HOLOCENE PALAEOENVIRONMENTAL EVOLUTION OF THE PAMPA COASTAL PLAIN (ARGENTINA) BASED ON CALCAREOUS MICROFOSSILS

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ABSTRACT – In the present contribution, we studied assemblages of benthic foraminifers, ostracods and charophytes in a Holocene outcrop in the southeast of the La Pampa coastal plain in Argentina. The main species recorded were *Spirillina* sp. A, *Buccella peruviana*, *Ammonia parkinsoniana*, *A. tepida*, *Elphidium margaritaceum* and *E. gunteri* among foraminifers, *Limnocythere cusminskyae* and *Cyprideis salebrosa* among ostracods. These species allowed to determine restricted environments characterized by significant changes in salinity. Qualitative and quantitative studies conducted on the faunal content in the outcrop allowed to identify four environments closely linked to the sea-level changes occurred during the Holocene. In a first stage, between 7500-7200 and 6300-6200 cal yr BP represent the development of a non-marine environment. Around 6300-6200 cal yr BP this environment change to brackish-estuarine with moderate energy. Sometime before c. 6000-5700 cal yr BP a clear-water lagoon, probably oligohaline, with abundant submerged vegetation is inferred. In a final stage, from 2300-2000 to 2000-1700 cal yr BP, a continental environment not influenced by the proximity of the sea was established. The new calcareous microfossils evidences and the new chronologies provided by this work, allowed us to adjust the moment of the maximum sea level rise during the Holocene transgression and contribute to a better knowledge of the evolution of coastal paleoenvironments in relation to sea level changes.

Key words: La Pampa coastal plain, paleoenvironments, mid- to late Holocene, sea level changes, calcareous microfossils, Argentina.

RESUMO – Na presente contribuição foram estudadas assembleias de foraminíferos bentônicos, ostracodes e carófitas num afloramento localizado a sudeste da planície costeira de La Pampa, Argentina. As principais espécies registradas foram *Spirillina* sp. A, *Buccella peruviana*, *Ammonia parkinsoniana*, *A. tepida*, *Elphidium margaritaceum* e *E. gunteri* entre os foraminíferos, *Limnocythere cusminskyae* e *Cyprideis salebrosa* entre os ostracodes. Estas espécies permitiram determinar ambientes restritos, caracterizados por alterações significativas na salinidade. Estudos faunísticos qualitativos e quantitativos conduziram à identificação de quatro ambientes estreitamente relacionados às mudanças no nível do mar que ocorreram durante o Holoceno. No primeiro estágio, entre 7500-7200 e 6300-6200 cal. anos AP, foi identificado o desenvolvimento de um ambiente não marinho. Em torno de 6300-6200 cal. anos AP o ambiente se transforma num estuário salobro com níveis moderados de energia. Algum tempo antes c. 6000-5700 cal. anos AP desenvolveu-se um ambiente lagunar de águas claras, provavelmente oligohalino, com abundante vegetação submersa. Em um estágio final, entre 2300-2000 e 2000-1700 cal. anos AP, estabeleceu-se um ambiente continental sem influencia marinha. Novas evidências trazidas pelos microfósseis calcários e as novas cronologias fornecidas por este estudo, permitiu ajustar o momento de máxima elevação do nível do mar durante a transgressão holocênica e contribuir para um melhor conhecimento da evolução dos paleoambientais costeiros em relação às alterações do nível do mar.

Palavras-chave: planície costeira de La Pampa, paleoambientes, Holoceno médio a tardio, mudanças do nível do mar, microfósseis calcários, Argentina.

