm/cgiar web page. Surface analyses were performed via the procedures content at the TerrSet program (Eastman et al., 2016). Synthetic Aperture Radar (SAR) images (Sao Com 1a, L band) were downloaded from the CONAE web page.

RESULTS

Beaches

Significant variations were recorded in relation to the tidal ranges and intertidal extension (Isla and Bértola, 2003). Open-ocean beaches have reflective characteristics while bay beaches present a dissipative profile. The Tehuelche Gravels are locally segregated at some beaches (Fig. 3). Foreshores with gravel contents have steeper slopes.
Fig. 3. Grain size distributions (phi units) from the extremes of these wide beaches. Grain-size distributions are represented by circles of different sizes.
**Balneario La Chiquita.**— This beach, surveyed in 2001, 2012 and 2013 (Table 1), is about 400 m long. During this interval, sand dunes dominate with an altitude of 1.5 m. Significant variations were recorded between the survey of 2001 and those performed in 2012-2013 (Fig. 4). The ridge and runnel system shows altitude differences of up to 0.6 m. Beach budgets indicate an erosion rate of 66 m$^3$/m.

![Fig. 4](image-url) Morphological variations of the studied beaches. Some beaches (Siete de Marzo, El Cóndor) are significantly affected by estuarine influence.
Balneario Pocitos.— Pocitos beach, located at Anegada Bay, is about 130 m width. It was surveyed in 2001, 2012, 2013 and 2014. The backshore and foreshore were very stable in those years: 38% of the profile was supratidal and 48% intertidal (only 14% of the surveyed profile remains under water). Wave action is very restricted, with oyster reefs colonizing the sandy intertidal areas (Fig. 2). Sand dunes 1.7 m high remained stable during the 2001-2014 interval. Erosion was estimated at around 12 m$^3$/m during that interval.

Faro Segunda Barranca.— The beach is located in front of a low cliff capped with 2.4 m high dunes. Although the beach is 120 m wide, little morphological changes were reported from the intertidal areas (5.3 m$^3$/m) during the analyzed period (2001-2014).

Balneario Siete de Marzo.— This beach is located north of the Río Negro River inlet (Buenos Aires Province). The area is subject to a very significant longshore transport (Del Rio et al., 1991). The survey showed lengthy beach profiles (450 m) height differences of 3.6 m. Significant variations are caused by the evolution of very deep intertidal channels (Fig. 4). The availability of sand at the coast is evidenced by the presence of parabolic dunes, 6 m height (Cortizo and Isla, 2012). A sediment accumulation of 163 m$^3$/m during the interval between surveys (December 2013 and August 2014) was calculated.

Balneario El Cóndor.— El Cóndor is the widest beach within this region. Between 2001 and 2013-14 the supratidal beach was very stable, although significant changes occurred at the intertidal areas (Fig. 4). Sand dunes located at the backshore are very stable since the forestation related to the construction of the resort village. Accumulation is induced by the outlet of the Negro River (ebb-dominated tidal delta) that migrates towards the east (Del Río et al., 1991). A volume of 250 m$^3$/m has been accumulated during the surveyed period (December 2013 to August 2014). Height differences of 0.8 m were recorded at the intertidal areas dominated by ridge-runnel systems dominated by fine gravels (Fig. 4).

Baliza San Matías.— The beach in front of the San Matías lighthouse is considered stable, due to the extended abrasion platform. Sand dunes have been limited to heights of 2 m since the construction of a paved road (RP 1). During the interval between surveys (2000 to 2013-14) the upper foreshore has receded 30 m (Fig. 4). During this time 163 m$^3$/m were eroded. The beach orientation to the south in this area means that they are very subject to temporal but constant winds from the south.

Balneario Las Grutas.— Las Grutas beach is composed of fine sand and had an extension of 180 m during the survey periods; the submerged beach is longer during the summer season. Only the upper beach was surveyed in 1986, 2013 and 2014 (Fig. 4). The backshore is protected from the strong winds by 10 m tall cliffs. Groundwater delivered from the village’s domestic sewage usually seeps from the middle of the cliff, enabling greater portions to be eroded (Fucks et al., 2011). During July 2009
strong and constant winds caused the erosion of most of the upper foreshore and exhumed rocky outcrops of the Patagonia Formation; however, in a few weeks sand returned naturally to the upper reaches of the beach. During the interval between December 2013 and August 2014, 129 m$^3$/m were estimated eroded.

