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Palaeoenvironmental reconstruction of La Olla, a Holocene archaeological site in the Pampean coast (Argentina)

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ABSTRACT

The evolution of littoral palaeoenvironments in the southern Pampas region of Argentina towards the end of the early Holocene and the beginning of the mid Holocene is discussed, and the formation processes of the archaeological site of La Olla are analysed. This site is located in the intertidal zone of the present beach and is remarkably well-preserved. The human occupation at the site has been dated at between 7400 and 6480 yrs BP, and is interpreted as a place for the processing and consumption of the southern fur seal (*Arctocephalus australis*) and southern sea-lion (*Otaria flavescens*). It is concluded that biostabilization by microbial mats of the sedimentary structures and archaeological remains that developed and are present on the tidal flat prevented their erosion by wind, turbulence currents and waves. This is what has permitted the exceptional preservation of the site. On the basis of the analyses of one of the sectors of the site it can be concluded that the sedimentary succession of the La Olla site is the result of the coastal environmental changes during the early–mid Holocene in the pre-maximum transgressive episode. During this interval a tidal flat developed on the Pleistocene abrasion platform. Human occupation occurred during the formation of mixohaline marsh, an upper intertidal–lower supratidal zone ecosystem.

1. Introduction

Though indigenous occupation of the Pampas region coastline has been a focus of interest for Argentine archaeology since the beginning of the 20th century (see reviews in Daino, 1979; Bonomo, 2005), it is only in recent decades that a few sites have been systematically excavated with good resolution and integrity with respect to stratigraphy. Besides, the archaeological record of the Atlantic Pampas littoral is dominated by sites linked to coastal dunes, which consist mostly of surface materials concentrated in deflation hollows due to wind action (Aparicio, 1932; Austral, 1968; Daino, 1979; Politis, 1984; Bayón and Zavala, 1997; Bonomo, 2005; Bayón et al., 2012). Just a few sites are located in a stratigraphic position in the littoral dune chain but they present a moderate resolution (Bayón and Zavala, 1997; Bonomo and León, 2010). In this context the La Olla (LO) coastal site (Politis and Lozano, 1988; Bayón and Politis, 1996, in press; Johnson et al., 2000; Fontana, 2004) is exceptional in its chronology, the quantity and quality of the preserved archaeological remains and the complexity of formation processes that can be inferred through geoarchaeological studies. Likewise the integrity of the sedimentary sequence allows environmental reconstruction in the framework of the regional coastal dynamics during the early–mid Holocene. At LO is recorded some of the first evidence in the South Atlantic providing information on human adaptation for the exploitation of the pre mid-Holocene ingression marine resources. At the same time special methodological problems for its excavation arise.

The current situation at the site is that the area is dominated by the deposition of sand covering the consolidated substrate making up an extensive abrasion platform along the shore. This has made possible the preservation of the archaeological site lodged in the finely stratified sediments filling ancient depressions formed in the aforementioned abrasion platform.

The purpose of this article is to provide information on environmental characteristics and their variation over time during the human occupation; to this end detailed stratigraphic and

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sedimentological studies were carried out in one of the sectors of the site (LO4).

In addition the palaeoenvironmental characteristics are discussed in relation to those inferred, by means of different proxies, at nearby sites such as Monte Hermoso 1, El Cangrejal, and El Ñandú, dated to the early/mid-Holocene (Aramayo et al., 1992, 1998; 2005; Aramayo and Malla, 1995; Costantini et al., 2006; Schillizzi et al., 2000; Gutiérrez Téllez and Schillizzi, 2002; Fontana, 1996, 2004, 2007; Martínez et al., 2010; Zavala et al., 1992). Finally this information is collated with regional palaeoclimatic models and with those of human occupation of the Pampas coast.

1.1. Environmental background

The La Olla site (38° 59′ South 61° 21′ West) is located in the southern strip of the Pampas region 6 km west of the town of Monte Hermoso and 110 km from the city of Bahía Blanca (Fig. 1). The coast in this sector is a broad bay that lies in an east–west direction 32 km in extent between Punta Sauce to the east and Pehuén Có point to the west (Marcos et al., 2009). It is in the coastal Pampas region (Dadon and Matteucci, 2006) in the Southern Dune Barrier (Barrera Medanosa Austral or BMA) defined by Isla et al. (1996) and within the Cliffs with Perched Dunes zone defined by Lopez and Marcomini (2011) extending over some 420 km of the southern coastal region of the Buenos Aires province. This coastal environment runs approximately from Miramar to Pehuén Có (Fig. 1). In this sector the beaches are broad and possess outcrops of an abrasion platform of Plio-Pleistocene consolidated fine muddy sands. Owing to the action of the sea in some stretches the cliffs are active (Isla et al., 1996; Monserrat and Celsi, 2009; López and Marcomini, 2011). The most ancient dunes in the BMA belong to a first generation of littoral dunes originating approximately 6500–4000 yrs BP (Isla et al., 1996; Isla et al., 2001; Isla and Bertola, 2005; Cortizo and Isla, 2007) and are the first to have climbed the sea cliffs and are today the closest to the coast. However, recent archaeological research at the Las Dunas site suggests an older age (Bayón et al., 2012).

The La Olla archaeological site, is located in a semidiurnal mesotidal beach environment. It is near the low-tide level and is almost permanently submerged and covered by sand-bars. Some very eroded outcrops of the abrasion platform are also to be found in this beach sector. This shelf is uncovered on occasions when the sand is moved during storm waves, which exert a powerful influence on the configuration of the beach and, though not of periodical recurrence, generally happen in summer and with strong south and southwesterly winds (Fernández et al., 2003 and Marcos et al., 2009). When the sediments of the abrasion platform remain exposed, attributed to the "Lujanense" (Aramayo, 1997) Land Mammal age, oval to circular depressions can be identified filled with stratified sediments that make up the La Olla sectors: LO1, LO2, LO3 and LO4.

At the Monte Hermoso 1 site (MH1), associated spatially and temporally with LO, outcrops of these sediments were found and named Lower Wakes by Zavala et al. (1992) and also attributed to the Lujanense age. The extent of this Pleistocene substrate towards the continent and under the dunes is as yet unknown (Monserrat and Celsi, 2009; Aramayo et al., 2002).

The infilling pools or depressions that characterize LO are some 40 or 50 m distant from each other over a stretch of around 150 m, and are similar in their areal development. They have a sub-oval shape and a maximum diameter of about 17 m (Fig. 2). Although the origin of these depressions is beyond the scope of this article, they might be related to the presence of crotovines in the Pleistocene sediments of the abrasion platform and its labile filler. The subsequent sedimentary infilling of these eroded depressions which contain the cultural material is in thin layers (0.20–0.70 m). The upper ones are partially eroded by littoral processes (littoral waves and longshore currents) when they are left exposed by the movement of the sand covering them (Fig. 2).

The most notable characteristic of the site is the integrity and resolution of the archaeological deposits. This is seen in the

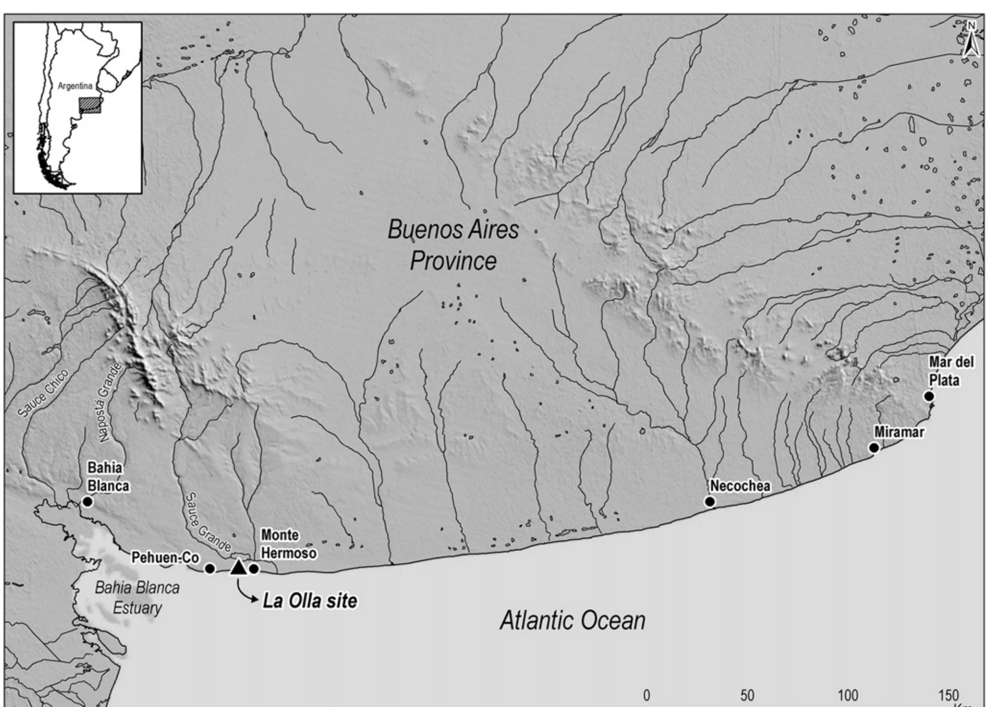

Fig. 1. Map showing the location of the city of Monte Hermoso and the La Olla archeological site, Buenos Aires province, Argentina.

