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Chronology and late-Holocene evolution of Caleta de los Loros, NE Patagonia, Argentina

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Abstract

Geomorphological and sedimentary records of Holocene coastal deposits may serve as archives for the local reconstruction of trends in coastal evolution and of the key forcing parameters controlling long-term change. We here present new observations on the sedimentology, chronology, and surface properties of a coupled beach ridge and coastal lagoon system located on the northern shore of San Matías Gulf, NE Patagonia, Argentina. The study is based on remotely sensed data, sediment cores, and a large number of samples dated using optically stimulated luminescence (OSL). The field site is located in a topographical depression within a cliffed shoreline composed of friable sand and gravel stones. The oldest preserved lagoonal deposits formed in the protected inner part of the system *c.* 2300 years ago. An up to 4-km-wide strandplain prograded rapidly between *c.* 1000 and 500 years in the more exposed western part of the system. Lagoonal deposition occurred primarily during the last 500 years. The chronology and spatial arrangement of landforms appear to result from a switch-over in sediment delivery probably caused by local implications of major shifts in climate regime. Even though we were not able to identify or benchmark the precise triggers of geomorphological change at Caleta de los Loros, our study presents an example of the potential importance of environmental changes on the rapid and non-linear development of coastal sedimentary systems.

Keywords

coastal deposits, coastal geomorphology, late-Holocene climate variability, optically stimulated luminescence, sediment supply, sedimentary archives, shoreline change

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Introduction

Climate forcing, relative sea level, and sediment supply are key parameters determining the long-term evolution of coastal sedimentary environments (Fruergaard et al., 2013, 2015; Hede et al., 2015; Hein et al., 2013; Oliver et al., 2017; Plater et al., 2009; Poirier et al., 2017; Sander et al., 2015a; Sorrel et al., 2012). It has been shown that natural systems may react quickly and sensitively to changes in these parameters (e.g. Billeaud et al., 2009; Fruergaard et al., 2013). An analysis of the spatial arrangement of coastal landforms and the chronology and characteristics of the associated sedimentary deposits may thus provide information on the type and magnitude of external forcing controlling coastal evolution over time (Milana and Kröhling, 2015; Poirier et al., 2017; Sander et al., 2015a, 2016). Coastal lagoons and prograded clastic barriers are two important depositional environments of global occurrence (Pilkey et al., 2009; Scheffers et al., 2012; Tamura, 2012). Lagoons and beach ridges often occur as coupled systems and the information from both sedimentary archives is complementary and thus favors a more complete reconstruction of past coastal dynamics (Fruergaard et al., 2017; Sander et al., 2015b). Establishing an improved understanding of past processes, drivers, and rates of coastal morphological change is very important to address pressing issues in future human-environmental relations.

Coastal lagoons and prograded barriers exist in many locations along the coast of Patagonia, and a large number of studies on the late Quaternary dynamics of coastal environments have been conducted (e.g. Aguirre, 2003; Pedoja et al., 2011; Ribolini et al., 2011; Schellmann and Radtke, 2010; Zanchetta et al., 2014). The age control in these studies relies on the dating of marine mollusk shells. This dating approach is widely used in the study of marine environments, but is unreliable in dynamic coastal settings (because of reworking) as well as in areas with

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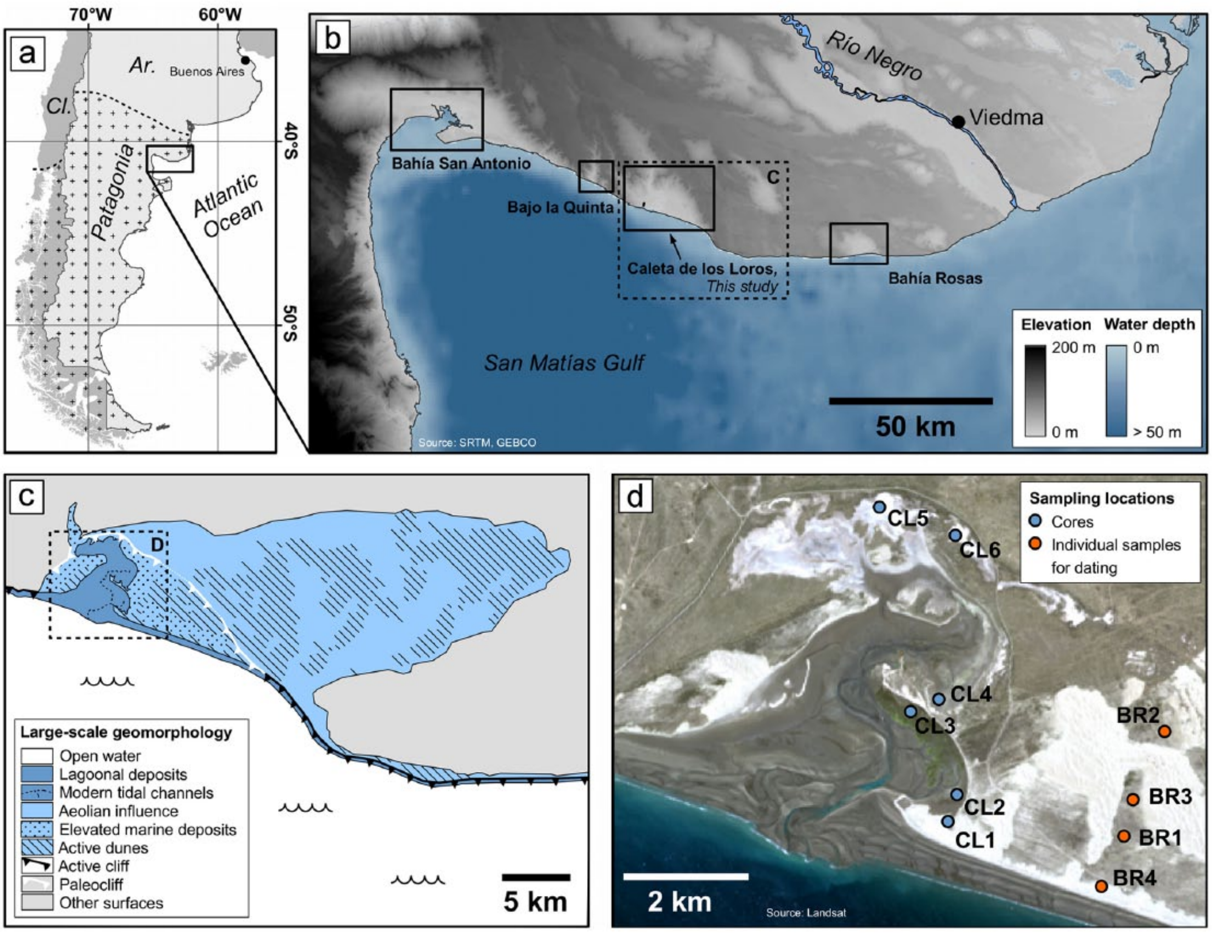

Figure 1. Caleta de los Loros is a coupled beach-ridge/lagoon system located in NE Patagonia, Argentina (a) and positioned in a topographic depression within the cliffed shoreline of northern San Matías Gulf (b). The field site is composed of a modern beach, active spits, and a lagoon system located adjacent to elevated marine deposits. The area is characterized by active and paleocliff sections as well as by eolian processes and a large dune system migrating in an ENE direction (c). Six cores from the modern lagoon and four near-surface samples from the prograded beach-ridge system were retrieved for this study (d). Ar.: Argentina; Cl.: Chile.

variable and unknown marine reservoir ages (Favier-Dubois, 2009; Gómez et al., 2008).

