Fundación Miguel Lillo
Tucumán
Argentina

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

Federico Ignacio ISLA[1], German BÉRTOLA[1], Juan Manuel FERNÁNDEZ[1], José Manuel BEDMAR[2], Mauricio TOFFANI[3], Pedro GARZO[1]

[1] Instituto de Geología de Costas y del Cuaternario (UNMDP-CIC), Instituto de Investigaciones Marinas y Costeras (CONICET-UNMDP). <fisla@mdp.edu.ar>, <gbertola@mdp.edu.ar>, <fernandezjuanmf@gmail.com>, <pgarzo@agro.uba.ar>
[2] Servicio Geológico Minero Argentino. Segemar, Av. General Paz 5445, Parque Tecnológico Miguelete, Edificio 14, <josebedmar@gmail.com>
[3] Instituto de Investigación en Paleobiología y Geología (IIPG), CONICET – Universidad Nacional de Río Negro, Av. Roca 1242, (8332) General Roca, Argentina; <mtoffani@unrn.edu.ar>

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

➤ Ref. bibliográfica: Isla, F. I.; Bértola, G.; Fernández, J. M.; Bedmar, J. M.; Toffani, M.; Garzo, P. 2023. "Beach-morphodynamic changes conditioned by the Holocene sea-level fluctuation: Mesotidal beaches of Northern Patagonia". *Acta Geológica Lilloana* 34 (2): 111-128. doi: https://doi.org/10.30550/j.agl/2023.34.2/1830
➤ Recibido: 6 de agosto 2023 – Aceptado: 19 de septiembre 2023
➤ URL de la revista: http://actageologica.lillo.org.ar

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, Rio Negro beaches are affected by the strong westerly winds blowing alongshore.

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

RESUMEN

La morfodinámica de playas fue enunciada como dependiendo del clima de olas, el rango de mareas y el tamaño de grano. La disponibilidad de sedimento es un factor condicionante heredado. Siete playas naturales del norte de Patagonia: 4 de la Provincia de Buenos Aires y 3 de Río Negro fueron relevadas durante 7 años. La playa de La Chiquita se caracteriza por la abundancia de arena fina aportada por el delta del Río Colorado. La Playa Pocitos es relativamente estable aunque está cambiando debido a la colonización por la ostra formadora de arrecifes *Crassostrea virginica*. Faro Segunda Barranca es una playa abierta muy afectada por tormentas extratropicales del SE. La playa de la Villa Siete de Marzo tiene una dinámica activa afectada por los embancamientos de la desembocadura del Río Negro y tormentas episódicas. La playa del Balneario El Cóndor es muy ancha con una caudalosa deriva litoral de oeste a este. La playa frente al Faro San Matías (Península Villarino) está controlada por una plataforma de abrasión cercana al límite de la bajamar. La playa Las Grutas está también controlada por una plataforma de abrasión aunque la abundancia de arena está relacionada al delta de reflujo de la Bahía de San Antonio. Las playas abiertas de la Provincia de Buenos Aires son muy afectadas por una deriva litoral hacia el norte inducida por olas del Atlántico Sur. Por el contrario, las playas de Río Negro son afectadas por fuertes vientos del oeste que fluyen paralelos a la costa.

Palabras clave — Morfodinámica, playas dominadas por olas, playas dominadas por mareas, Golfo San Matías.

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 "Entrerriense" 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

Fig. 1. Location of the beaches surveyed in relation to the tidal ranges of Buenos Aires and Río Negro.

Table 1. Morphologic and dynamical characteristics of the beaches of Southern Buenos Aires (light gray) and Eastern Rio Negro (dark gray). L: Length; H: altitude differences; Ao: tidal range; Hb: wave height at the breaker; T: wave period; Ws: settling velocity (sensu Masselink and Short, 1993); RTR: relative tidal range; Ω: Omega parameter.

Beach	L (m)	H (m)	Slope (°)	Ao (m)	Hb (m)	T (s)	Ws (m/s)	RTR	Ω
La Chiquita	260	5	1	2.26	0.2	4	0.01365	11.3	3.66
Pocitos	180	4	3	0.61	0.1	4	0.00773	6.1	3.23
Segunda Barranca	50	5	5.7	1.65	0.6	9	0.02716	2.75	2.45
Siete de Marzo	280	9	2.7	3.05	0.3	9	0.7	10.16	0.04
El Condor	530	5	0.8	3.05	0.4	9	0.02367	7.62	1.87
Bal. San Matías	90	8	4	6.73	0.4	8	0.054	16.82	0.92
Las Grutas	110	6	2.9	6.73	0.3	10	0.01364	30	0.2

at La Lobería. Similar variations are expected regarding maximum wave heights. The breaker wave heights also increase from 0.59 m at Anegada Bay to 0.94 m at Segunda Barranca lighthouse, and decreasing to breaker heights of 0.80 m towards La Lobería (Worner *et al*., 2019). Wave heights diminish significantly within the gulf as fetchs are more restricted (Isla *et al*., 2006).