Fig. 2. Photograph of La Olla 4 archaeological site during the archaeological filed work.

aforementioned exceptional state of preservation of organic remains, bones, and especially plant tissue and wood; it is also seen in the excellent state of maintenance of the sequence of sediments and their mechanical and biosedimentary structures within the depressions.

These infilling pools are to be found at the limit of the lowest tide, where their subaerial exposure depends on diverse factors: the cover of sand on the beach, the daily variation in tidal levels and the wind direction and strength. The sector is exposed during only 2 or 3 h at low tide when there is no southern wind from the sea and the action of the littoral currents has removed the sand covering the site (Fig. 2). It was possible to observe each of the sectors of the site at different times years apart, and for short periods of just a few days. Only at those times was it possible to carry out quick excavation and recovery tasks.

1.2. Archaeological background

LO1 (38° 59′22.44″ South 61° 21′3.84″ West) remained exposed on two occasions at the end of 1983 and at the beginning of 1984 (Johnson et al., 2000; Politis and Lozano, 1988). During winter 1993 it was left exposed for a third time and it was possible to recover a small but very important collection of materials, in particular a wooden artifact (Bayón and Politis, 1996). LO2, close to LO1, remained exposed only once and for just a short time, in 1995. It was not possible at the time to take the coordinates. LO3 (38° 59′22.5″ South 61° 21′3.3″ West) and LO4 (38° 59′22.44″ South 61° 21′8.16″ West) were discovered in the summer of 2008. This was an exceptional exposure lasting several weeks allowing recovery work, stratigraphic studies and sedimentological sampling.

At LO1 abundant anatomically and taxonomically determinable faunal remains were recovered ($n = 300$) (Johnson et al., ms), a few stone artifacts ($n = 38$), a wooden one, and one made quickly from a southern fur seal (*Arctocephalus australis*) bone (Johnson et al., 2000). The faunal context consists predominantly of sea species: the southern sea-lion (*Otaria flavescens*) and the southern fur seal (*A. australis*). Finally, rock was employed to fashion cores, flaking tools, anvils. Samples for radiocarbon dating were taken from sea-lion bone (7314 ± 55 and 6640 ± 90 yrs BP). Fontana (2004) dated 5 levels at between 7920 ± 90 and 7040 ± 55 yrs BP from *Ruppia* sp. and macrovegetal remains (Table 1). It should be mentioned that the lower levels did not contain archaeological remains (Fontana, 2004; Bayón and Politis, in press). The LO2 context shows similar characteristics, with a predominance of pinnipeds in the archaeofauna and few artifacts. This collection is the smallest as it was only briefly exposed and it was not possible to carry out recovery tasks. It was dated at 7400 ± 95 yrs BP from a pinniped bone sample. An important point to mention is that at both sites the datings taken from *Otaridae* bone and wood coming from the same stratigraphic level – from the same laminae – gave similar ages (Table 1) suggesting very low reservoir effect values, and therefore not supportive of the offset $r = 783 \pm 55$ ^{14}C years BP calculated for LO1 by Fontana (2007).

Sites LO3 and 4 offer the most complex contexts in the amount of remains as well as in the technological variety. The collection includes 13 wooden, 3 bone and 14 stone artifacts, as well as abundant plant macro-remains ($n = 35$) and faunal bones ($n = 315$, see León and Gutiérrez, 2011). The stone artifact context (LO3 $n = 8$; LO4 $n = 6$) is composed of a small collection of tools, carved, abraded or worn by use (Bayón and Politis, in press).

Altogether 16 radiocarbon datings were carried out for the La Olla site on samples of different provenance: 5 of them corresponding to Otaridae, 3 on woods, 4 on seeds, 1 on plant macro-remains, 1 on a land mammal and 2 on organic material (Bayón and Politis, in press). The body of evidence recovered at La Olla indicates that the deposit of archaeological material occurred at the end of the early to mid-Holocene, at least from *ca.* 7500 to *ca.* 6480 yrs BP. Yet both are extreme dates in a series of datings with a more restricted distribution (Table 1). For LO3 and LO4 the lapse of the occupation would have been much more limited, with a maximum antiquity of 6960 ± 71 yrs BP and an estimated mean of 6911 ± 24 yrs BP.

Table 1
Radiocarbon dates fron La Olla archeological site of diferentes autors for the La Olla site.

Sector	Sample code	Material dated	Lab. number	$\delta^{13}C$	Date in ^{14}C in yrs BP
La Olla 1	LO1a	Otaridae bone	LP-303	–	6640 ± 90
La Olla 1	LO1b	Otaridae bone	AA-7972	−13.7	7315 ± 55
La Olla 1*	Prof. 0–1.1	*Ruppia sp.*	NSRL 11044	–	7580 ± 60
La Olla 1*	Prof. 5.5–6.2	*Ruppia sp.*	NSRL 11045	–	7750 ± 60
La Olla 1*	Prof. 8.3–8.9	*Ruppia sp.*	Ua 16106	–	7635 ± 75
La Olla 1*	Prof. 22.1–23.1	Macrovegetal remain	NSRL 11046	–	7040 ± 55
La Olla 1*	Prof. 33.7–34.4	*Ruppia sp.*	NSRL 11047	–	7920 ± 90
La Olla2	LO2a	Otaridae bone	AA19292	−12.3	7400 ± 95
La Olla 3	L03-52	Wood	AA-80666	−26.1	6885 ± 47
La Olla 3	L03-99	Wood	AA-80668	−25.4	6898 ± 47
La Olla 3	LO3 42	Otaridae bone	AA-80663	−10.2	6904 ± 71
La Olla 4	LO4m1	Organic matter	LP-1946	–	6480 ± 140
La Olla 4	LO4m2	Organic matter	LP-1949	–	6700 ± 110
La Olla 4	L04-142	Wood	AA-80667	−27.3	6931 ± 47
La Olla 4	L04-166	*Lama guanicoe*	AA-80664	−19.9	6960 ± 71
La Olla 4	L04-60	Otaridae bone	AA-80665	−13.1	7176 ± 91**

* From Fontana (2007).
** Laboratory reported problems in the line during the dating process.

1.3. Regional and local geology background

The first geological characterization of the area was by Frenguelli (1928), who observed a step during the low tide consisting of, from bottom to top, estuary and fluvial sediments which he ascribed to the Querandinense and Platense deposits respectively. Later sedimentological, micropalaeontological, palaeoecological, and archaeological research, carried out in the neighbourhood of Monte Hermoso, took place in the mesolittoral area (Aramayo et al., 1992, 1998, 2002, 2005; Aramayo and Malla, 1995; Bayón and Politis, 1996, 1998; Gutiérrez Téllez and Schillizzi, 2002; Fontana, 1996, 2004, 2005, 2007) as well as the more distal mesolittoral area relative to the site (Aramayo et al., 1992, 2002; Zavala et al., 1992).

Principally the geological, palaeoenvironmental and palaeontological procedures as well as the radiocarbon datings were carried out at La Olla 1 (Fontana, 2004, 2007; Johnson et al., 2000), at Monte Hermoso 1 (Holocene sediments in which hundreds of human footprints were detected, Zavala et al., 1992; Bayón and Politis, 1996 and Bayón and Politis, in press) and at the Sauce Grande, El Cangrejal, El Pisadero (which is actually a sector of Monte Hermoso 1), El Ñandú, Arena Floja, and Monte Simón sites (Gutiérrez Téllez and Schillizzi, 2002; Aramayo and Malla, 1995; Aramayo et al., 1992, 1998, 2002, 2005). All these profiles show that the Holocene sedimentary sequence is thin (from 0.20 to 1 m) and lies above the Pleistocene sediments. These sites are dated between 7920 ± 90 and 6570 ± 90 yrs BP and were affected by the relative high sea level during the Holocene ingression (Gutiérrez Téllez and Schillizzi, 2002; Aramayo and Malla, 1995; Aramayo et al., 1998, 2002; Bayón and Politis, 1996, 1998; Zavala et al., 1992; Fontana, 2004, 2005, 2007) (Table 2).