A previously unstudied field site featuring a coastal lagoon and a beach-ridge system was chosen for our investigation (Figure 1). The aims of this study are to (1) reconstruct the Holocene coastal evolution of Caleta de los Loros in NW Patagonia; (2) discuss the evolution of the coastal system in relation to changes in forcing conditions, for example, sea level and climate; and (3) compare the new data with the local archeological record.

Area of study

Caleta de los Loros (41°01′ S, 64°05′ W) is located on the northern shore of San Matías Gulf in the Argentinean Province of Río Negro and is composed of a wide beach-ridge system (*c.* 34 km^2), dominated by waves and longshore sediment transport, and a tide-dominated coastal lagoon (*c.* 28 km^2). An important third sedimentary environment is a large transgressive dune system (*c.* 300 km^2; Figure 1c).

The current climate on the northern shore of San Matías Gulf is characterized by semi-arid and temperate conditions with an annual mean temperature of 12°C and an annual precipitation of between 200 and 350 mm with a gradual decrease in the total amounts from east to west (Labraga and Villalba, 2009; Martínez et al., 2013; Schäbitz, 2003). The northern shore of San Matías Gulf lies in a transition zone under the influence of two atmospheric circulation systems, which locally determine marked changes in the available humidity, temperature and wind regime over time (Piovano et al., 2009).

Caleta de los Loros formed in a topographical depression incised by fluvial processes into the underlying pre-Holocene sedimentary deposits and is located within a stretch of cliffed coastline (Del Río et al., 2007; Sander et al., 2015c; Figure 1b). The geology of the area is dominated by sedimentary rocks of primarily fluvial origin, which formed in association with the orogeny of the Patagonian Andes and the shifting of the location of the Negro River since the Miocene (Del Río and Colado, 1999; Gélos et al., 1992; Ramos and Ghiglione, 2008). The modern cliffs east of Caleta de los Loros have elevations of between 10 and 55 m and presently retreat at an average rate of 0.8 m/yr (Del Río et al., 2007). The origin and the friable character of the deposits determine the high availability of sand- to gravel-sized material in the area (Gélos et al., 1992; Martínez and Kutschker, 2011). San Matías Gulf itself is a more than 200 m deep basin separated from the open Atlantic Ocean by a sill (Isla, 2013; Moreira et al., 2011; Perillo et al., 2006).

Holocene sea-level change along the coast of Argentinean Patagonia is in broad terms characterized by a marked eustatic rise since the last glacial maximum (Guilderson et al., 2000) reaching a relative highstand around 7000–6000 years ago (Cavalotto et al., 2004; Gómez and Perillo, 1995; Gonzalez and Weiler, 1994; Perillo, 1995; Schellmann and Radtke, 2010; Vilanova et al., 2010). The rates of post-glacial isostatic and neotectonic uplift movements of Patagonia are in the order of *c.* 0.1

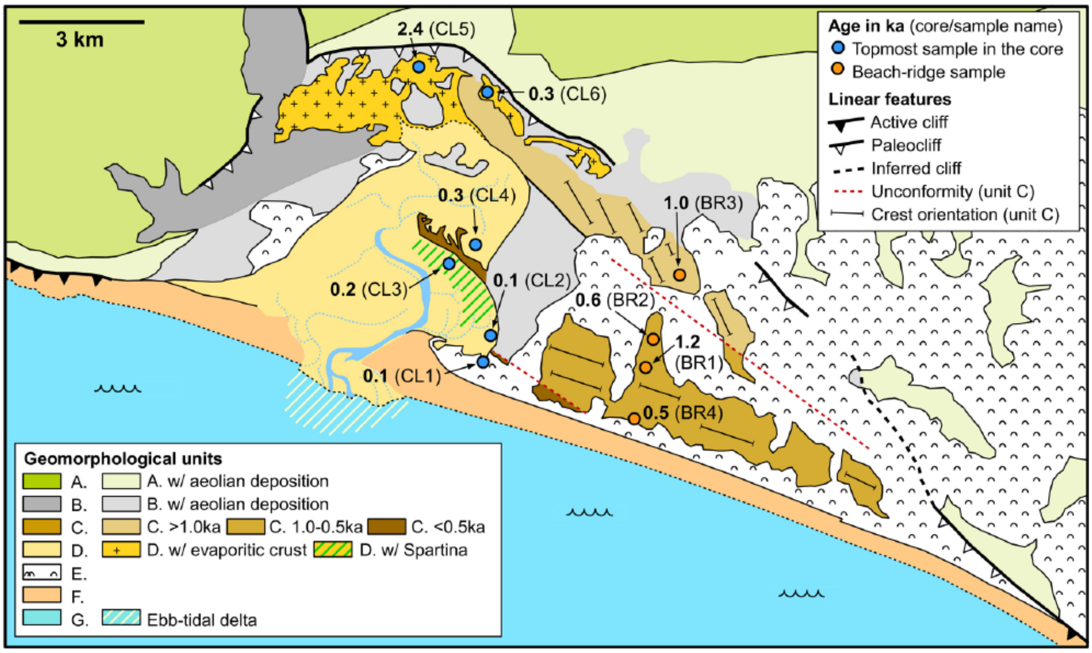

Figure 2. Spatial distribution of modern geomorphological units and the OSL ages determined for the near-surface deposits. Legend: (A) Elevated areas uninfluenced by marine or eolian geomorphic processes, (B) areas with ambiguous morphological indication, (C) beach ridges and spits, (D) lagoon environment, (E) areas dominated by eolian processes, (F) exposed shoreline, and (G) subtidal areas.

mm/yr (Codignotto et al., 1992; Rostami et al., 2000), leading to a falling relative sea level (RSL) since the mid-Holocene highstand. The regional rates of surface elevation change are regionally variable (Codignotto et al., 1992; Pedoja et al., 2011).