Gathering radiocarbon datings from cores taken by the Lamont-Doherty Geological Observatory (Guilderson *et al*., 2000) and those collected at the coast, a sea-level curve was performed timing the flooding of San Matías Gulf (Isla, 2013).

BEACHES DESCRIPTIONS

Seven beaches were analyzed in their morphological variations and grain-size composition. Four are located in the Buenos Aires Province, and the remaining 3 in Río Negro Province (Fig. 1). Some of the beaches were already subjected to morphological studies (Isla and Bujalesky, 1995; Isla *et al*., 2001; Isla and Bértola, 2003); this manuscript provides new monitoring data 12 years after. The mollusk distribution along these beaches was analyzed in a doctoral thesis (Charó, 2013). Each beach profile series were surveyed during a period of less than two days in order to allow for comparative analyses of topographic variations and morphodynamics parameters (Table 1). However, the descriptions redacted below summarize characterizations performed during the last surveying series: December, 2013 (summer) and August 2014 (winter).

La Chiquita is a very wide beach between two distributary channels of the Colorado Delta (Fig. 1). It is related to the most recent barrier of the four sand barriers recognized from the deltaic plain progradation (Fayó *et al*., 2018).

Pocitos Beach, located within the Anegada Bay (Fig. 1), is facing tidal flats colonized by *Spartina* and *Sarcocornia* (Isla *et al*., 2010; Fig. 2). In the last years, this beach was very affected by the introduction of a reef-building mollusk, *Crassostrea virginica* (Escapa *et al*., 2004). The original sandy beach is changing due to the extended intertidal reefs. A Lagrangian transport model was applied to explain its dynamics, and the exportation of larvae during the summer season (Alvarez *et al*., 2001; Sepúlveda and Olivares, 2013). Segunda Barranca is a narrow open-ocean

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 (DEMs) 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.