The evolutionary history of the environments developed in this area during this time-lapse and after 8800 yrs BP was studied in detail by Aramayo et al. (2002, 2005). According to these authors, a period occurred at around 7100 yrs BP of interconnected coastal lakes (the spring system of Zavala and Quattrocchio, 2001; the upper section of Agua Blanca sequence of Quattrocchio et al., 2008). These lakes were shallow and of limited extension within a morphology of shifting-dune zones and bodies of water with increasing levels; they were also related to a transitional marine

Table 2
Holocene sites with the paleoenvironmental interpretation. The list of the sites in the table are ordered from east to west.

Site	Sample	Dates ^{14}C yr BP	Distance from LO	Inferred environment	Author
Monte Hermoso 1	Otaridae *Ruppia* seeds *Geoffroea decorticans* Wood Human bones	7125 ± 75 to 6.795 ± 120	0.5–2 km E	Interdunal lakes with some marine influence	Bayón and Politis 1996 Zavala et al. 1992 Quattrocchio et al. 2008 Constantini et al. 2006
El Ñandú	Egg shell *Rhea americana*	8.836 ± 65	0.5 km W	Interconnected lakes within a field of mobile dunes	Gutiérrez Téllez and Schillizzi 2002
Barrio Las Dunas	Otaridae *Pogonias romis*	6.924 ± 69 6.820 ± 100	1.5 km W	Sand dunes near a costal lake with subsequent continentalization	Bayón et al. 2012
El cangrejal	*Frankenia Juniperoides* Tallos fosilizados de gramínea	6930 + 70 6570 + 90	2 km W	Marginal lagoons with subsequent continentalization	Aramayo and Malla 1995 Gutiérrez Téllez and Schillizzi 2002 Aramayo et al. 2005 Aramayo et al. 1998.
Balneario Sauce Grande 1	*Pitar rostrata*	4840 + 70	10 km W	Intertidal flat Shallow marine	Aramayo et al. 1998
Balneario Sauce Grande 2	*Zidona*	6830 ± 120	10 km W	Intertidal flat Shallow marine	Gutiérrez Téllez and Schillizzi 2002
Balneario Sauce Grande 3	*Nucula puelcha*	5328 ± 70	10 km W	Intertidal flat Shallow marine	Gutiérrez Téllez and Schillizzi 2002

environment that developed close by and towards the east of the coast. Between 6900 and 6500 yrs BP this area had an abundant low bushy vegetation typical of salty environments, such as *Frankenia juniperoides*, related to a medium colonized by the *Chasmagnathus granulata* crab that evolved, according to the authors and due to the presence of *Spartina* sp. stems, adapting to a terrestrial mode of life. After this period, and between 5300 and 4800 yrs BP during the last part of the Hypsithermal, the borders of the Holocene continental shelf were under water. Aramayo et al. (2005) correlate this episode with the coastal plain deposits at Sauce Grande beach where sandy sediments contain a rich fauna of bivalves and gastropods of marine littoral habitat. These deposits could be included in the period of relative sea-level stability (Cavallotto et al., 1995) that took place between 5000 and 3000 yrs BP. In this regard, according to Aguirre and Farinati (1999), the transgressive mid-Holocene deposits on the southern coast of Buenos Aires province are represented fundamentally by chain, beach, estuary facies, or lagoon deposits. In the nearby Bahía Blanca estuary, a body of evidence shows fluctuations in sea level during the Holocene. These fluctuations have been observed at the mouths of the two main rivers (the Napostá Grande stream and the Sauce Chico river) (Grill and Quattrocchio, 1996; González et al., 1983; Quattrocchio et al., 1998; Olivera Grill and Zavala, 2006), in coastal chains that run parallel to the present coast between Punta Alta and Ingeniero White, in beach rocks, in samples taken from channels deposits and in cores from the outer area of the estuary (Aliotta et al., 2008, 2009; Aliotta and Farinati, 1990; Gómez et al., 2005; Perillo, 1995).

Grill and Quattrocchio, 1996 and Quatroccio et al. (1998) inferred, on the basis of marine palaeomicroplankton recorded in a profile at the mouth of the Napostá Grande stream (which flows into the Bahía Blanca estuary), an advance of the coastline with a maximum transgression some 6000 yrs ago followed by a gradual retreat by 3300 yrs BP. In the Sauce Chico river, at the inner part of the estuary, the advance of the sea during the Holocene happened in three stages. The first was passive flooding in an area of lagoons. The second stage presents high-energy foreshore/shoreface facies, followed finally by a clastic progradation with a regressive tendency (Olivera Grill and Zavala, 2006). Concerning this, Aliotta et al. (2009) state that the coastal morphosedimentological evidence for the Punta Alta area (Bahía Blanca estuary) indicates that the maximum sea-level (4 m) was reached during the Holocene around 6000 yrs BP, when the regressive process of the sea began. Previously for the same area, the maximum transgressive episode represented by beach chains had been calculated by Gonzalez (1989) as having a minimum mean age of 5990 ± 115 yrs BP. More recently, dates taken from fossil shells in the sand-shell ridges in the vicinity of Punta Alta, considered the most ancient, offer values between 5200 and 6650 yrs BP (Aliotta et al., 2008). Further north on the Atlantic coast near Necochea city, records of the Holocene ingression at the mouth of the Quequén Grande river were dated at approximately 7600 yrs BP and the sea level in this area, inferred by different authors will have been between 2 and 2.5 m above the current level 6000–6500 yrs ago (Grill et al., 2007).

2. Material and methods

As previously mentioned, the particular situation of La Olla did not permit detailed observations owing to the short time for which each of the four sectors remained exposed; additionally, only one sector was exposed at a time. However LO4 was exposed twice during several days in 2008, which allowed a more complete stratigraphic-sedimentological study to be made and samples to be taken more systematically. During the low tide in this sector the topographic map of the structure and sedimentological sampling was carried out. This consisted of the extraction of oriented blocks of sediments (one of them is an erosional remnant of the top of the succession), and of PVC cores of 0.08 m diameter and varying length, which depended on the depth of contact with the consolidated substrate abrasion platform (cores1, 2, 3, and 4).

Using the samples obtained, the presence of mechanical sedimentary structures, colour, organic material content, granulometry, mineralogical composition, and biological content were ascertained. For the granulometric analysis, material corresponding to a sedimentation unit on a scale of a millimetre to a centimetre was taken; this was processed prior to dispersion by means of ultrasound, with 5% acetic acid, 100 vol. hydrogen peroxide for the elimination of cements and organic material and 1% sodium hexametaphosphate as a deflocculant. Particle-size analysis was done with a Malvern Mastersizer 2000 LASER particle counter. The distribution of particle sizes was measured in damp samples. The values obtained were processed statistically according to Folk and Ward (1957). Sediments were classified according to Folk (1954). To determine the organic material content, the Walkley and Black (1934) method was employed. Dry colour was taken by comparison with the Munsell colour chart. Mineralogical composition of sands was carried out by polarization microscopy from loose grain samples prepared with immersion liquid, and those of clays by X-ray diffraction of powdered and oriented samples. Scanning Electron Microscopy (SEM) was utilized for the study of grain coverings of authigenic minerals and microbiological material.

3. Results of the sedimentological analyses

The sedimentological analyses led to the identification of two siliciclastic lithofacies: sands and silty sands, and two biosedimentary ones, one being sandy silt microbial mat and diatomaceous earth with evaporated crystals, which are part of different sedimentary facies.

Each of these facies is characterized by a set of lithological and biological content features which allow the characteristics of the medium during its deposition to be defined. Changes in the facies provide evidence of environmental changes, sometimes recurrent or alternating, that occurred during the depositional process that took place at LO4 (Fig. 3). There follows a detailed description of these facies.

3.1. Facies A: dark grey sandy silt

This is made up of silt and bioturbated sandy silt (Fmb in Fig. 3), and is dark grey in colour (Table 3). It shows a grain size distribution that is unimodal, poorly sorted, has fine skewness and is mesokurtic. The Mz value is 2.58 phi while organic material content was 2.30%. These sediments contain a lot of ancient crab burrows.

It was recognized in the top of the sedimentary succession but it is not present in any of the PVC cores. The sampling was performed using block samples given that, in the field, it was present only as the remains of a much larger deposit that had been eroded (Fig. 4).