The modern tides at Caleta de los Loros are semidiurnal and have a mean amplitude of *c.* 6 m (Servicio de Hidrografía Naval (SHN), 2017). Regional-scale model results suggest an annual average wave height of *c.* 0.5 mm southern to south-eastern direction (Reguero et al., 2013). Swell waves in excess of 6 m approaching from the south have been recorded for the Argentinean coast (Lanfredi et al., 1998).

Materials and methods

Geodata

Information on the regional geographic setting and the main morphological units at the field site was retrieved from a Landsat satellite image time-series (1973–2015) and was analyzed in conjunction with surface elevation data based on the SRTM-*DSM* (Farr et al., 2007; Hirt et al., 2010) and bathymetric data obtained from the GEBCO dataset (IOC and BODC, 2003). For a detailed description of data properties, processing procedures, and interpretation, see Sander et al. (2015c). A ground-truthing of the observations in the inter- and supratidal areas was conducted during the main field campaign in March and April 2013.

Cores

Six vibracores were taken within the lagoon environment using a custom-built vibracore system and aluminum tubes with an external diameter of 8 cm and a wall thickness of 2 mm. The coring sites were chosen at protected locations on sandflats of upper intertidal and supratidal environments, where least influence by tidal channel incision and the highest preservation potential were expected (cf. Fruergaard et al., 2011; Figures 1d and 2). The elevation of the coring sites was assessed with a Sokkia Radian GPS-RTK System (Global Positioning System – Real Time Kinematic; vertical accuracy: ±2 cm) using a geodetic reference point (Argentinean National Geographical Survey) located on the western side of Caleta de los Loros. The cores (CL1, CL3-6) were cut into shorter pieces for transport and *c.* 2 cm of core material were lost on each side of each cut (cf. Figure 3). The cores were opened in a sediment laboratory under subdued red-light conditions and described in detail. All cores were sampled for grain-size analysis at intervals of *c.* 10 cm or less. The <1.4 mm fraction of the samples was analyzed using a Malvern Mastersizer 2000 laser-diffraction particle sizer. The presence of material >1.4 mm was noted in the log sheets. Mechanically induced compaction in the cores was corrected for linearly and all elevations throughout the article are relative to WGS84 (World Geodetic System reference ellipsoid).

Chronology

Because of the dynamic hydrographic conditions and the dominance of sand-sized deposits in the area, optically stimulated luminescence (OSL) dating was chosen for the establishment of age control. A total of 24 samples were taken from the lagoon cores, chosen on the basis of interpreted sedimentary units (Figure 3). Four additional samples were taken from the beach-ridge system (locations based on morphology) and one additional sample was taken from the modern beach.

Material was sampled directly from the cores and split into two subsamples: one intended for luminescence measurements and one for radionuclide analysis. The sample for luminescence measurements was wet-sieved and the 180−250 µm grain-size fraction was extracted. Routine chemical treatment was used to obtain a clean quartz extract; this first involved HCl (10%) and H_2O_2 (10%) to remove carbonates and organic material, followed by treatment with HF (40%) for 40 min to remove unwanted feldspars, and finally HCl (10%) to remove any remaining soluble fluorides (Aitken, 1985). The purity of the quartz extract was investigated using infrared (IR) stimulation. A single layer of the quartz grains was mounted on 9.7 mm stainless steel disks using silicone oil. The aliquots were measured in automated Risø TL/OSL luminescence readers (Bøtter-Jensen et al., 2000, 2002) and a single aliquot regenerative dose (SAR) protocol (200°C preheat, 180°C cut heat) was used to obtain the equivalent dose (D_e) (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006). The

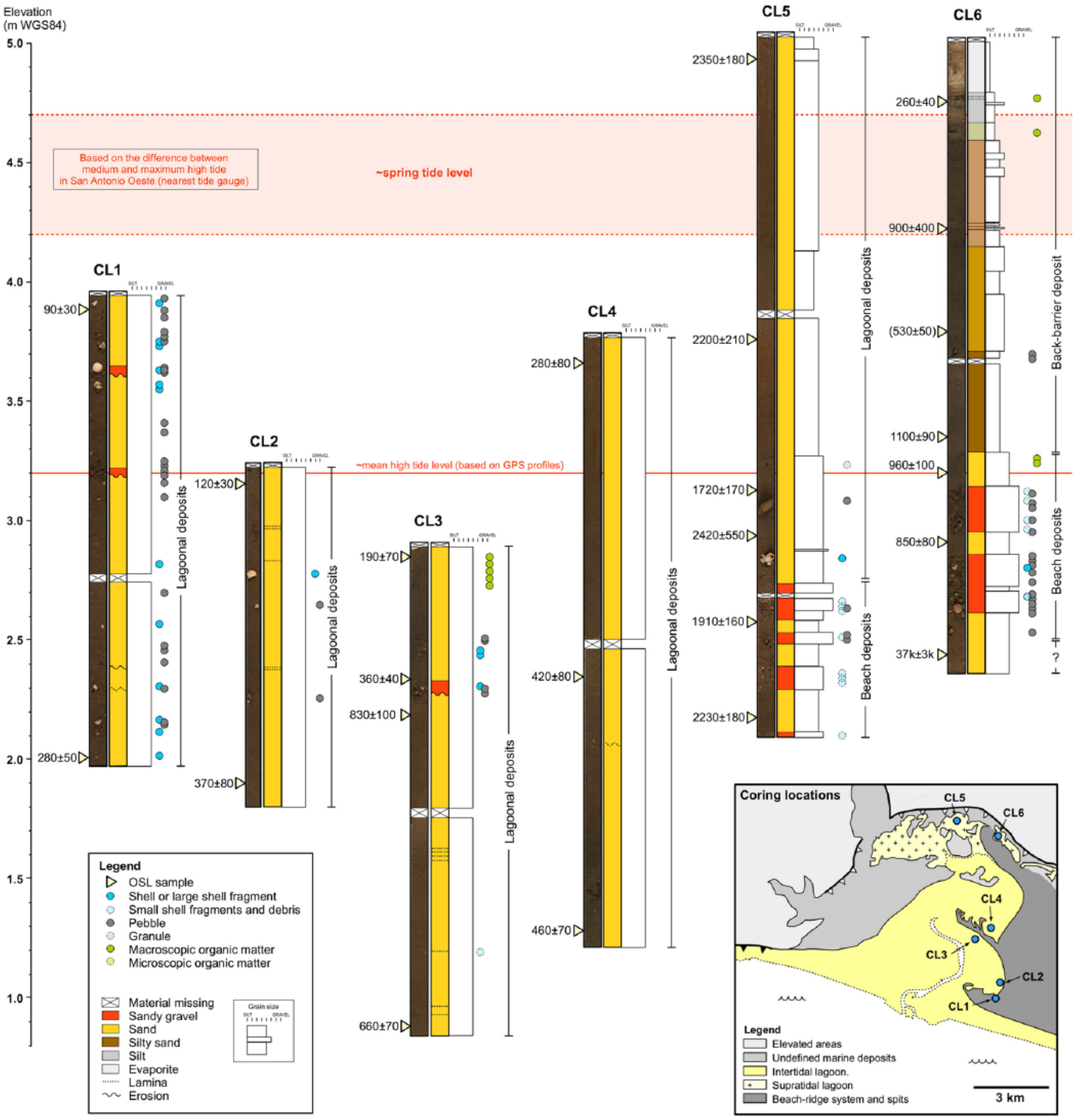

Figure 3. An overview of the sedimentology of the six vibracores retrieved on the eastern side of the lagoon (see Figure 1d for location). Each core is represented by a core photo, the core description, and grain-size distribution, along with the content of coarse shell material, pebbles, and organic matter. The OSL ages are given to the left of each core (age reversals in parentheses). Note that the distance between the core logs is not to scale.