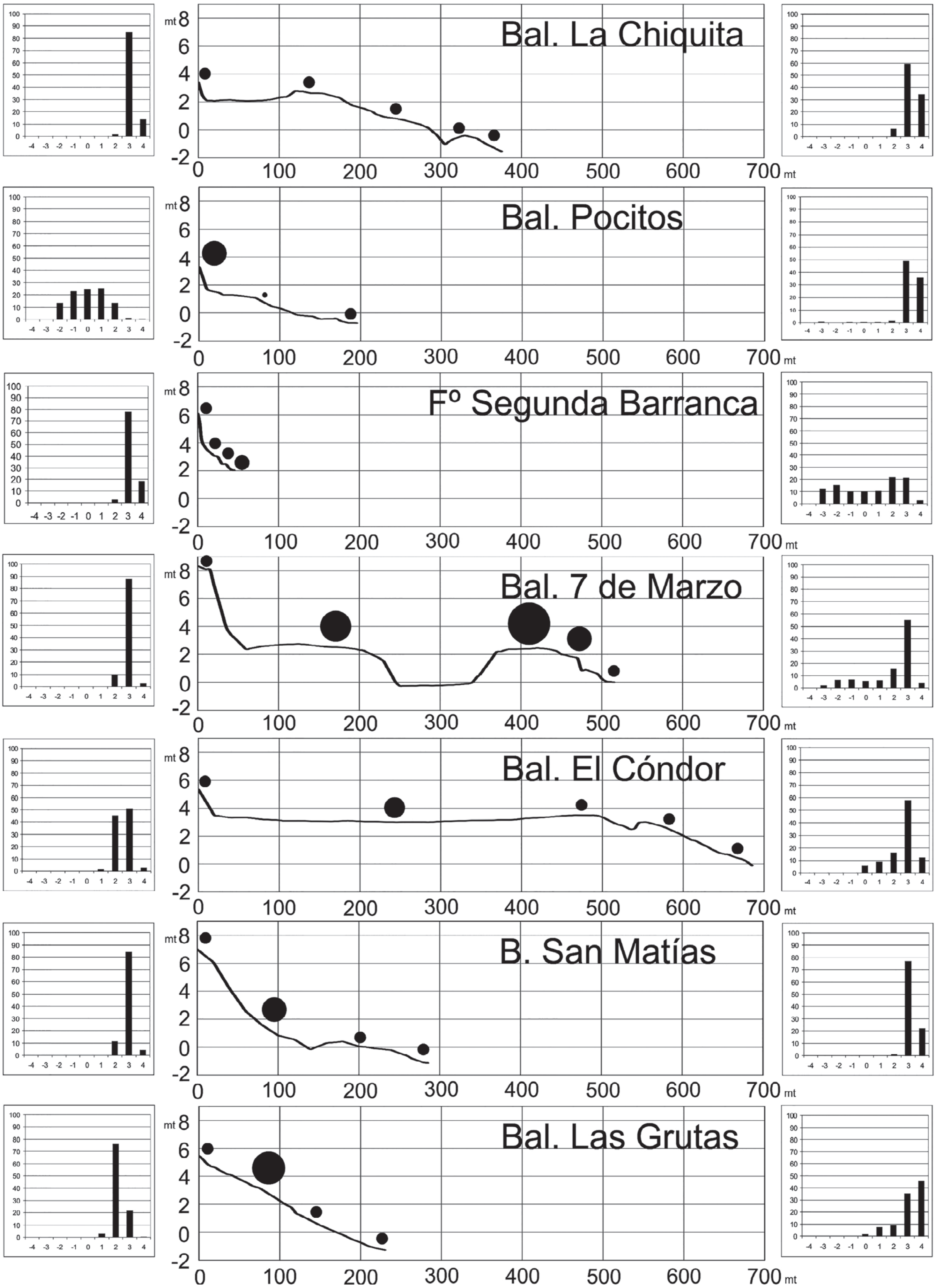

Fig. 3. Grain size distributions (phi units) from the extremes of these wide beaches. Grain-size distributions are represented by circles of different sizes.

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.