Its textural features are similar to those recognized for the deposits found by Aramayo et al. (1992, 1998, 2002, 2005) 500 m west of the Monte Hermoso locality and described as fine and silty sandstones, dark grey in colour, 0.30 m thick, that contain remnants of an estuarine crab, *C. granulata* (Dana), as well as the burrows excavated by these decapods. Thus it is possible to assume this facies is correlatable with the fossil *C. granulata* crab-bed deposit reported by Aramayo et al. (1992), dated by remains of charred *F.*

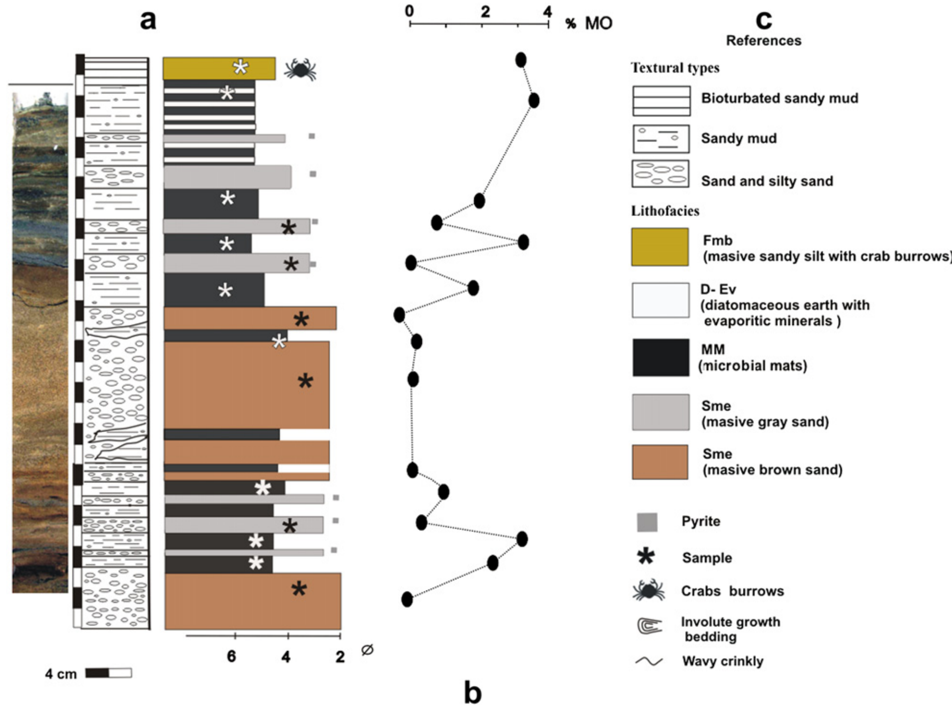

Fig. 3. Sedimentological analysis of core 1(from left to right), (a) picture of the profile in the core, scale, textural clasificattion of the lamines and lithofacies; (b) organic matter content in the different samples; (c) references.

juniperoides stems at 6930 ± 70 yrs BP (Aramayo and Malla, 1995) and by fossilized grass stalks at 6570 ± 90 yrs BP (Aramayo et al., 1998) *ca*. 1000 m away from the La Olla site.

3.2. Facies B: siliciclastic biolaminites

This facies corresponds to an interbedding of biofilms or microbial mats (MM in Fig. 3), dark grey in colour and a few centimetres to millimetres thick, laminates of diatomaceous earth with authigenic evaporite precipitates (D-Ev in Fig. 3) light grey to white in colour, and sporadic massive thin layers of grey silty sands (Sme, in Fig. 3) (Figs. 3 and 5). In the field, the facies show a complex biosedimentary structure related to mat growth (Bouougri and Porada, 2007) which appears in the cores with strong inclination of the upper layers (Fig. 6).

The biofilms or microbial mats (Fig. 3) have the most organic matter content of the analysed lithofacies in the succession. In this regard, the organic matter to mean value ratio (Mz) has shown a good positive correlation. This content varies between 2% and 3.5%. Sometimes these layers, when wet, have green colours. A microbial mat (Fig. 7a–b) includes coccoid (Fig. 7c) and filamentous cyanobacteria (Fig. 7e). It also shows extracellular polymer substances (EPS) and the siliciclastic grains (Fig. 7b) that were embedded in mucus (EPS) and other groups of microorganisms such as fungi or diatoms (Fig. 7f). The presence of framboidal pyrite was also observed (Fig. 7f). Involute deformation and the development of desiccation polygons were observed as macroscopic biosedimentary structures. The main feature of the mats at the site is the millimetre to centimetre thickness of the beds or laminae covering the irregularities of the surface they rest upon, an aspect already pointed out by Gerdes (2007) and Cuadrado and Pizani (2007) for modern microbial mats. These sedimentary lithofacies were also detected in the blocks, in which bone fragments, ostracod shell fragments, phytoliths, and carbonaceous plant debris were found.

As for the lithofacies made up of diatomaceous earth layers with evaporite crystals (D-Ev in Fig. 3) (Fig. 7a–b), it is represented by

Table 3
Association of facies, lithofacies and the environmental interpretation of the lithostratigraphic profiles. (Between brakets the subordinated lithofacies types).

Facies Association		Sector	Facies	Lihtofacies	Interpretation
Tidal flat	Intertidal flats	Upper sector	A	Fm	Intertidal flats Flooding by astronomical tides
	Upper intertidal to supratidal flats	Middle sector	B	MM, D-Ev (Sme)	Upper intertidal to supratidal flats with desiccations periods flooding by wind-induced tides and astronomical tides. Mixohaline marsh.
			C	MM, Sme	Upper intertidal to supratidal flats flooding by astronomical tides or wind-induced tides. Mixohaline marsh.
	Supratidal flats	Lower sector	D	Sme, (MM)	Abrasion platform with sparse aeolic deposits flooding by exceptionality wind induced tides.

Fig. 4. Picture showinng the sediement with crab beds in the top of the sequence, (arrow: crab burrow).

clear laminae of millimetric thickness that always rest on a biofilm or microbial mat. The laminae are made up of a thanatocenosis of halophile oligohalobial and mesohalobial planktonic diatoms, and showing a predominance of central forms: *Cyclotella meneghiniana* (Fig. 7d) and *Chaetoceros* sp. over the penniform types, *Surirella striatula* (Turpin), *Campylodiscus* sp. and *Navicula* sp. In addition, poacean phytoliths have been found (49%), followed by cyperaceae, juncaceae and unidentified dicotyledons. Among the grasses, a notable presence of species of the *Spartina* genus was observed. Among the phytoliths derived from the cyperaceae the predominance of *Scirpus* is noticeable, and as for the juncaceae, with sparse representation, *Juncus* sp.

In these laminae are found anhydrite, calcite, gypsum, and some quartz crystals, and feldspar grains.

The silty sand lithofacies have abundant very rounded quartz grains, quartzite lithic fragments, and heavy minerals as well as organic matter and authigenic pyrite which coat the siliciclastic grains (Fig. 8a). The organic matter content varied from 0.5% to 1.10%. (Fig. 3). The authigenic pyrite crystals (Fig. 8b) represent an anoxic condition and the presence of reducing bacteria.

Facies B is present in all cores with thickness varying between 2 and 15 cm (Figs. 3 and 5). In cores 2 and 4 it appears both in the lower and mid upper section. In cores 1 and 3 it is found only in the upper part. In the base of core 2 it was possible to see and count some 50 laminae (Figs. 3 and 5).

Owing to its sedimentological characteristics it could be correlated with the facies of deformed pelites recognized by Zavala et al. (1992) at the Monte Hermoso 1 site, and described as a fine lamination of pelites and fine light grey sandstone with numerous deformation structures such as pipes and convoluted stratification, and which present the greatest concentration of palaeoichnites.

3.3. Facies C: interbedding of thin microbial mats and grey silty sands

This consists of an intercalation of light grey silty sands (Sme) and microbial mats (MM). The light grey silty sands show an organic matter content of less than 1%. These contain some mat chips, and shell fragments can also be present, while sandy silt sediments are dark grey in colour and possess a quantity of organic matter that varies between 2.15% and 3%. In certain sectors a notable precipitation of calcium carbonate was detected (see Fig. 5b), which turns the biosedimentary layer into a marl that presents phytolith cells and organic material (plant tissue). The sandy silts making up the silicoclastic material of the microbial mats show unimodal distributions, the modal class size being very fine sand, coarse silt, and medium silt sizes, poorly sorted, positively asymmetric, with fine skewness and leptocurtic to mesocurtic grain distributions. The Mz values lie between 4.11 phi and 5.52 phi (very fine sand or coarse silt size). In this facies, these mats show a greater thickness than those found in facies B.