applicability of our SAR protocol was examined using a dose recovery test on laboratory-bleached aliquots of all samples from the lagoon core set; the average ratio of the measured to given dose was 0.98 ± 0.04 (n = 57). Although the relative standard deviation in these data is large (~30%), presumably because of low signal intensities, the average is consistent with unity and confirms that our protocol can accurately measure a known dose given before any prior thermal treatment.

The other subsample was used for dosimetry measurements. About 200 g of sediment was dried, homogenized by grinding and cast in wax in a cup-shaped form to provide a fixed counting geometry. After storing for 3 weeks to allow buildup of ^{222}Rn, the radionuclide concentrations were measured using high-resolution gamma ray spectrometers (Murray et al., 1987). The measured radionuclide concentrations were converted to dose rates using conversion factors from Guérin et al. (2011). Cosmic ray dose rates are based on Prescott and Hutton (1994) and known depth below modern surface. Saturated water contents were measured in the laboratory, and dose rates were calculated assuming that all lagoonal samples were fully water saturated throughout burial. The measured field water content was used to derive the dose rates for the beach and beach ridge samples. All ages are reported relative to the year 2013 CE (year of sampling) at a confidence level of 68%.

Results and interpretations

Modern geomorphological units

Seven distinct geomorphological units (Figure 2) were outlined based on the surface properties observed in the available geodata and are supplemented by information obtained in the field. These units and their modern spatial arrangement are presented in the following subsections.

Elevated areas uninfluenced by marine or eolian geomorphic processes (A). In places where an eolian cover is absent or thin, the SRTM data allows outlining sections of paleo cliffs located in the distal parts of both the lagoon and the beach-ridge system (Figures 1c and 2). The orientation of this apparent break in topography is aligned with the active cliffs on the modern shoreline.

Areas with ambiguous morphological indication (B). The available geodata reveal little information about the morphological properties of these areas. Some parts are covered by remnants of eolian landforms. From the elevation data, these areas are located below the foot of the paleo-cliff sections and above the modern spring tidal level, thus suggesting a marine origin for the deposits.

Beach ridges and spits (C). An up to 4-km-wide beach-ridge system covering an area of *c.* 34 km^2 is located on the eastern side of Caleta de los Loros. The position of these wave-built deposits in relation to the tidal inlet of the lagoon suggests a large supply of sediment by longshore drift from the east (cf. Boyd et al., 1992). Most of the visible ridges within the main system have a sub-parallel orientation in relation to the modern shoreline (*c.* 110°). The crest orientation of the innermost ridges, however, is more oblique (*c.* 160°). The transition between these two beach ridge sets is characterized by clear unconformities. Three distinct spit systems reach out into the lagoon environment. The most landward spit is aligned with the most landward beach ridges and the most seaward spit is aligned with the modern beach. Both spits are rather wide and uniform. The most seaward spit is separated from the main beach ridge set by a marked unconformity. The central spit is, in contrast, characterized by multiple smaller, welded, or partly cannibalized hooks. The orientation of the central spit conforms with the orientation of the inner beaches of the lagoon.

Lagoon environment (D). The modern lagoon covers an area of *c.* 20 km^2 and is composed of an intertidal zone (*c.* 12 km^2) and a protected inner zone located above mean spring-tide elevations (*c.* 8 km^2). The geomorphology of the intertidal part is dominated by a single main tidal channel that connects several smaller tributaries with the tidal inlet. Over the 40-year time-span of satellite-image observation, the spatial arrangement of tidal landforms has remained relatively stable. Most areas are dominated by sandy surface deposits with a locally increased content of shells and other organic debris. A larger area south of the central spit is covered by a dense meadow of *Spartina* spp. The supratidal parts of the system are characterized by a flat topography and a high reflectance due to the formation of evaporitic crusts. Microbial mats were observed in the most restricted parts of the lagoon. Pioneer vegetation (such as *Salicornia* spp.) is found along the uppermost fringe of these supratidal flats.

Areas dominated by eolian processes (E). A large dune system with a length of *c.* 36 km and a width of 5–14 km stretches into an ENE direction from the source area of sediment at Caleta de los Loros (Figure 1c). The dune front moves presently at an average rate of *c.* 10 m/yr. The elongated shape of the dune field and the orientation of individual dune crests suggest that ENE is the dominating direction of eolian mass transport.

Exposed shoreline (F). The modern shoreline of Caleta de los Loros is characterized by gently inclined beaches. They are up to *c.* 500 m wide during low tide and are characterized by a bar and trough morphology in most Landsat images, suggesting extended periods of constructive wave conditions.

Subtidal areas (G). A dynamic ebb-tidal delta has formed offshore from the inlet of the lagoon and is reflected in the Landsat images by breaking waves in the surf zone.

Beach-ridge system: Field observations and age control

The modern beach and the beach-ridge system are characterized by mixed-sediment conditions composed of sand- and pebble-sized deposits with abundant shell material. Although the orientations of the different beach-ridge sets can be identified in the Landsat data, the ridges are not apparent in the field. Deflation has increased the pebble-sized material at the surface of the ridges, compared to the underlying deposits. GPS-RTK elevations were measured along two transects across the main direction of ridge orientation, and the data reveal an almost flat topography in the outer parts of the system, while regular ridges are visible in the inner parts.

Four samples for OSL dating were taken between 0.3 and 0.5 m below the present surface and yielded ages of 1000 ± 110 years in the inner part of the beach-ridge system, 1160 ± 110 and 630 ± 90 years about halfway to the modern shoreline and 490 ± 50 years behind the modern foredune ridge. These dates constrain the period of beach-ridge development to between 1300 and 400 years.

Lagoon deposits: Sedimentology and age control

Six cores were retrieved in proximity to the spits on the eastern side of the lagoon (see Figures 1d, 2, and 3 and Table 1 for overview and orientation).