INTRODUCTION

The South American Atlantic coast has been extensively affected by the sea-level fluctuations that followed the Last Glacial Maximum. After this maximum, the sea level rose rapidly, exceeding the modern level between 9000 and 7000 yr BP in Tierra del Fuego, between 6500 and 6000 yr BP along the Pampa plain of Argentina and at 5500 yr BP in Brazil (Isla, 1989). In the Pampa coastal plain, several authors have proposed different sea level curves that record the relative level of the sea during the maximum transgression. In the Río de la Plata River (northeast of the Pampa coastal plain), the relative level of the sea about 6000 yr BP was 6.5 m above the present one (Aguirre & Whatley, 1995; Cavallotto *et al.*, 2004; Violante & Parker, 2004). In Mar Chiquita (southeast of the Pampa coastal plain), the maximum sea level around 6000-5000 yr BP has been proposed to be about 2-2.5 m above the present one (Schnack *et al.*, 1982; Isla, 1989). In the Bahía Blanca estuary (southwest of the Pampa coastal plain), the sea level 6000 yr BP was between 5 and 6 m above the present one (González, 1984, 1989; Gómez & Perillo, 1995). All these curves later show a regressive trend characterized by a stepped sea-level fall to the present position (Vilanova *et al.*, 2006).

The Holocene marine fluctuations of the Pampa plain allowed large sectors to be affected by processes generated by changes in coastlines, giving rise to coastal environments associated with coastal barriers, beach ridges, coastal lakes and lagoons (Violante *et al.*, 2001; Schnack *et al.*, 2005; Laprida *et al.*, 2007). In order to refine the interpretations of the evolution of these environments, several studies using indicators for different groups of microfossils, such as pollen, diatoms, foraminifers, ostracods and nanofossils have been carried out (Ferrero, 1996, 2006, 2009; Stutz *et al.*, 1999, 2005; Espinosa, 2001; Espinosa *et al.*, 2003; Prieto *et al.*, 2004; Gómez *et al.*, 2005, 2006; Hassan *et al.*, 2011; Calvo-Marcilese *et al.*, 2013).

Benthic foraminifera and ostracods are widely recognized as useful tools in the reconstruction of aquatic environments, being good indicators of, among others, paleosalinity, paleodepth, and other biotic and abiotic features. Foraminifera inhabits mainly marine and brackish environments while ostracods inhabits continental as well as marine and transitional water bodies, so the joint study of both is complementary and particularly useful in the reconstruction of coastal environment. Charophytes are multicellular submerged green algae, recorded as fossil mainly by their reproductive structures. They live in various types of freshwater aquatic environments, with only a few species occurring in brackish water. They are most common at the bottom of clear lakes, usually forming extensive growths (Lee, 2008). Several studies applying these groups in paleoenvironmental reconstructions have been carried out on the Pampa coastal plain (Bertels & Martínez, 1990, 1997; Laprida & Bertels-Psotka, 2003; Fontana, 2004; Gómez *et al.*, 2005, 2006; Laprida *et al.*, 2007; Cusminsky *et al.*, 2009; Ferrero, 2006, 2009; Marquez & Ferrero, 2011; Calvo-Marcilese *et al.*, 2011, 2013).

In this study, we recovered foraminifera, ostracods and charophyte oogonia from a Holocene sedimentary outcrop near Las Brusquitas Creek, southeast of the Pampa coastal plain. Previously, other authors have carried out studies on the sedimentology, micropaleontology, palynology, and malacology as well as isotope analysis on the same sequence (Espinosa *et al.*, 1984; D'Antoni *et al.*, 1985; Isla *et al.*, 1986; Bonadonna *et al.*, 1995; Tonni *et al.*, 1999; Prieto *et al.*, 2003; Vilanova *et al.*, 2006). The aims of the present study are 1) to contribute to the knowledge of the environmental evolution of the coastline of the Pampa plain in relation to sea level changes, based on the combined study of foraminifera, ostracod and charophyte assemblages recovered from Las Brusquitas outcrop and 2) to assess the response of these assemblages to environmental changes compared with other proxies.

STUDY AREA

The province of Buenos Aires presents a very varied geomorphology. It has over 1300 km of a diverse coastline, including the low flood plain of the Río de la Plata Estuary, the wetlands surrounding Samborombón Bay, Bahía Blanca Estuary and Anegada Bay, succeeded by the cliffs of the Mar del Plata area (Diez *et al.*, 2007).