The intercalated silty sands (Sme) show unimodal distributions with fine or very fine sand modal class, poorly selected, fine to very fine skewness, and very leptocurtic. The Mz values lie between 2.75 phi and 3.17 phi (fine to very fine sand). They are composed of lightweight translucid minerals, sedimentary lithic clasts (quartzite), quartz, feldspar, and volcanic glass, generally with a coating of authigenic octahedral pyrite and heavy minerals such as pyroxenes, amphiboles, and well-rounded opaque minerals (Fig. 8a and b). They are sterile as regards diatomological content, but include ostracod remains, fish scales, fragments of indeterminate shells, bone fragments, plant debris, etc.

This facies had hardly any archaeological remains of any kind. Only the odd bone was found in the upper biosedimentary laminae of dark grey sandy silts. Sample LO4-166 comes from one of these laminae, a guanaco bone in a horizontal position, with evidence of human action, and dated at 6960 $\pm$ 71 yrs BP.

This facies could be correlated with that of the grey pelites, more precisely that of discontinuous pelites (Zavala et al., 1992), at the Monte Hermoso 1 site.

3.4. Facies D: brown sand with sporadic isolated microbial mats

This is made up of light-coloured sands (Sme). It is composed of medium to fine yellowish-brown sands, moderately sorted with a symmetrical to very fine skewness and a very leptocurtic unimodal (fine sand modal class) distribution. The mean lies at 2.09 phi to 2.07 phi (fine, almost medium, sand). The thickness is very small, varying from 2 to 8 cm. In the samples from the blocks a few broken shell fragments were observed. They show the lowest values for organic matter in the whole succession (less than 0.2%). They are composed of highly rounded quartz grains, plagioclases and heavy minerals (olivines, pyroxenes, amphiboles and opaque ones).

The sands are present at the base of core 1 and core 3 (Figs. 3 and 5b). By their granulometry (Mz = 2.07 phi), their being moderately to well sorted and by the distribution of symmetrical sizes, they are interpreted as a wind deposit accumulated at the beginning of the deposition in the depression or pool bases. No remains were found

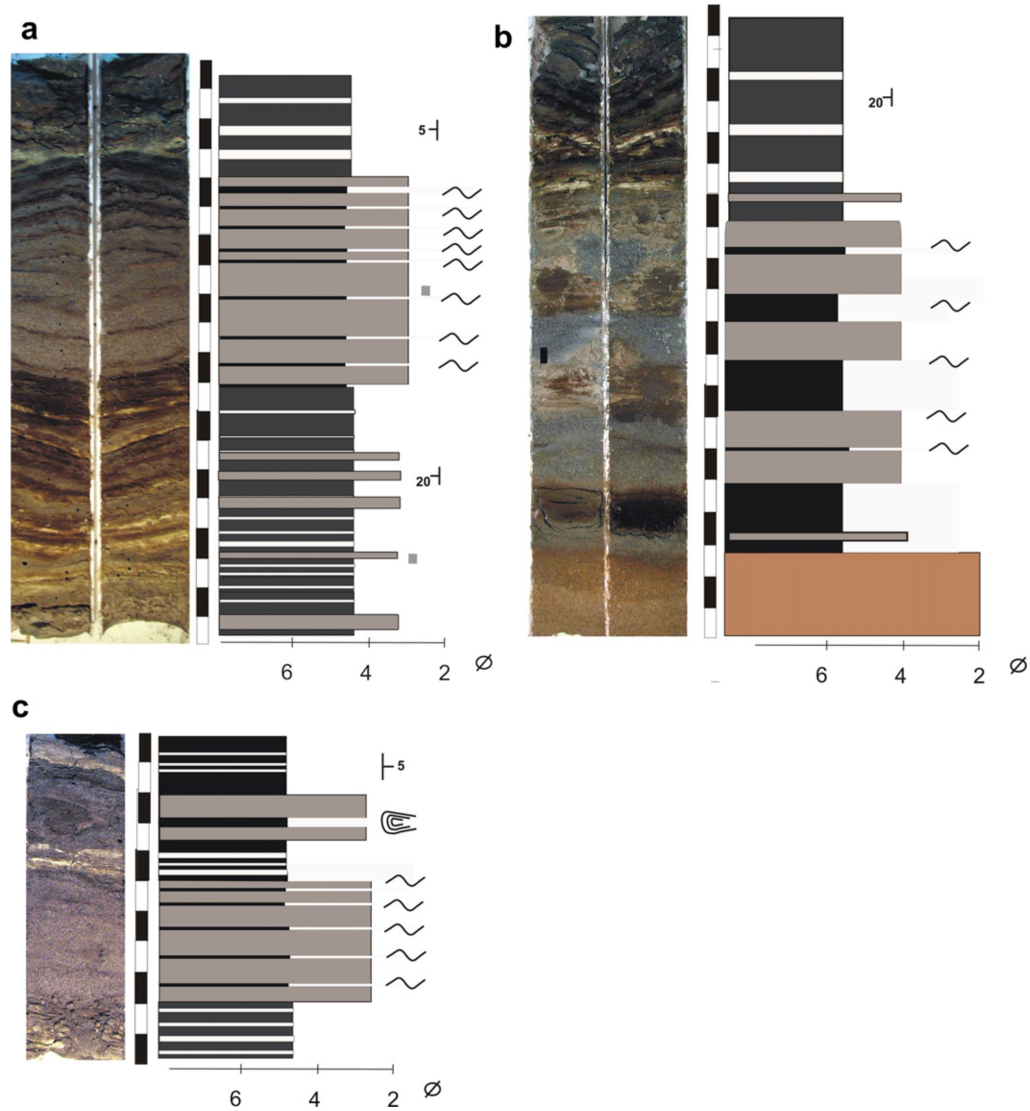

Fig. 5. Sedimentological detail analysis of core (a) Core 2; (b) Core 3; (c) Core 4. Same references as Fig. 3.

indicating human activity; only isolated fish remains (like a black sea-bass vertebra) the presence of which seems to be natural.

4. Discussion

4.1. Environmental characteristics before and during human occupation

At the lowest part of the succession there is an episode of aeolic deposition, represented by well-sorted yellowish-brown coloured sands, Facies D, found only at the base of the longest core (C1 and C3). This would allow the inference that, during the inception of the filling up of the existing pools in the Pleistocene sediments, in their deepest parts accumulated some deflated sandy materials blown up from dunes, sand-flats or nearby beaches. In this environment only brief or exceptional flooding will have occurred, with a growth of exiguous microbial mats. These accumulations could correspond to that of an area with peritidal dynamics.

In the middle section Facies B and C are seen, which would indicate the alternation of two events (Table 3), one linked to periods when the depressions (and the Pleistocene substratum) were alternately submerged and exposed owing to tide dynamics and the influence of the wind on the accumulation of facies C; the other, which took place in the depressions and the substratum, linked to a frequently tidal flooded environment, with growth of biofilms, alternating with periods of drought and intense evaporation, with sporadic aeolian silty sand accumulations (Facies B).

Facies C will have arisen in an upper intertidal–lower supratidal zone, affected by tidal floods and persistent humidity allowing a faster growth of microbial mats. In this regard Gerdes (2007) reports that, for the formation of a significant succession of biofilms longer exposure time spans are required and, fundamentally, non-burial. This growth will have been interrupted by aeolic events, with the deposition of silty sands covering the mats, and would then have been affected by anoxic subsurface conditions generated below the following mat with the precipitation of authigenic octahedral pyrite in the silty sands. It is also possible to consider a biological degradation of organic matter by nanobacterias in the formation of authigenic pyrite (Howarth, 1988), with the generation of framboidal pyrite. It has also been recognized that the pyrite is most noticeably present in mixohaline marshes in contrast with freshwater, or salt, marshes (Feijtel, 1988).