Core CL1. This core was taken in a small side-basin of the lagoon on the inner side of the most seaward spit at an elevation of 4.0 m, slightly above the observed mean high tide level during the field campaign. The surface was soft, wet, and weakly compacted. Small embryonic dunes are observed both within and around the basin. The sediment in the 1.9-m-long core consists mostly of fine- to medium-grained sand (median: 254 µm; standard deviation (SD): 31 µm). Pebbles, mollusk shells, and shell fragments are present throughout the core, but are not evenly distributed.

Two samples were taken for OSL dating and yielded ages of 90 ± 30 years at the top of the core and 280 ± 50 years at its bottom.

Core CL2. The core was taken on a sandflat at the eastern side of the lagoon. The surface is characterized by small wave ripples (crest spacing: 10–20 cm) and weak compaction. The top of the 1.3-m core lies at an elevation of 3.2 m. Grain size and composition are homogeneous throughout (median: 237 µm; SD: 8 µm) with few shell fragments or pebbles. Except for five dark laminae, the core is massive and does not show any physical and biological structure.

Two samples provided ages of 120 ± 30 years at the top of the core and 370 ± 80 years at the bottom.

Core CL3. The core was taken close to the central spit on a sandflat covered by cordgrass (*Spartina* spp.). The top of the 2.0-m-long core lies at an elevation of 2.9 m and the core is 2.0 m long. Meandering tidal channels of <1 m in width are found on the vegetated sandflats, and the channel-bed surfaces are made up of sand to pebble-sized material, with sand forming the dominant fraction. All of the core material is composed of fine-to-medium grained sand (median: 235 µm; SD: 28 µm). At an elevation of 2.3 m, a thin layer of pebble-sized material in a fine- to medium-grained sand matrix is observed.

Four samples were dated from core CL3. The topmost sample lies close to the surface and was dated to 190 ± 70 years, the lowermost sample close to the bottom of the core was dated to 660 ± 70 years. The material above the channel lag was dated to 360 ± 40 years, while the material below yielded an age of 830 ± 100 years.

Table 1. Overview of optically stimulated luminescence ages from Caleta de los Loros.

Sample code	Laboratory code	Elevation, m (WGS84)	Age, years	Dose, Gy	*n*	Dose rate, Gy/kyr	Water content, %
CL1-1	Risø 145501	3.9	90 ± 30	0.13 ± 0.04	13	1.51 ± 0.06	48
CL1-2	Risø 145502	2.0	280 ± 50	0.52 ± 0.08	17	1.84 ± 0.07	29
CL2-1	Risø 145503	3.2	120 ± 30	0.20 ± 0.05	15	1.68 ± 0.07	31
CL2-2	Risø 145504	1.9	370 ± 80	0.66 ± 0.14	21	1.80 ± 0.07	28
CL3-1	Risø 145505	2.9	190 ± 70	0.31 ± 0.12	8	1.69 ± 0.07	30
CL3-2	Risø 145506	2.3	360 ± 40	0.67 ± 0.07	24	1.86 ± 0.07	28
CL3-3	Risø 145507	2.2	830 ± 100	1.34 ± 0.14	21	1.61 ± 0.06	33
CL3-4	Risø 145508	0.9	660 ± 70	1.15 ± 0.10	22	1.73 ± 0.07	38
CL4-1	Risø 145509	3.7	280 ± 80	0.51 ± 0.14	17	1.83 ± 0.07	30
CL4-2	Risø 145510	2.4	420 ± 80	0.77 ± 0.15	21	1.83 ± 0.07	34
CL4-3	Risø 145511	1.3	460 ± 70	0.94 ± 0.13	22	2.04 ± 0.08	34
CL5-1	Risø 145519	4.9	2350 ± 180	3.64 ± 0.22	24	1.55 ± 0.07	34
CL5-2	Risø 145520	3.8	2200 ± 210	4.19 ± 0.37	23	1.91 ± 0.07	33
CL5-3	Risø 145521	3.1	1720 ± 170	3.61 ± 0.31	22	2.09 ± 0.08	28
CL5-4	Risø 145522	2.9	2420 ± 510	3.47 ± 0.77	12	1.43 ± 0.07	29
CL5-5	Risø 145523	2.6	1910 ± 160	4.39 ± 0.32	24	2.29 ± 0.09	21
CL5-6	Risø 145524	2.2	2230 ± 170	4.43 ± 0.30	22	1.99 ± 0.08	30
CL6-1	Risø 145512	4.8	260 ± 40	0.31 ± 0.04	22	1.18 ± 0.07	55
CL6-2	Risø 145513	4.2	900 ± 400	1.31 ± 0.58	16	1.46 ± 0.05	40
CL6-3	Risø 145514	3.8	530 ± 50[a]	0.93 ± 0.08	14	1.74 ± 0.07	31
CL6-4	Risø 145515	3.4	1100 ± 90	2.21 ± 0.16	24	2.02 ± 0.07	38
CL6-5	Risø 145516	3.2	960 ± 100	1.69 ± 0.17	21	1.76 ± 0.07	27
CL6-6	Risø 145517	2.9	850 ± 80	1.69 ± 0.15	23	1.99 ± 0.08	29
CL6-7	Risø 145518	2.3	37000 ± 3000	71.67 ± 5.27	24	1.94 ± 0.08	24
BR-1	Risø 141203	7.8	1160 ± 110	2.67 ± 0.23	23	2.31 ± 0.10	14
BR-2	Risø 141204	8.4	630 ± 90	1.66 ± 0.21	32	2.65 ± 0.12	12
BR-3	Risø 141205	10.2	1000 ± 110	2.34 ± 0.24	31	2.34 ± 0.10	14
BR-4	Risø 141206	5.9	490 ± 50	1.27 ± 0.10	34	2.57 ± 0.11	14
CL beach	Risø 135501	0.08[b]	0.009 ± 0.003	0.016 ± 0.005	44	1.90 ± 0.08	28

[a]Age reversal.
[b]Depth below surface, in meters.

Core CL4. This 2.5-m-long core is located on the landward side of the central spit system, at an elevation of 3.8 m. The surface is compact and not vegetated. The deposits in the core are almost exclusively composed of homogeneous fine- to medium-grained sand (median: 257 µm; SD: 17 µm) and no sedimentary structures are visible.

Three samples were taken for age determination. The top of the core was dated to 280 ± 80 years, while the bottom was dated to 460 ± 70 years. A third sample in the middle of the core yielded an age of 420 ± 80 years.

Core CL5. This 2.9-m-long core is located in the innermost parts of the lagoon, at an elevation of 5.1 m. The coring site is located *c.* 0.4 m above the average spring tide level and is thus only occasionally flooded in wind-enhanced high tides. There is slight indication of root penetration in the upper 0.4 m of the core. All sediment in the top 1.6 m of the core (between core top and 3.3 m) is composed of fine- to very fine-grained sand (median: 139 µm; SD: 28 µm). Between 3.3 and 2.8 m, a slight upward-fining trend can be observed. The lowermost 0.8 m of the core consists of coarser and layered material, mainly fine- and coarse-grained sand (median: 315 µm; SD: 110 µm) although pebble-sized material is present and even dominant in several of these layers.