The study area is located in the southeastern part of the Pampa coastal plain (Buenos Aires province) (Figure 1). Las Brusquitas outcrop (38° 14' S - 57° 46.5' W) has a drainage basin of 58 km² on a lowland depression formed by a low gradient valley, which developed during the Pleistocene. The landscape, along the coastal area, is flat with a relief more pronounced eastward and originally dominated by herbaceous vegetation. The climate is temperate and humid. The air temperature ranges from 8 to 21°C and precipitation from 40 to 95 mm/month with summer months (December to February) rainier than winter months (June to August) (Isla & Espinosa, 1998).

This area has a microtidal regime dominated by episodic storms from the south. This storm system is greater eastward and northward toward open sea conditions and a narrow continental shelf. The mean wave height is about 0.91 m in Mar del Plata and significantly decreases westward (Isla & Espinosa, 1998).

LAS BRUSQUITAS LB SITE PROFILE

The material comes from a sedimentary sequence 4 m long from Las Brusquitas (Figure 2). Based on Prieto *et al.* (2003) four main stratigraphic units have been distinguished from the bottom to the top. Unit 1 consists of deposits of fine quartz sand, more or less clayey dark greenish-gray compact, passing to reddish brown silty sand, both without mollusks. Towards the top of this unit, the sequence continues with a deposit of very fine sand, reddish brown clay, rudely stratified, with intercalations of friable sand and a bank of marine mollusks which is located at 2.4 ± 0.2 m asl (Espinosa *et al.*, 1984). Unit 2 is constituted by a succession of silt, clay and

Figure 1. Location map showing the position of Las Brusquitas outcrop.

Figure 2. Sedimentary profile of Las Brusquitas outcrop (based on Vilanova *et al.*, 2006).

fine sand well stratified with several discontinuities. The basis of this level consists of intercalations of sand and mud with abundant shells: *Heleobia parchappii*, *Heleobia australis* and some *Tagelus plebeius* to the top. Unit 3 consists of clayey silts with coarse stratification and whole and fragmented shells of *H. australis* and *H. parchappii*, *Biomphalaria peregrina*, *Gundlachia concentrica* and fragmented remains of Mytilidae. Unit 4, which lies unconformably on Unit 3, conform by eolian sand dune deposits with evidences of pedological processes.

MATERIAL AND METHODS

The outcrop was sampled every 2, 5 or 10 cm depending on the sedimentological features from 335 to 118 cm. A total of 30 samples were obtained and water washed through a 63- μ m mesh screen (Zonytest No. 230). Systematic analysis was based on Loeblich & Tappan (1988) for foraminifera genera and mainly on the works by Boltovskoy (1954a, b, 1957), Boltovskoy *et al.* (1980), Ferrero (2006, 2009) and Calvo Marcilese (2011) for species. The quantitative values determined were total abundance, relative species abundance and diversity. To calculate total abundance, we calculated the number of specimens present in 10 g of gross sediment per sample. Regarding diversity, we calculated species richness S , Shannon-Wiener (H) and Fisher's α indices. Taphonomic signatures, such as fragmentation, oxidation and alteration were taken into account to improve environment characterization. Ostracoda were determined based mainly on Ramírez (1967), Bertels & Martínez (1990, 1997), Ferrero (2006), Laprida (2006), Ramón-Mercau *et al.* (2014). Quantitative analysis

was performed considering adult valves. Ostracoda taxa according their saline preferences were classified in fresh-water/fresh-brackish water and marine-brackish. Additionally, adult/juvenile ratio was used to improve taphonomic analysis. Charophyte gyrogonites abundances were also recorded to complete paleoenvironmental analysis.

The diagrams of relative frequencies and outcrop zoning based on foraminiferal and ostracod assemblages was done using Coniss software, included in the TILIA 1.7.16 statistic package (Grimm, 1991). The analysis considered only the species with relative abundances equal to or greater than 1% in at least two levels of the core. Standardized Euclidian distance was applied as the distance coefficient, and data transformation by standardization to mean 0 and typical deviation 1 was used. Clusters were formed according to the sum of squared error hierarchical clustering method (Grimm, 1991).