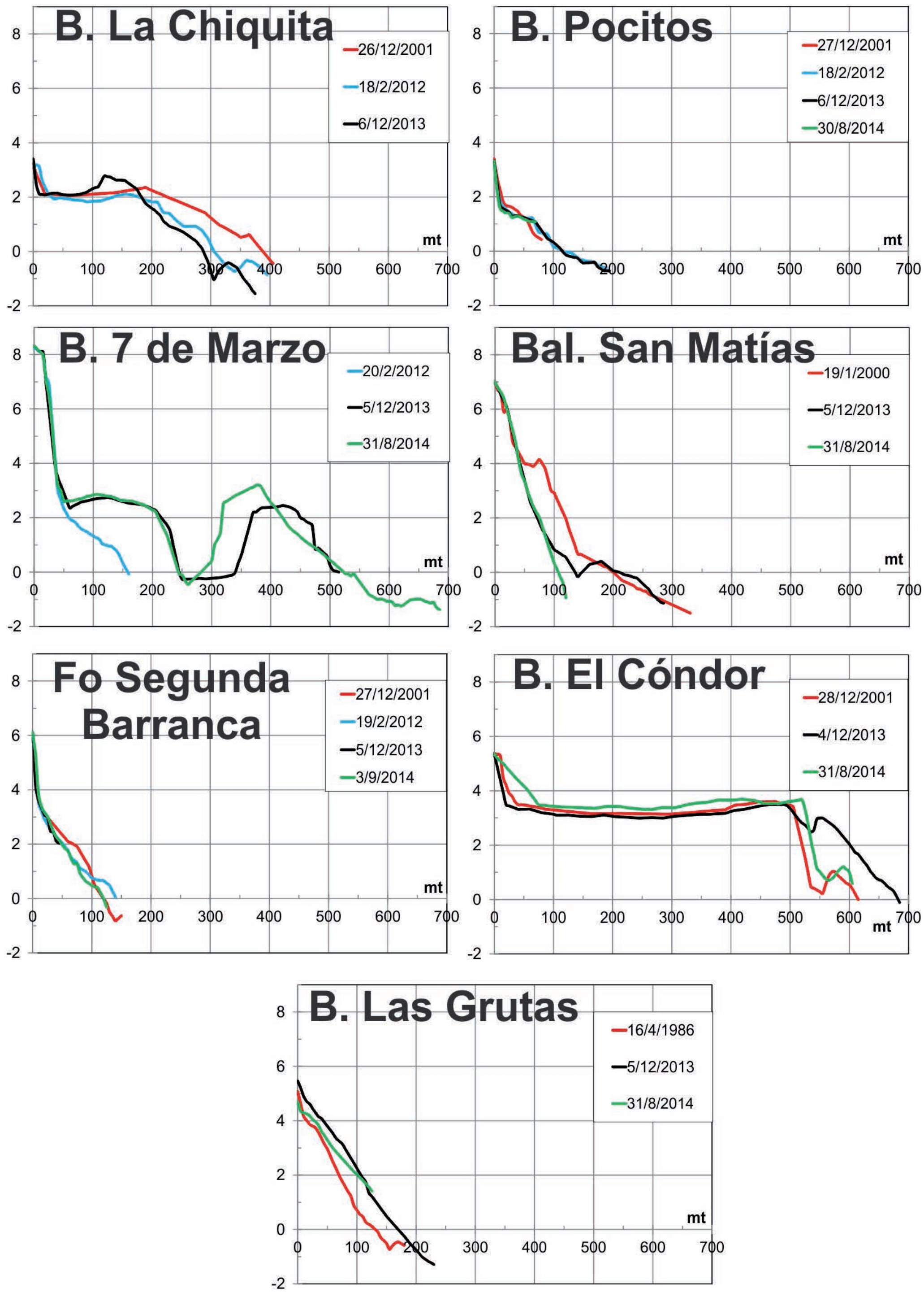

Fig. 4. Morphological variations of the studied beaches. Some beaches (Siete de Marzo, El Cóndor) are significantly affected by estuarine influence.

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 Rio 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

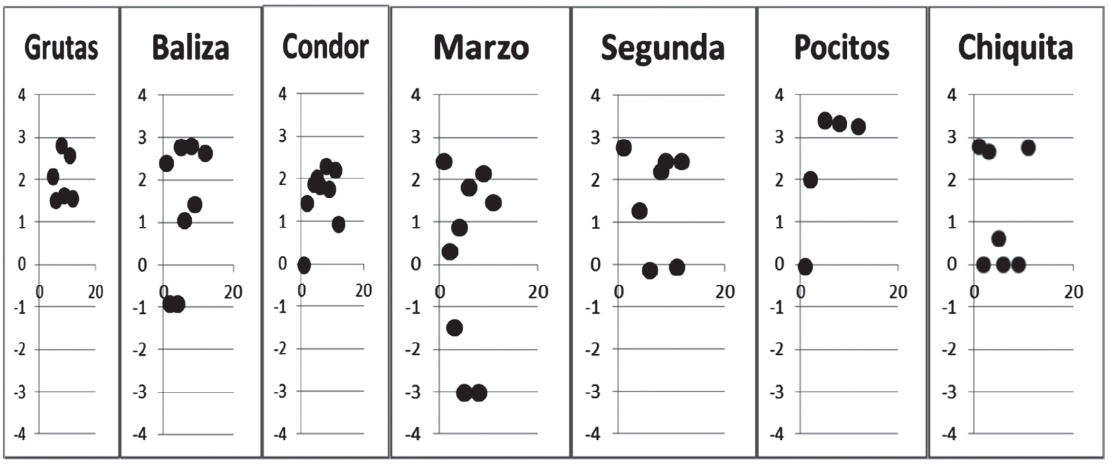

Fig. 5. Grain-size variations (phi units) along different beaches. The Tehuelche Gravels dominate at El Condor and Siete de Marzo beaches.

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 form the Tehuelche Formation (Fig. 5). The western beaches of Rio Negro Province (Las Grutas and Baliza San Matìas) 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).

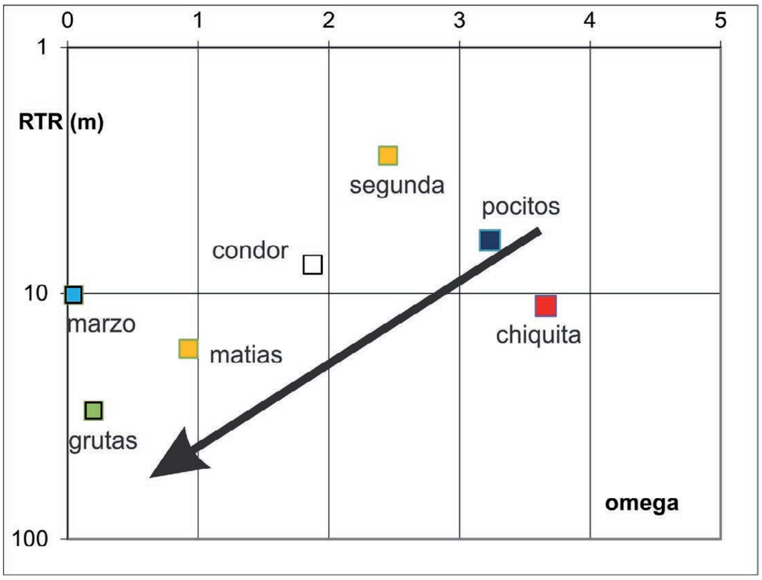

Fig. 6. Omega parameter vs. relative tidal range (modified from Masselink and Short, 1993, Isla *et al*., 2006). The arrow indicates the increase in tidal range towards the western beaches. Wave effects diminished from open-ocean beaches to those located within the San Matías Gulf.