At the same time facies B is related to deposition in the upper intertidal or lower supratidal sub-environment of a tidal flat

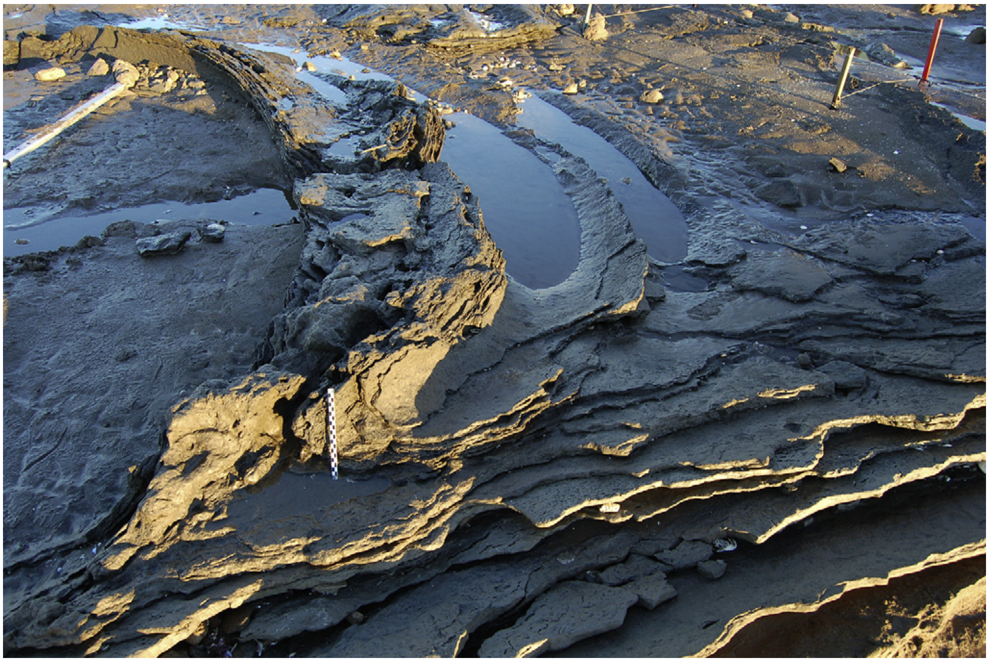

Fig. 6. LO4 sector showing the deformed layers produced by the growth of microbial mats. Note the involuted structure in the upper layers (where the scale is placed).

flooded by spring tides or wind tides. It represents the development and growth of biolaminae and masses consisting mainly of cyanobacteria and sandy silt material, trapped in and bound by the mucilage secreted by some cyanobacteria, the extracellular polymeric matrix (EPS). The biolaminites are composed not only of cyanobacteria (cocoidal or filamentous) but also include heterotrophic bacteria and other groups of microorganisms such as fungi or diatoms (Noffke, 2010).

During subaerial exposition and under processes of intense evaporation, and in semi-arid cycles (water deficit) there was an increase in salt concentration in the water of the pools and a drying out of the depression. Under these conditions, the thanatocenosis of diatoms and the precipitation of gypsum and/or anhydrite and calcite took place, giving rise to the clear laminae. Episodically events of aeolian deposition on the mats will also have occurred. Thus facies B is interpreted as a product of the interaction of the effect of tides with the development of microbial mats, alternating with drought episodes and aeolic events. The accretional process of these biofilms must have been exceedingly slow. Both facies, B and C, are found in all the cores (Figs. 3 and 5).

The association of facies (B, C, and D) recognized in the analysed cores (Table 3) with a significant presence of sandy and silty sand sediments in its lower and middle sectors, plus the small thicknesses of the units, would allow the existence of a wind-tidal flat to be inferred (Miller, 1975). The aeolian deposition processes and flood tides induced by wind were aided by the presence of strong winds. This is an area that bordered a tidal flat in an estuary or a lagoon which was affected by wind-induced tides and at the time had characteristics similar to those of a supratidal zone. Sedimentary records in this sort of tidal flats are complex, and show associations of aeolic and tidal factors (Weimer et al., 1982). The slight differences in elevation in the flat markedly affect the frequency with which the area was flooded (Miller, 1975). This author also acknowledges, via the dating of the microbial mats, that the rate of aggradation of the flat decreases gradually towards the continent and is in the order of 50 mm/100 yrs to 25 mm/100 yrs or even less.

Towards the top of the succession Facies A can be identified, consisting of a bioturbated silty sandy lithofacies recognized as erosional remnants (Table 3). This facies has been related to an intertidal zone, with sandy silt deposition and colonized by crab populations. The bioturbation of these sandy silts by crabs allows them to be correlated to the upper sector of the LO1 sedimentary sequence located nearby (Fontana, 2004) and with the deposits of the fossil crab-bed emerging some 1000 m eastward, dated between 6900 and 6500 yrs BP (Aramayo et al., 1992). It is likewise considered that this would represent the first effects of the Holocene marine ingression in the area with the development of an intertidal flat.

So these sub-zones typical of a tidal flat, developed on an abrasion platform, would have been connected to an early/mid-Holocene estuary at this part of the Buenos Aires provincial coast. In this regard, Frenguelli (1928: 55) was the first to mention the development of a Holocene estuary coast at Monte Hermoso linked to ancient fluvial mouths of the Las Mostazas creek or the Sauce Grande river before, according to the author, their migration eastwards. The formation of the Southern Dune Barrier from approximately 6500 yrs BP (Isla et al., 1996) and the shift of active dunes may have been the fundamental factor in this process.

The described tidal flat can be correlated with the estuarine or intertidal flat described by Gutiérrez Téllez and Schillizzi (2002) and Aramayo et al. (2005) on the basis of the diatomological content from the "El cangrejal" profile. This view is supported by the presence of carbonized *F. juniperoides* stems (Aramayo and Malla, 1995) and those of grasses from the mid-Holocene (Aramayo et al., 1998) which are linked to the development of a marginal lagoon (Aramayo et al., 1998) at the Sauce Grande bathing resort (the "Sauce Grande" profile). It is also presumably connected with the low-energy marginal marine environment, that is, the shallow coastal lake or lagoon of mesohaline conditions, recognized from the presence of foraminiferae and submerged macrophytic pollen and seeds by Fontana (1996, 2004, 2005) at the LO1.

A study of ostracods by Martínez et al. (2010) was made at LO4, where an association of dominant and very abundant populations of *Cyprideis salebrosa*, next to sparse *Sarscypridopsis aculeata* valves