The most representative specimens were photographed with a scanning electron microscope (Jeol JSM-6460LV) and then stored at the repository of the Instituto de Geología de Costas y del Cuaternario, Universidad Nacional de Mar del Plata, Buenos Aires, under the initials CGC-F and CGC-O.

Radiocarbon dates

Radiocarbon dates and calibrations are presented in Table 1. Two new radiocarbon dates were performed for this study in order to adjust the dates made over 20 years ago (Espinosa *et al.*, 1984; Bonadonna *et al.*, 1995). An anomalous chronology was observed between one of the new dating (303-304 depth) and that made by Espinosa *et al.* (1984). Because the new dates have been made with the technique of AMS (Accelerated Mass Spectrometry) and the selected material offers greater accuracy has chosen not to consider, for discussion, the dating of Espinosa *et al.* (1984).

All radiocarbon dates named in this work has been calibrated with Calib 7.0.4 software (Stuiver *et al.*, 1986) using the curve for the Southern Hemisphere (SHCal13) (Hogg *et al.*, 2013). Correction for reservoir effect was not made because the existing database is still insufficient and the calculated values for the Argentine coast range widely from 191 to 2482 yr. probably related to differences

in the contributions of carbonates dissolved in rivers and groundwater (Gómez *et al.*, 2008).

RESULTS

Of the 30 samples observed, level 335 was sterile and no foraminifera were found in levels 310, 170 and 155-118 cm. Throughout the sediment sequence, 11 genera of benthic foraminifera were determined, distributed among 11 species and 5 species with open nomenclature (Figure 3, Appendix 1). Total abundance ranged from 7 (level 163 cm), *S* extend from 1 (levels 290, 249-236, 216-205, and 188-183 cm) to 9 (level 280 cm), values for *H* ranged from 0 (levels 290, 241-236, 216-183 cm) to 1.6 (level 280 cm), and Fisher's α from 0 (level 163) to 2.7 (level 280 cm) (Figure 4). In general, foraminiferal fauna is composed of tests with a variable state of preservation, with a few fragmented materials. At the bottom of the section are mostly the tests having orange stain. Towards the middle part, the material presents a regular preservation state with damage not exceeding 5% of the original shell. Towards the top of the section there is less material, more fragile, often damaged but not exceeding 30% of the original test.

Ostracoda were present in almost all levels. They were very abundant mainly between levels 228 cm and 183 cm (up to 30750 valves/10 g), scarce in levels 315-304 cm, 294-290 cm and 118 cm (less than 100 valves/10 g) or absent (levels 335-325 cm). A total of 20 taxa were determined (Appendix 1). Most of them are well represented by adults and juvenile stages. Juveniles range from 45% to 95% of total valves along the sequence (Figure 4). Only juvenile valves of *Candona* sp. and *Darwinula*? sp. and pieces of adults and juveniles of *Chlamydotheca incisa* were recovered. A good preservation of valves was common, but in some levels part of the very abundant and fragile juvenile valves was fragmented. Diversity values, considering only adults, ranged from 1 (levels 188-170cm) to 10 (level 270 cm) for *S*, and from 0 (level 188-170 cm) to 1.9 (level 300 cm) for *H*. Assemblages were dominated by fresh-water/brackish ostracods; marine-brackish group was only present in a few

Table 1. Radiocarbon dates obtained from Las Brusquitas outcrop.

Depth (cm)	¹⁴ C yr BP	Cal BP 2σ	Material	Laboratory no.	References
120-125	2040 ± 80	2154-1741	Organic matter	Beta 152124	Prieto <i>et al.</i> (2003)
161-163	2210 ± 70	2332-2010	Organic matter	Beta 157779	Prieto <i>et al.</i> (2003)
228	3921 ± 33	4418-4224	Organic matter	D-AMS 010663	This study
225-230	3900 ± 70	4441-4082	<i>Heleobia australis</i>	LP 317	*
250-260	5180 ± 80	6024-5660	<i>Tagelus plebeius</i>	LP 307	*
280-290	6190 ± 160	7336-6669	<i>Tagelus plebeius</i>	AC 434	Espinosa <i>et al.</i> (1984)
303-304	5425 ± 33	6284-6171	Organic matter	D-AMS 010662	This study
325-330	6380 ± 60	7425-7156	<i>Mytilus platensis</i>	Beta 156145	Prieto <i>et al.</i> (2003)

* (Bonadonna *et al.*, 1995; Vilanova *et al.*, 2006; Latyr, p.c.)