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 (Toffani, 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

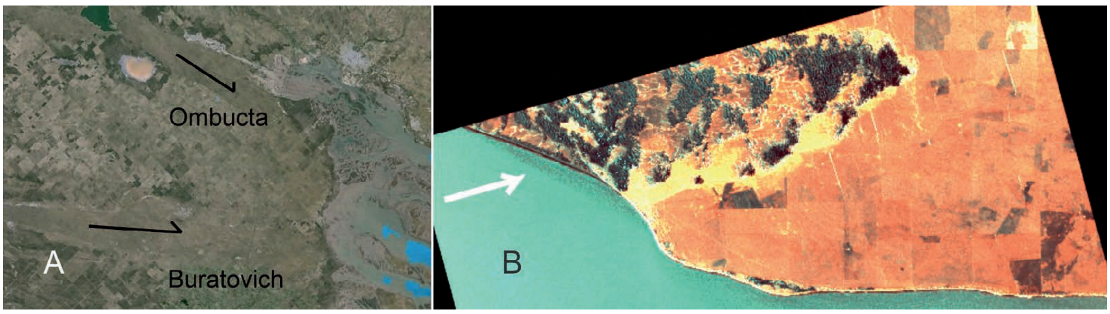

Fig. 7. Different sediment supply paths. A) The Ombucta and Buratovich aeolian corridors supply fine sand from the Colorado River to La Chiquita and Pocitos beaches. B) The sand field of Bahia Creek is originated from sand accumulated at Caleta Los Loros that climbed sandstone-composed cliffs. Arrows indicate wind transport direction.

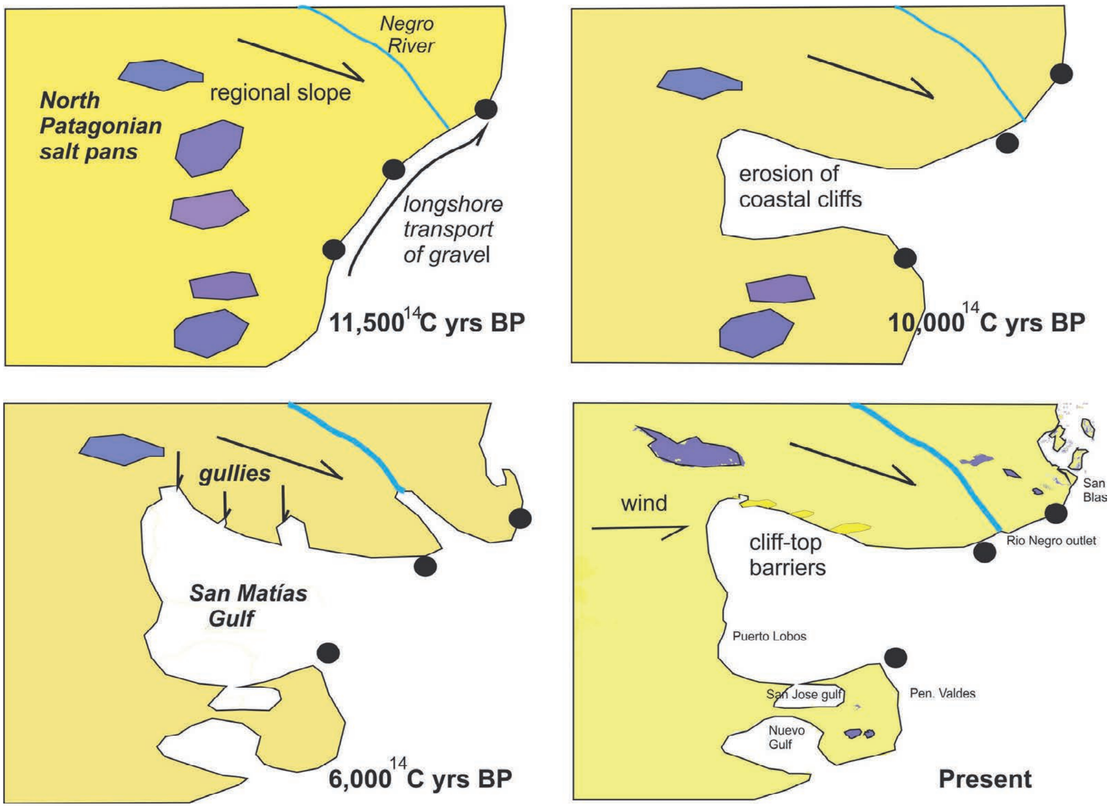

Fig. 8. Evolution of the San Matías Gulf and the related beaches (modified from Toffani and Isla 2022).

Fig. 9. After the storm of July 2009, the beach of Las Grutas lost significant quantity of sand. In 2014 berms were recovered; groundwater seepage dominated during low tide (Isla and Garzo, 2023).

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 concetrations 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.