Six samples were dated in the core, ranging between 1720 ± 170 and 2420 ± 510 years and with no apparent upward decreasing age trend (Figure 3). This means that the whole succession contained in the core deposited within dating uncertainty and that there is no hiatus in deposition despite the marked facies change in the core sediment. The succession's mean age is 2140 ± 270 years.

Core CL6. This 2.6-m long core is located behind the most landward barrier close to the paleo cliff in the distal parts of the lagoon, at an elevation of 5.1 m. The spit is primarily composed of gravels and the lagoon is connected to open water at the far end of the spit, but at the sampling site, flooding occurs rarely because of the elevation. The surface is covered by thick reddish to grayish microbial mats and there is no present-day morphological indication of any tidal or wave-related processes. The core can be divided into two main parts: (1) the top part is composed of silt-rich deposits. The upper 0.5 m contains in situ formed evaporitic material and dark interbeds of biogenic origin, whereas the lower 1.2 m is characterized by finer sediment (median: 91 µm; SD: 55 µm); and (2) the bottom part of the core is composed of sand beds (median: 230 µm, SD: 50 µm) and gravel with shells debris.

Seven OSL ages were obtained from core CL6. A sample close to the core top was dated to 260 ± 40 years. Three samples from the middle of the silt-rich unit yielded ages of 900 ± 400, 530 ± 50 and 1100 ± 90 years (Figure 3). The sample dated at 530 ± 50 years is considered to be erroneously young (Table 1, Risø 145514) and is not further considered. Two samples from the sand- and gravel-rich unit yielded ages of 960 ± 100 and 850 ± 80 years. The mean of the four ages from the two mid-intervals is 950 ± 110 years and they show no apparent upward-decreasing trend. The lowermost sample, close to the bottom of the core, yielded an age of 37,000 ± 3000 years.

Discussion

The OSL chronology from Caleta de los Loros reveals the relatively recent age and rapid buildup of these investigated coastal deposits over late-Holocene time scales. This is perhaps surprising; favorable conditions for the formation of continuously prograded coastal deposits have likely existed over most of the Holocene, given the proposed positive rates of isostatic uplift (e.g. Rostami et al., 2000), the relative sea-level fall (e.g. Schellmann and Radtke, 2010), and the presently high availability of mobile sediment in the area (Del Río et al., 2007).

The development of Caleta de los Loros mainly during the late-Holocene suggests that the study site is very sensitive to changes in the parameters controlling long-term coastal evolution. The absence of older Holocene deposits suggests a morphological reconfiguration of the studied field site, presumably caused by changes in RSL, sediment supply, and climatic forcing. We here discuss the late-Holocene evolution of the system based on our new observations and contextualize these with a review of the environmental history of the area; this discussion is used to then identify potential controls of the observed changes.

Core units and depositional environments

The sediment in the cores can be divided into three units: (I) intertidal marine deposits, referred to here as lagoonal deposits; (II) mixed sediment deposited under more energetic conditions, referred to as beach deposits; and (III) upper intertidal to supratidal back-barrier deposits.

The lagoonal unit I (intertidal deposits of marine origin preserved as the topmost unit in cores CL1-5; Figure 3) is characterized by grain sizes between 200 and 280 µm and a variable content of shells, shell debris, and pebbles. Sedimentological structures are almost entirely absent with the exception of lag deposits formed by either eolian deflation (CL1) or channel migration (CL3). The interpretation of the lagoonal unit is in sedimentological terms complicated by its homogeneity, a problem that at least in part arises from the available grain-size fractions from 'pre-sorted' sedimentary rock of primarily fluvial origin. Cohesive sediments, especially clay, are almost entirely absent in all of the cores. As a result, deciphering the processes involved in the deposition of the lagoonal sediment is very difficult because a large part of the sorting process is masked by the homogeneity of the parent material (e.g. the input of wind-blown material, bedding structures). Because of this, the interpretation of processes controlling the formation of the lithological units is primarily based on the location, elevation, and age of the respective units, rather than on an interpretation of detailed sedimentological and depositional information.

The beach unit (II) is characterized by mixed sediment in the pebble-, to gravel-, to sand-sized fractions and was encountered in the lowermost parts of core CL5 and CL6. These deposits are characterized by a clear separation into beds with a marked difference in grain size and are presumed to have formed in a wave-dominated environment. The units preserved in core CL5 thus provide evidence for a transition from more exposed conditions to a more protected lagoonal deposition.

Back-barrier deposits (III) were only found in the top 1.7 m of core CL6 and are made up of fine-grained sand and silt fractions in various proportions. The deposition of the fine sediment requires the formation of a barrier to separate the coring site from wave and tidal processes; core CL6 was retrieved from a location where sedimentation only occurs in association with high-water events creating a small, shallow, and ephemeral water body. These characteristics are further confirmed by the existence of dark interbeds toward the core top stemming from microbial mats similar to those observed at the coring site.

The late-Holocene evolution of Caleta de los Loros

With the establishment of the mid-Holocene sea-level highstand, a topographic depression of fluvial origin was inundated at Caleta de los Loros. The limit of marine influence is clearly traceable in the form of inactive paleo-cliffs (Figure 1c). The timing of the last activity of the cliffs remains unknown. However, a former connection with the exposed shoreline is inferred from the orientation and location of the cliffs (Figure 2). A formation in association with the sea-level highstand thus appears a probable scenario.

The oldest ages for marine samples from Caleta de los Loros were established in the northern part of the lagoon (core CL5). Intertidal sandflats were deposited over a short period of time about 2100 years ago and remained in place until present. These deposits are located about 1 m higher than the comparable units observed in core CL4, which were deposited after *c.* 500 years ago. The most landward set of beach ridges was dated to *c.* 1000 years ago. The morphology of these ridges connects with the most landward spit separating core CL6 from the lagoon. In core CL6, the transition from a unit of coarse sediment to an overlying finer unit was dated to *c.* 1000 years ago. This further corroborates that the innermost spit formed around that time. A second and much wider set of beach ridges prograded rapidly between 1000 and 500 years (Figure 2). It is unclear whether the system reached an equilibrium at that time or if the shoreline has prograded further and experienced a period of retreat at some point in time after 500 years ago. None of the near-surface samples from the modern intertidal parts of the lagoon (CL1-CL4) yield modern ages. The uppermost samples in the cores were dated to 90 ± 30 years (3.9 m), 120 ± 30 years (3.2 m), 190 ± 70 years (2.9 m), and 280 ± 80 years (3.7 m) (from core CL1 to CL4, sample elevations in parenthesis; Figure 3). This means that almost all samples are younger than the main (seaward) part of the preserved beach-ridge system, indicating that, not surprisingly, the presence of barrier spits has increased the preservation potential in the tidal lagoon. The chronology also shows that the deposition of sandflats, and hence the infill of accommodation space in the lagoon, occurred rapidly and that no further (preserved) deposition took place after the available space was filled.