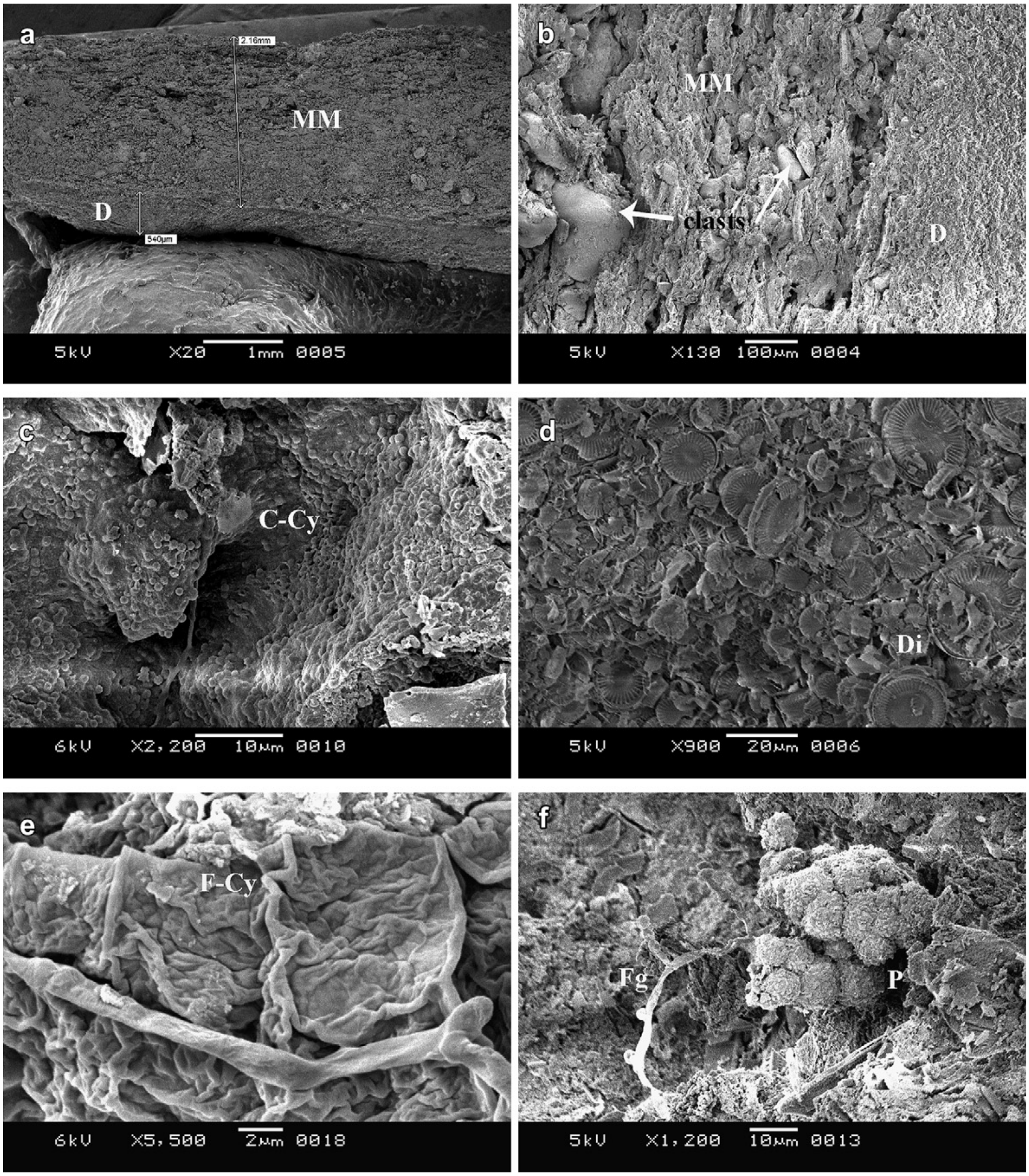

Fig. 7. SEM image of facies B: (a) contact between microbial mat (MM) and diatomaceous layer (D); (b) detail of microbial mat (MM) and diatomaceous layer (D); (c) colony of coccoid cyanobacteria (CCy) and extracellular polymeric substances (EPS); (d) detail of diatomaceous layer with predominance of *Cyclotella meneghiniana* (Di); (e) filamentous cyanobacteria (F-Cy) and ropy biofilms; (h) fungus (Fg) and authigenic framboidal pyrite (P).

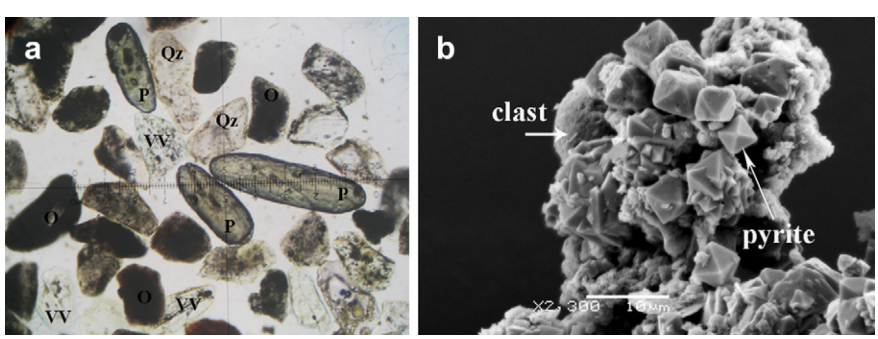

Fig. 8. Mineral composition of sand fraction in lithofacies Sm: (a) Microphotograph of well-rounded piroxene grains (P), grains coated with an authigenic pyrite (O), volcanic glass (VV), Quartz (Qz); (b) SEM image of clast with octahedral pyrites coating.

also indicates the presence of salty bodies of water, enriched in Cl^- and Na^+ through the influence of nearby seawater.

The Monte Hermoso 1 archaeological site was studied on the basis of the pollinic and ostracod collections and of the sedimentary record by Zavala et al. (1992) and Costantini et al., 2006. It was interpreted as a continental zone of interdunal lakes, with a certain marine influence some 400–1000 m away. It might also have been connected with the processes at LO4, as Fontana (2005) proposed for the upper zone of LO1. In this regard, Bayón and Politis (1994), due to the proximity and synchrony of the occupations, have suggested a close link with the La Olla site. There is also a lot of similarity between the Holocene facies of grey pelites, more specifically of discontinuous pelites (Pdis) and deformed pelites (Pdef) and facies B and C respectively are recognized to be of the succession he described (LO4).

Also, a similar process in the sedimentary infilling of LO3 and LO4 can be postulated on the basis of observations in LO1 by Fontana (1996, 2004, 2005), Johnson et al. (2000), and Grill et al. (2007), although LO1 is probably slightly older. Datings taken from sea mammal femora in LO1 gave ages of 7300 and 6600 yrs BP (Johnson et al., 2000).

Finally it must be stated that the facial variations in the succession from the lower section (facies B, C and D) to the upper (facies A) leads to the inference of a gradual passage from a supratidal sub-environment to a lower supratidal-upper intertidal and finally intertidal zone. This passage is presumably closely related not only to climatic factors, mainly the wind, but to the transgressive process, with the consequent displacement of estuarine conditions (from the outer estuary) inland. This aspect closely coincides with the advance of the coastline around 6000 yrs BP inferred by Grill and Quattrocchio (1996). This is on the strength of marine palaeomicroplankton recorded in a fossil profile at the mouth of the Napostá Grande stream in the Bahía Blanca estuary, the deposits from coastal flatlands present in the Sauce Grande river area dated by Aramayo et al. (2005) and the ingressive records studied and dated by Gonzalez (1989) and Aliotta et al. (2008, 2009) in the Bahía Blanca estuary. This is how the abrasion platform exposed during the early–mid Holocene with seaward slopes could have been affected by pre-maximum transgressive peritidal deposition and later covered by the aeolic deposits that formed the BMA. An example of them would be the dunes resting on estuarine deposits at the Quequén Grande river dated at 5740 ± 110 yrs BP (Isla et al., 2001).

It is specially important in many tidal flats to consider the fluctuation of energy and great variety in the strength of currents common not only in a single tidal cycle, but over monthly or even seasonal cycles, or under varying wind conditions. So the contact between the supratidal zone and the intertidal flat zone may be gradual and can vary over time, particularly in the wind tide flat (Weimer et al., 1982). Salinity is another important parameter to be measured in the development of biological communities in these tidal flats because it can vary in the different sub-environments across the tidal flat and under different climatic conditions: firstly, because of the regional variations both in freshwater inflows from rivers and in salt water interchange from tidal passes; and secondly on account of seasonal and cyclic climatic variations that produce substantially higher than normal salinities during dry periods and lower than normal salinities during wet periods.

4.2. Site formation processes

Nearly all the archaeological remains (stone, bone, and wooden artifacts and abundant faunal remains) come from the interlaminated levels of facies B. The materials were generally in a horizontal position, resting on the surface of the natural laminae without disruptions. In cases in which they were inclined they did so following the inclination of the laminae (Fig. 9). Also to be noted is that several collections of bones were articulated, in some cases as many as 6 pieces, which suggests very little post-depositional displacement.

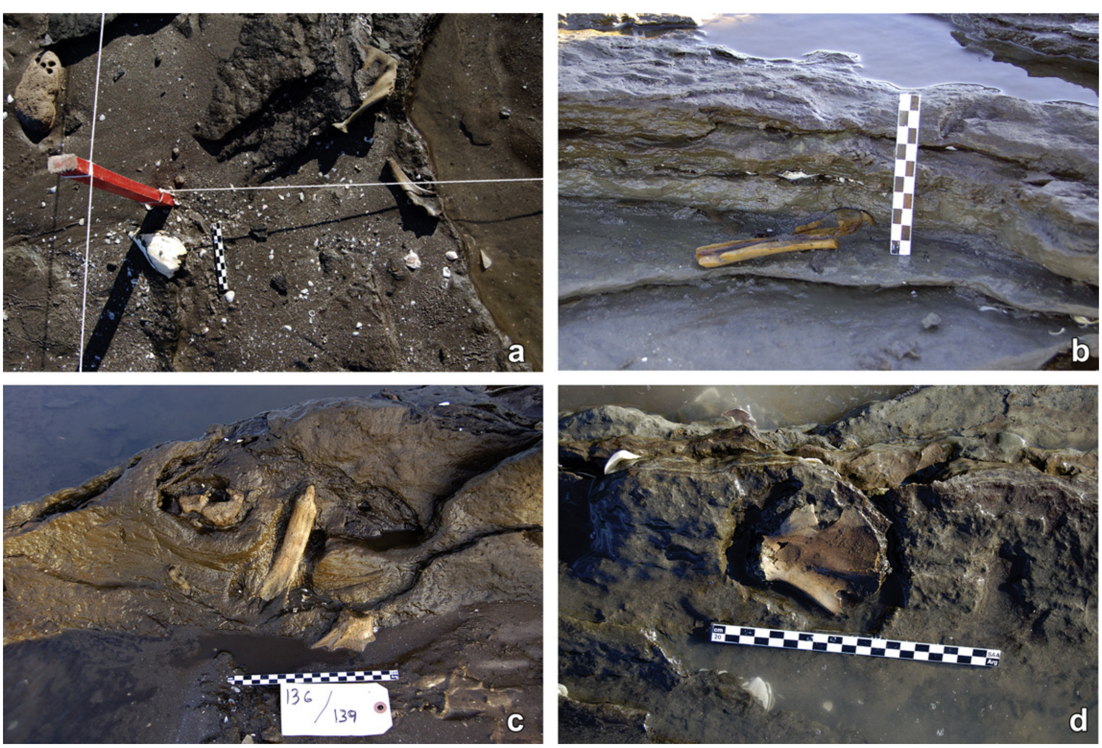

Fig. 9. Photograph of different examples of bones in situ, following the orientation of the layers. Note the vertical position of the seal scapulae in (d).