ACKNOWLEDGEMENTS

Silvina Cardelli helped to survey Las Grutas beach in 1986. Financial support was provided by the PICT 1146/16 about the Evolution of the estuaries of Northern Patagonia. Two reviewers contributed to improve the original manuscript.

REFERENCES

Agosta, E. A., Martin, P. B. and Serio, L. A. 2019. Persistent easterly winds leading to precipitation in the Atlantic Coast of Patagonia. *International Journal of Climatology* 39: 5063-5090. 10.1002/joc.6127

Alvarez, L.I., Cuadrado, D. y Perillo, G..M.E. 2001. Aplicación de un modelo de trazadores lagrangianos en Bahía Anegada, Argentina. *Revista de Biología Marina y Oceanografía* 46 (2): 199-206.

Andreis, R.R. 1965. Petrografía y paleocorrientes de la Formación Río Negro (tramo General Conesa – boca del Río Negro). *Revista del Museo de La Plata*, V, Geología 36: 245-310.

Angulo, R., Fidalgo, M. A., Gómez Peral, M. y Schnack, E. J. 1978. Geología y geomorfología del bajo de San Antonio y alrededores, Provincia de Río Negro. Centro de Investigaciones Científicas de la Provincia de Río Negro. *Estudios y documentos* 8, 32 pp.

Bonuceli, R. S. y Navarte, M. 2017. *Manejo de aguas residuales en Las Grutas (Río Negro): ¿matando a la gallina de los huevos de oro?*. Informe técnico 2, Universidad Nacional del Comahue, Escuela Superior de Ciencis Marinas, 15 pp.

Charó, M. P. 2013. *Caracterización paleoambiental y paleodiversidad malacológica en los depósitos marinos cuaternarios del norte patagónico (sur de Buenos Aires y norte de Río Negro)*. Tesis Doctoral inédita. Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, 309 pp.

Coronato, A. M. J., Coronato, F., Mazzoni, E. and Vazquez, M. 2008. The Physical Geography of Patagonia and Tierra del Fuego. *Developments in Quaternary Science* 11: 13-55.

Cram, J. M. 1978. The influence of continental shelf width on tidal range: paleoceanographic implications. *Journal of Geology* 87: 441-447.

Cortizo, L. C. e Isla, F.I. 2012. Dinámica de la barrera medanosa e islas de barrera de Patagones (Buenos Aires, Argentina). *Latin American Journal of Sedimentology and Basin Analysis* 19 (1): 47-63.

Darwin, C. 1846. *Geological Observations on South America, being the third part of the Geology of the Voyage of the «Beagle», during 1832 to 1836*. London.

Del Rio, J. L., Colado, U. y Gaido, E. S. 1991. Estabilidad y dinámica del delta de reflujo de la boca del Río Negro. *Revista de la Asociación Geológica Argentina* 46 (3-4): 325-332.

del Valle, H. F., Rostagno, C. M., Coronato, F. R., Bouza, P. J. and Blanco, P. D. 2008. Sand dune activity in north-eastern Patagonia. *Journal of Arid Environments* 72: 411-422. 10.1016/j.jaridenv.2007.07.011

Eastman, J. R. 2016. *TerrSet. Geospatial monitoring and modelling system v. 18.2*. Clark Labs, Clark University, 298 pp.

Escandell, A., Espinosa, M. A. e Isla, F. I. 2009. Diatomeas como indicadoras de variaciones de salinidad durante el Holoceno tardío en el Río Negro, Patagonia Norte, Argentina. *Ameghiniana* 46 (3): 461-468.

Escapa, M., Isacch, J. P., Daleo, P., Alberti, J., Iribarne, O., Borges, M., Dos Santos, E. P., Gagliardini, D. A. and Lasta, M. 2004. The distribution and ecological effects of the introduced Paficic oyster Crassostrea gigas (Thunberg, 1793) in Northern Patagonia. *Journal of Shellfish Research* 23 (3): 765-722.

Espinosa, M. and Isla, F. 2011. Diatom and sedimentary record during the Mid-Holocene evolution of the San Blas estuarine complex, Northern Patagonia, Argentina. *Ameghiniana* 48 (4): 411-423.

Favier-Dubois, C. M. and Kokot, R. 2011. Changing scenarios in Bajo de la Quinta (San Matías Gulf, Northern Patagonia, Argentina): Impact of geomorphologic processes in subsistence and human use of coastal habitats. *Quaternary International* 245: 103-110.

Fayó, R., Espinosa, M. A., Vélez-Agudelo, C., Pan, J. and Isla, F. I. 2018. Diatom-based reconstruction of Holocene hydrological changes along the Colorado River Floodplain (northern Patagonia, Argentina). *Journal of Paleolimnology* 60: 427-443.