The overall relatively recent age of the deposits seems to be at odds with values presented in the literature on the evolution of similar coastal systems since the mid-Holocene transgression elsewhere in the region (e.g. Ribolini et al., 2011; Rutter et al., 1990; Schellmann and Radtke, 2010; Zanchetta et al., 2014). Favorable conditions for the formation of wide beach-ridge systems exist along wave-dominated coasts in locations with high sediment supply and shallow, low-gradient shelves (Hein et al., 2013; Roy et al., 1994). Along the cliffed shoreline of northern San Matías Gulf, an ample supply of sediment contrasts with the limited availability of accommodation space. This contrast is an important parameter in explaining the rapid accretion and progradation observed at Caleta de los Loros.

Figure 4 displays an overview of ages from the literature obtained from studies of different Holocene coastal sedimentary environments along the Atlantic seaboard of Argentina. The figure clearly shows that the deposits began to form with the establishment of the Holocene relative sea-level highstand and that the new OSL ages obtained from Caleta de los Loros are young in comparison. The presence of mid-Holocene deposits elsewhere and their absence at our study site suggests changes at Caleta de los Loros toward the late-Holocene, which either reduced the preservation potential of older deposits, or which favored deposition over late-Holocene time scales.

Based on the geographical setting and a review of the literature, it is reasonable to expect that Caleta de los Loros developed primarily under the influence of changes in RSL (i.e. accommodation space, shoreline retreat) and climate (i.e. direction of wave-energy approach and sediment supply). These parameters

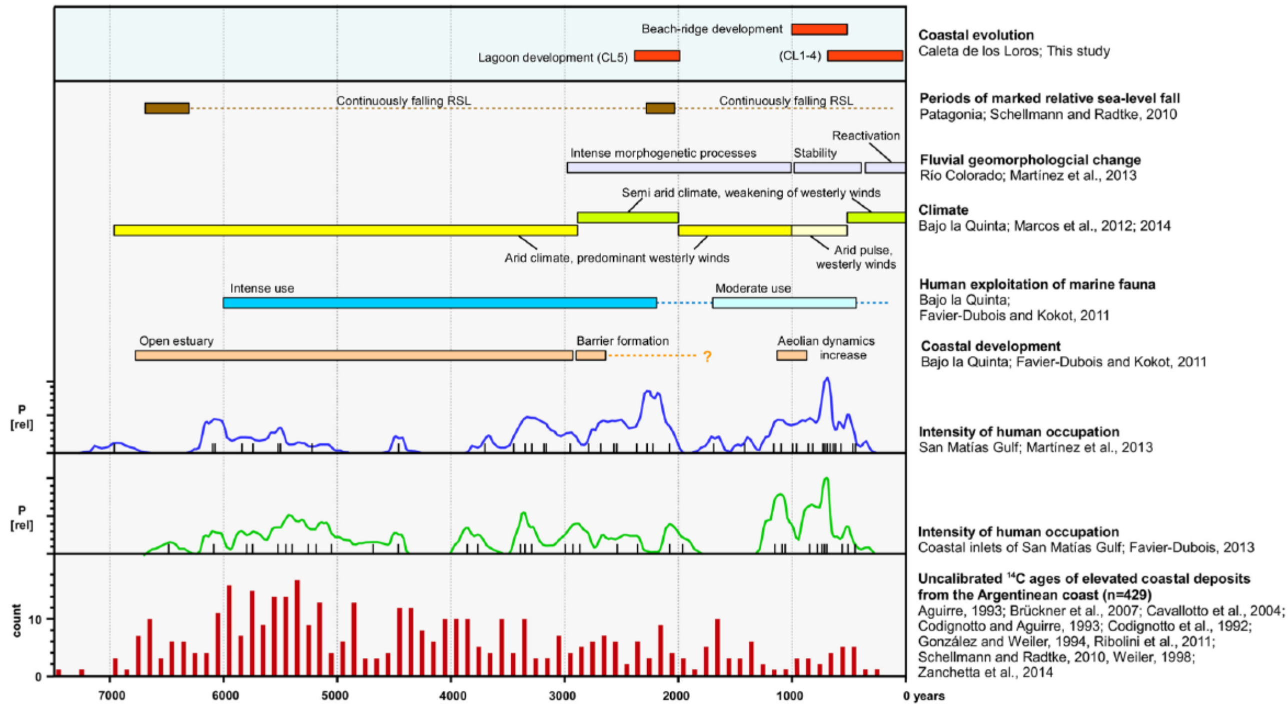

Figure 4. The observed timing of coastal morpho-sedimentary development of Caleta de los Loros is compared with changes in the natural environment and observations from the regional archeological record (see parameter, location, and references in the figure). It can be observed that the periods of lagoonal deposition coincide with periods of reduced influence of westerly winds, while the formation of the beach-ridge system occurred during a dry pulse with an increase in westerly winds. The timing of coastal change appears to be reflected in the intensity of human occupation as reflected in the amount of dated artifacts encountered. P (rel): relative probability.

will be discussed in the following section in order to identify potential environmental controls for the inferred late-Holocene evolution of the study site.

The role of sea level and climate

Several authors have proposed marked oscillations in RSL over late-Holocene time scales. These starkly contradict the assumption of a linear trend in isostatic uplift superimposed on a near-stable eustatic sea level (e.g. Rostami et al., 2000). Gómez et al. (2005, 2006) present evidence for a lower than present MSL at some point between the mid-Holocene RSL highstand and *c.* 2400 years in the Bahía Blanca estuary, Argentina. The existence of similar lowstands along the east coast of Brazil for a comparable time period has been proposed based on data, which is neither unambiguous nor generally accepted, and thus remains a matter of debate (cf. Angulo et al., 2006 and references therein). Schellmann and Radtke (2010) argue for the existence of a significant sea-level fall of at least 1–2 m between 2300 and 2050 years ago for the coast of Patagonia south of Negro River, based on extensive field observations. Hein et al. (2013) attribute the formation of a transgressive barrier within a continuously prograded strandplain around 3300 years ago in Brazil to ‘a significant extrinsic perturbation’ (p. 490). While none of the above observations is entirely suitable to explain the chronology of deposition at Caleta de los Loros, the timing of the observed change appears to fit strikingly well. The tidal flat deposits in core CL5 likely formed in association with the local creation of accommodation space and may in their elevation be indicative of a slightly higher RSL 2400–2200 years ago. The ages from this core are much older than the rest of the OSL dates from Caleta de los Loros, supporting the suggestion of formation of beach and lagoonal deposits over the last 1000 years. This either suggests the onset of a period of increased sedimentation or a large-scale reconfiguration of the system after 2200 years ago.