**Grain Sizes**

Mean grain sizes of the different beaches have spatial and temporal variations. La Chiquita and Pocitos beaches receive fine sand from aeolian corridors. Those in the vicinity of the Negro River outlet (El Condor, Siete de Marzo and Segunda Barranca) contain volcanic gravel from the Tehuelche Formation (Fig. 5). The western beaches of Rio Negro Province (Las Grutas and Baliza San Matías) received fine sand transported by westerlies.

**DISCUSSION**

Although they are quite close, these beaches respond to different tidal ranges and to wide spectra of wave parameters, sediment availability and grain sizes. Most of these variations can be related according to the bivariate graph relating the relative tidal range (RTR) and the Omega parameter (Masselink and Short, 1993; Fig. 6).

Although tidal beaches are conditioned by morphodynamic parameters, they are also subject to the sediment availability (Isla et al., 2006). Mesotidal beaches of Patagonia are therefore biased to the gravel availability supplied from the erosion of cliffs crowned by the gravity-dominated deposits described originally as Tehuelche Gravels. Macrotidal beaches of Tierra del Fuego differ completely from this behaviour. They have higher gravel availability supplied from glacial processes: steep higher foreshores composed exclusively by gravel, while the low-tide terraces are composed of fine sand (Isla et al., 2005).
In Southern Buenos Aires, fine sand is supplied from the Northern-Patagonia coast by aeolian corridors derived from allochthonous rivers, such as the Colorado and Negro (Fig. 7; Spalletti and Isla, 2003). In Rio Negro fine sand is eroded from the Rio Negro Formation sandstones (Tofani, 2020; Toffani et al., 2020). From the feet of these cliffs, it is transported towards the top by westerly winds (Fig. 7).

The composition of beach sediments is related to the recent history of this desert region. During the Upper Pleistocene (about 11,500 yrs BP) the depressions of the San Matías Gulf are assumed to be emerged, dry and below sea level. The coast during those days was 70 m below present MSL (Isla, 2013) and there was a significant northward longshore transport of gravel (Fig. 8). At the boundary between Pleistocene and Holocene (10,000 yrs BP) the seal level raised to -60 m. Both depressions were rapidly flooded when the sea level overpassed the sill of the present San Matías Gulf. As sea level continued rising the former Pleistocene cliffs were

Fig. 6. Omega parameter vs. relative tidal range (modified from Masselink and Short, 1993, Isla et al., 2006). The arrow indicates the increase in tidal range towards the western beaches. Wave effects diminished from open-ocean beaches to those located within the San Matías Gulf.

Fig. 7. Different sediment supply paths. A) The Ombucta and Buratovich aeolian corridors supply fine sand from the Colorado River to La Chiquita and Pocitos beaches. B) The sand field of Bahía Creek is originated from sand accumulated at Caleta Los Loros that climbed sandstone-composed cliffs. Arrows indicate wind transport direction.
reactivated and began to retreat rapidly. Gullies were carved towards the headlands of the sandstones of Rio Negro Formation, while reorienting towards the gulf (Fig. 8). At the outlet of these gullies fine sand became abundant and entrained by the wind to form dunes which climbed towards the top of the cliffs (Toffani and Isla 2022). Littoral drift to the east increased as the fetch from the west was becoming longer. Therefore, westerly winds originated tongues of dune fields climbing to form cliff-top barriers.
Several problems have been arising at these beaches according to increasing touristic pressure. The input of water derived from the Rio Negro watershed (canal Pomona-San Antonio) at Las Grutas are inducing seepage processes at the boundary between the Patagonia Formation and the overlying Rio Negro sandstones (or sandy-composed barrier). At the end of the summer season, the seepage from domestic sink holes are draining to the coastal cliff (Fucks et al., 2011; Bonucelli and Navarte, 2017; Isla and Isla, 2020). According to samplings performed in November 2017, higher coliform concentrations occur in Bajada Cero (Bonucelli and Navarte, 2017).

CONCLUSIONS

Inherited conditions in relation to the availability of gravel and fine sand are the forcing factors to the development and maintenance of Northern Patagonian beaches. Tidal ranges and wave dynamics are responsible for the morphological variations.

During the Holocene and while the depressions became progressively flooded the coast evolved from microtidal to macrotidal. Open-ocean waves from the Atlantic Ocean were progressively replaced by wind-driven waves from the west.

These changes within the gulf conditioned the morphodynamics of the beaches, although the inherited sediment availability plays a new role now.

Buenos Aires beaches are today dominated by an open-ocean-delivered drift from the Atlantic Ocean. Instead, Rio Negro beaches —due to their E-W configuration— are dominated by an easterly drift induced by westerly winds.

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REFERENCES