Fucks E.E., Scalise A.H. y Schnack E.J. 2011. *Evaluación de alternativas para la conservación y manejo del frente costero en Las Grutas*. Informe Consejo Federal de Inversiones. ISBN 978-987-510-099-2. 79 pp.

Fucks, E., Schnack, E. J. y Charó, M. 2012. Aspectos geológicos y geomorfológicos del sector N del Golfo San Matías, Río Negro, Argentina. *Revista de la Sociedad Geológica de España* 25 (1-2): 95-105.

Genchi, S.A., Carbone, M. E., Piccolo, M. C. y Perillo, G. M. E. 2010. Déficit hídrico en San Antonio Oeste, Argentina. *Revista de Climatología* 10: 29-43.

Genchi, S. A., Carbone, M. E., Piccolo, M. C. and Perillo, G. M. 2011. Hydrologic response of the drainage basins that intersect Las Grutas town, Argentina. *Investigaciones geográficas* 75: 23-36.

Guilderson, T. P., Burckle, L., Hemming, S. and Peltier, W. R. 2000. Late Pleistocene sea level variations derived from the Argentine Shelf. *Geochemistry, Geophysics, Geosystems* 1, 2000G000098.

Isla, F. I. 2013. The flooding of San Matías Gulf: the Northern Patagonia sea-level curve. *Geomorphology* 203: 60-65.

Isla, F. I. 2017. Coastal barriers from Argentina: Buenos Aires, Patagonia and Tierra del Fuego. *Quaternary and Environmental Geosciences* 7 (1): 1-9.

Isla, F. I. y Bértola, G. R. 2003. Morfodinámica de las playas meso y micromareales entre Bahía Blanca y Rio Negro. *AAS Revista* 10 (1): 65-74.

Isla, F. I., Bértola, G. R. y Schnack, E. J. 2001. Morfodinámica de playas meso y macromareales de Buenos Aires, Rio Negro y Chubut. *AAS Revista* 8 (1): 51-60.

Isla, F. I. y Bujalesky, G. G. 1995. Tendencias evolutivas y disponibilidad de sedimento en la interpretación de formas costeras: Casos de estudio de la costa argentina. *Revista Asociación Argentina de Sedimentología* 2 (1-2): 75-89.

Isla, F. I., Bujalesky, G. G., Bertola, G. R., Iantanos, N. and Estrada, E. 2006. Typology of Argentine beaches: composition, tidal range and wave energy. *Journal of Coastal Research* SI 39: 375-378.

Isla, F. I., Bujalesky, G. G., Galasso, M. L. and De Francesco, C. G. 2005. Morphology, grain-size and faunistic composition of the macrotidal beaches of Tierra del Fuego, Argentina. *Revista de la Asociación Geológica Argentina* 60 (3): 433-445.

Isla, F. I., Espinosa, M., Gerpe, M., Iantanos, N., Menone, M., Miglioranza, K. S. B., Ondarza, P., González, M., Bertola, G., Aizpún, J.E. and Moreno, V. J. 2010. Patagonian salt marshes: the soil effects on the NDVI response. *Thalassas* 6 (1): 23-31.

Isla, F. I. y Garzo, P. 2023. Playas y pluviales: los impactos de la impermeabilización y el drenaje de barreras medanosas. *Revista MAR. Material de Arquitectura* 1: 72-98.

Isla, F. I. and Isla, M. del P. 2020. Coastal urbanization strategies for resort locations, Argentina. *Revista Geográfica del Sur* 9 (11): 57-66.

Isla, F. I. y Rivero D' Andrea, I. 1993. Procesos retro-tafonómicos en secuencias costeras poco profundas. *Revista Pesquisas* 20 (2): 90-95.

Kana, T. W., Traynum, S.B., Gaudiano, D., Kaczkowski, H.L. and Hair, T. 2013. The physical condition of South Carolina beaches 1980-2010. *Journal of Coastal Research, Special Issue* 69: 61-82.

Kokot, R. R. y Chomnalez, F. 2012. Retroceso de la línea de costa en las Grutas, provincia de Río Negro. *Revista de la Asociación Geológica Argentina* 69 (1): 88-96.

Loon, H. 1967. A climatological study of the atmospheric circulation of the Southern Hemisphere during IGY; part II. *Journal of applied meteorology and climatology* 6 (5): 803-815. DOI: https://doi.org/10.1175/1520-0450

Lucas, A. J., Guerrero, R. A., Mianzán, H. W., Acha, E. M. and Lasta, C. A. 2005. Coastal oceanographic regimes of the Northern Argentine Continental Shelf (34-43°S). *Estuarine, Coastal and Shelf Science* 65 (3): 405-420. https://doi.org/10.1016/j.ecss.2005.06.015

Masselink, G.and Short, A. D. 1993. The effect of tidal range on beach morphodynamics and morphology: a conceptual beach model. *Journal of Coastal Research* 9 (3): 785-800.