In reconstructions from a nearby coastal sedimentary system composed of Holocene marine and freshwater deposits at Bajo la Quinta (40°56′ S, 64°20′ W; Marcos et al., 2012, 2014), it was proposed that the climate on the northern shore of San Matías Gulf underwent significant changes affecting local vegetation composition and coastal morphodynamics during the Holocene. From *c.* 7500 to 2900 years, dry climate conditions prevailed with periods of intensified aridity and predominant winds from westerly directions (Marcos et al., 2012). Martínez et al. (2013) state that the ‘Middle Holocene was characterized by arid conditions and eolian morphodynamic processes’ (p. 125). Between 2900 and 2000 years a change from arid to semi-arid conditions occurred coinciding with a weakening of westerly winds, and a correspondingly increased influence of more humid Atlantic air masses. This observation supports earlier observation of a wetting trend around 3000 years ago (Schäbitz, 2003; Schäbitz and Liebricht, 1998). The time period between 2000 and 1000 years is again dominated by dryer climate conditions and probably caused by an increase in westerly winds (Marcos et al., 2012). For the time between 1000 and 500 years, Marcos et al. (2012, 2014) suggest the occurrence of an arid pulse with the influence of westerly winds. Favier-Dubois and Kokot (2011) show evidence for a general increase in coastal geomorphic activity with the formation of beach ridges and dunes occurring at around 1000 years. Over the last *c.* 500 years, semi-arid conditions were reestablished, which continue until present day (Marcos et al., 2012). An arid climate with westerly winds has predominated between 7500 and 2900 years ago as well as between 2000 and 1000 years ago (Figure 4; Marcos et al., 2012). The time frame coincides with periods for which no preserved deposits were obtained in the scope of this study. Sandflats at Caleta de los Loros deposited between 2400 and 2200 years ago (CL5) and over the last *c.* 600 years (CL1-4). These time periods coincide with the proposed periods of slightly wetter climate conditions under a reduced influence of westerly winds. The main period of beach-ridge progradation (between 1000 and 500 years ago) at

Caleta de los Loros is concurrent with a dry pulse and predominant westerly winds. However, the arrangement of landforms that formed over the last 1000 years at Caleta de los Loros suggests the importance of constructive conditions with sediment and energy supply from the east (Figures 1c and 2). This is in accordance with modeling results suggesting the prevalence of a relatively calm wave climate with the predominance of wave energy approach from the south-east (Reguero et al., 2013). Nevertheless, the timing of regional-scale climatic changes inferred from Bajo la Quinta fits strikingly well with the evolution of Caleta de los Loros, although the controlling mechanisms remain unexplained. This is partly because the relative importance of energy from swell waves in the long-term geomorphic evolution of coastal systems in NE Patagonia has not been assessed. At present, the formation and course of extratropical cyclones over the South Atlantic result in the transfer of energy to the northern shore of San Matías Gulf and this is an important factor for the occurrence of high energy events (Mendes et al., 2010). Our data show an increased supply of sediment between 1000 and 500 years ago from an eastern direction and would thus suggest increased influence of allogenic wave forcing.

Coastal evolution: A comparison with the archeological record

Archeological studies have been conducted at several locations in NE Patagonia, including the northern shore of San Matías Gulf (Borella and Cruz, 2012; Favier-Dubois and Alberti, 2014; Favier-Dubois et al., 2009; Martínez et al., 2013; Scartascini, 2012): these investigations describe a close relationship between trends in human occupation and environmental changes in the region. The oldest ages for indications of fishing activities at Caleta de los Loros are about 5300–5900 years old (Favier-Dubois and Scartascini, 2012). While climate change is an obvious parameter to study in a semi-arid environment in order to unravel the history of human occupation, coastal morphological evolution and shoreline change are of special importance along the northern shore of San Matías Gulf (Favier-Dubois, 2013; Favier-Dubois et al., 2016). This is mainly because of the importance of access to marine resources (primarily fisheries); this is limited along a coastline dominated by high cliff sections. The amount of dateable archeological artifacts in the area varies strongly throughout the mid- to late-Holocene (i.e. intensity of the archeological signal; Favier-Dubois et al., 2016; Martínez et al., 2013; Figure 4). Favier-Dubois et al. (2016) state that the large number of ages obtained from the northern shore of San Matías Gulf suggests the importance of marine depositional environments as places for human settlement. The variation of the signal thus may reflect changes in the characteristics and in the overall existence of active tidal inlets.

At Bajo la Quinta, human occupation increased with the establishment of the mid-Holocene sea-level maximum at least 6000 years ago (Favier-Dubois and Kokot, 2011), but human population has been present since *c.* 7200 years (Martínez et al., 2013). The formation of beach ridges has been described here for the time period of between 2800 and 3000 years, which is most likely associated with a fall in RSL at that time (Favier-Dubois and Kokot, 2011; Marcos et al., 2014; Schellmann and Radtke, 2010). A concurrent transition from net fisheries to line fishing occurred at Bajo la Quinta (Favier-Dubois and Kokot, 2011) owing to a transition in the availability of marine food sources to terrestrial food sources. This change in diet is attributed to the increased rectification of the coast of San Matías Gulf (Favier-Dubois and Kokot, 2011). A study of human remains revealed dietary changes from an intensive to moderate use of marine resources between 3100 and 2200 years ago and 1500 and 400 years ago (Favier-Dubois et al., 2009).

Conclusion

A high-resolution chronological framework, based on OSL dating, was constructed from lagoon and beach-ridge deposits at Caleta de los Loros, NE Patagonia, Argentina. Information on the geomorphological and sedimentary context were obtained from remotely sensed data, sediment cores, and field measurements. The new chronology shows that the oldest deposits from the lagoon formed about 2100 years ago and that the beach-ridge system formed between 1000 and 500 years ago, while the majority of the deposited sediment from the lagoon is younger than 500 years. The controls of the inferred sedimentary and geomorphological changes at the field site could not be identified in detail, but potential links with sea-level oscillations and changes in wave climate have been proposed. The timing, rate, and scale of deposition at Caleta de los Loros present an atypical example of a prograded coastal sedimentary system along the Atlantic seaboard of Argentina and illustrates the sensitive morphological response of coastal systems to changes in major forcing parameters such as sea-level, sediment availability, and wind direction. The study demonstrates the characteristic complexity of the depositional history of macrotidal coastal lagoon systems, regarding both stratigraphy and chronology. Furthermore, it highlights the need for more research into systems in similar settings to improve understanding of the depositional mechanisms and feedbacks controlling their evolution.

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