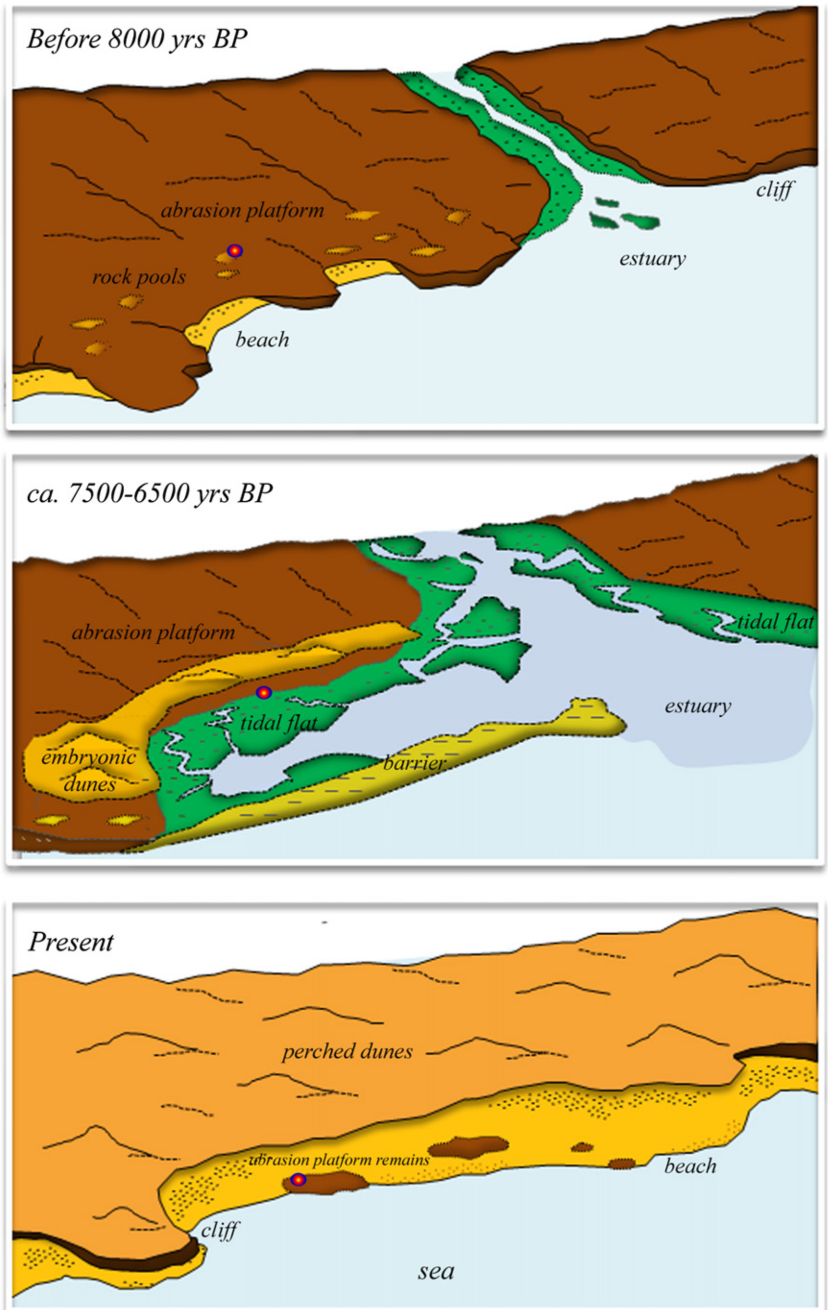

Fig. 10. Schematic representation of the environmental evolution of the coastal area of Monte Hermoso. The circle shows the position of the site throughout the time.

In the preservation of the site it is necessary to highlight the biostabilization by microbial mats of the sedimentary structures and archaeological remains (ripples, footprints, bones, etc.) preventing their erosion by wind, turbulence currents, and waves (Cuadrado and Pizani, 2007). In this regard, the microbial mats increase the critical shear stress value required to resuspend deposited grains (Cuadrado and Pizani, 2007; Friend et al., 2003). Cuadrado and Pizani (2007) and Carmona et al. (in press) verified the effect mentioned on observing the preservation of footprints over several months even with the submersion of the tidal flat under spring tides and its being affected by currents and waves, including strong storm waves.

Another aspect of great importance in the formation process of the site is that the mats are waterproof to some degree (extremely or quite waterproof). This quality was mentioned as relevant in the preservation of ephemeral sedimentary biological structures, such as footprints and traces of locomotion. So the phenomenon of the waterproof mats must also be seen as a fundamental factor in isolating the more labile archaeological material from degrading or destructive post-depositional geochemical conditions (principally for wood) such as the conditions generated by the circulation of waters with an acid pH. The generation of anoxic (Eh negative) sectors below each mat must also be considered as acting in the preservation of the material; likewise, the degrees of relative humidity, the growth of microbial mats, and cyclic sedimentation are also variables to bear in mind when considering the preservation of the material, as was pointed out regarding the preservation of footprints (Marty et al., 2009).

Finally the preservation of the archaeological site LO, principally in facies C and B, was favoured by being lodged in the sedimentary filling-in of the depressions, which generated their post-depositional post-ingressive isolation from agents of erosion. To this has been added the protection provided by the present marine littoral sand.

5. Conclusions

On the basis of the analyses of LO4, and integrating the available information for LO1 and LO3, it can be concluded that the sedimentary succession of the La Olla site represents the coastal environmental changes during the early–mid Holocene just before the ingression reached its maximum. During this interval a tidal flat developed on the Pleistocene abrasion platform, which occurs in protected areas of the coast associated with an estuary. In these low relief and relatively low energy areas diverse sub-environments develop in terms of the extent of the tides, the time interval in which they were under water and the climatic conditions (wind and water deficit).

On the basis of the sedimentological results, the development of two zones during the early to mid-Holocene was ascertained. The lower part of the sedimentary succession will have developed before *ca*. 7500 yrs BP, and was interpreted as the accumulation of sands from nearby dunes or beaches and the development of an area sporadically prone to flooding similar to supratidal zone (Fig. 10). This is how there will have been a predominance of wind deposition in the pools formed in the abrasion platforms and they will, on occasion, have been reached by exceptional or wind-induced tides (facies D). Later during *ca*. 7000 yrs BP they will have been affected more often by high spring tides or wind-induced ones (Facies B and C) and under marked climatic seasonality with episodes of water shortage (Fig. 10). During this time, a mixohaline marsh developed in this upper intertidal-lower supratidal zone.

Gradually towards *ca*. 6400 yrs BP this sector of the tidal flat will have been reached more frequently by the tides, with the origination of an intertidal sub-environment and the development of a crab-bed. The upper sedimentation events would coincide with the transgressive maximum. Their absence in the record of this area leads us to think that they have been eroded and/or covered by the deposits from the BMA dunes (Fig. 10). It should be noted that the Monte Hermoso 1 site could be synchronous with La Olla if the altitudinal variations in the palaeorelief offered by the abrasion platform (Pleistocene sediments) that emerge in the area and which correspond to the Lower Wakes in Zavala et al. (1992) are considered.

In LO3 and LO4 the lapse of the human occupation would have been limited, with a maximum antiquity of 6960 ± 71 yrs BP and an estimated mean of 6911 ± 24 yrs BP. Within this tidal environment, and mainly in the mixohaline marsh, the occupation of Pampas hunter-gatherers took place. It is probable that La Olla represents transitory camp-sites for activities related to the butchering of sea-mammals (Bayón and Politis, in press). Finally, the first anthropic signs at LO are recorded at around 7400 yrs BP, and will have continued with greater intensity till *ca*. 6400 yrs BP. During this time a strong human presence is detected at LO3 and LO4 at around 6960 yrs BP. The start of the sedimentation of the depression seems to coincide with the first pieces of evidence of human adaptation to littoral Pampas environments since, at MH1, there are datings of human bones at 7866 ± 75 yrs BP, the isotopic values of which already point to significant consumption of marine resources (Politis et al., 2009).

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