Moreira, D., Simionato, C., Dragani, W. and Nuñez, M. 2009. Tidal and residual currents observations at the San Matías and San José gulfs, Northern Patagonia, Argentina. *Journal of Coastal Research* 24 (4): 957-968.

Perillo, G. M. E., Piccolo, M. C. and Marcovecchio, J. 2006 Coastal oceanography of the Western South Atlantic continental shelf (33 to 55° S). In Robinson, A. and Brink, K. H. (Eds.) *The Sea. The Global Coastal Ocean: Interdisciplinary Regional Studies and Syntheses*. Volume 14 – Part A, Ch. 9: 295-328. Harvard University Press (ISBN-0-674-01527-4).

Piola, A. R. y Scasso, M A. 1988. Circulación en el Golfo San Matías. *Geoacta* 15 (1): 33-51.

Rutter, N., Schnack, E. J., Fasano, J. L., Isla, F. I., Del Rio, L. and Radtke, U. 1989. Correlation and dating of Quaternary littoral zones along the Patagonian coast, Argentina. *Quaternary Science Reviews* 8: 213-234.

Sander, L., Pejrup, M., Murray, A. S., Perillo, G.M. E., Raniolo, L. A. and Fruergaard, M. 2018. Chronology and Late-Holocene evolution of Caleta de los Loros, NE Patagonia, Argentina. *The Holocene* 28 (8): 1276- 1287.

Schillizzi, R., Luna, L. y Falco, J. I. 2010. Estructuras de deformación (sismitas?) en la Formación Río Negro, Provincia de Río Negro, Argentina. *Latin American Journal of Sedimentology and Basin Analysis* 17 (1): 17-32.

Sepúlveda, H. H. y Olivares, G. 2013. Comentarios a “Aplicación de un modelo de trazadores lagrangianos en Bahía Anegada, Argentina” de Alvarez et al. (2011). *Revista de Biología Marina y Oceanografía* 48 (1): 199-201.

Short, A. D. and Wright, L. D. 1984. Morphodynamics of high energy beaches: an Australian perspective. In Thom, B. G. (Ed.) *Coastal Geomorphology in Australia* 3: 43-68. Academic Press.

Spalletti, L. A. e Isla, F. I. 2003. Evolución del delta del Río Colorado (“Colú Leuvú”), Provincia de Buenos Aires, República Argentina. *AAS Revista* 10: 23-27.

Toffani, M., 2020. Estudio morfodinámico de las dunas del campo eólico de Bahía Creek, Río Negro, Patagonia Argentina. *Latin American Journal of Sedimentology and Basin Analysis* 27 (1): 55-79.

Toffani, M., Caselli, A. T. y Lothari Inaudi, L. D. 2020. Estudio de los acantilados activos y del campo de dunas de Bahía Creek, Río Negro, Argentina, como base para la elaboración de un mapa de peligro geológico. *Revista de la Asociación Geológica Argentina* 77 (1): 31-46.

Toffani, M. and Isla, F. I. 2022. Evolution and composition of cliff-top barriers at the northern shore of San Matías Gulf, Patagonia, Argentina. *Journal of South American Earth Sciences* 119: 104033.

Vara, C. D. y Mazio, C. A. 1983. *Corrientes de marea en el Golfo San Matías*. SHN, Depto. Oceanografia, informe técnico s/n, 1-3.

Weiler, N. E. 1983. Rasgos morfológicos evolutivos del sector costanero comprendido entre Bahía Verde e Isla Gaviota, Provincia de Buenos Aires. *Revista de la Asociación Geológica Argentina* 38: 392-404.

Weiler, N. E. 2000. *Evolución de los depósitos litorales en Bahía Anegada, Provincia de Buenos Aires, durante el Cuaternario tardío*. Tesis Doctoral inédita. Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, 184 pp. Disponible en http://digital.bl.fcen.uba.ar/Download/Tesis/Tesis_3340_Weiler.pdf

Worner, S., Dragani, W. C., Echevarria, E. R., Carrasco, M. and Barón, P. J. 2019. An estimation of the possible migration path of the Pacific Oyster (*Crassostrea gigas*) along the northern coast of Patagonia. *Estuaries and Coasts* 42: 806-821.

Zavala, C. y Freije, H. 2005. Geología de los acantilados. En: Masera, R., Lew, J. y Serra Peirano, G. (Eds.) *Las mesetas patagónicas que caen al mar: la costa rionegrina. Viedma, Argentina*. Gobierno de Río Negro, 187-197.