Figure 3. A, *Spirillina* sp. A, SV, CGC-F345, Level: 241 cm. B, *Spirillina* sp. A, UV, CGC-F346, Level: 236 cm. C, *B. peruviana* (d'Orbigny), UV, CGC-F347, Level: 270 cm. D, *A. parkinsoniana* (d'Orbigny), SV, CGC-F348, Level: 270 cm. E, *A. parkinsoniana* (d'Orbigny), UV, CGC-F349, Level: 270 cm. F, *A. tepida* Cushman, SV, CGC-F350, Level: 259 cm. G, *A. tepida* Cushman, UV, CGC-F351, Level: 259 cm. H, *E. gunteri* Cole, CGC-F352, Level: 270 cm. I, *E. margaritaceum* Cushman, CGC-F353, Level: 270 cm. J, *Cypridopsis vidua*, LV, CGC-O-130, Level: 137 cm. K, *Sarscypridopsis aculeata*, C from left side, CGC-O-131, Level: 228 cm. L, *Cyprideis salebrosa*, female RV, CGC-O-132, Level: 270 cm. M, *C. salebrosa*, male LV, CGC-O-133, Level: 259 cm. N, *Limnocythere cusminskyae*, female RV, CGC-O-134/1, Level: 236 cm. O, *L. cusminskyae*, male RV, CGC-O-134/2, Level: 236 cm. P, *Limnocythere solum*, female LV, CGC-O-135/1, Level: 270 cm. Q, *Limnocythere multiperforata*, male LV, CGC-O-136, Level: 270 cm. R, *Cytherura dimorphica*, female RV, CGC-O-137, Level: 223 cm. S, *Limnocytheridae* gen. et sp. indet, female RV, CGC-O-138/1, Level: 249 cm. T, *Limnocytheridae* gen. et sp. indet, female RV internal view, CGC-O-139, Level: 259 cm. U, *Limnocytheridae* gen. et sp. indet, male LV, CGC-O-140, Level: 223 cm. SV: spiral view; UV: umbilical view; LV: left valve; RV: right valve; C: caparace; Scale, 100 μ m (letters C, G, J-Q, U); 50 μ m (letters D-F, H-I, R); 20 μ m (numbers A, B).

Figure 4. A: absolute abundance in 10 g of sediment (F: foraminifera, ad O: adult ostracod valves, juv O: juvenile ostracod valves, S: species Richness, H: Shannon-Wiener diversity index, α : Fisher α index, f/f-b/m-b: groups of species frequencies according with salinity tolerances of ostracods (f: mainly freshwater; f-b: freshwater-brackish; m-b: marine-brackish species), ad/juv: proportion of adults/juveniles of ostracods. Continuous line: foraminifera, dashed line: ostracods.

Figure 5. Stratigraphical distribution and relative abundances of foraminifera, ostracods (species with $\geq 1\%$) and charophytes at Las Brusquitas outcrop (LB). It includes radiocarbon dates (^{14}C yr BP) and the cluster analysis showing the recognized zonation.

levels in the lower section of the sequence (levels 300; 284–270; 259; 228–223 cm).

Gyrogonites, non-calcified oogonia and vegetative remains of charophytes were common mainly from 284–197 cm.

Cluster analysis showed two zones (Figure 5).

Zone LB-I (335–310 cm): This zone represents the lower part of the sequence and is comprised of four levels without foraminifera while a few juvenile valves of *Limnocytheridae* and charophyte gyrogonites were present.

Zone LB-II (310–118 cm): This zone was divided in two subzones:

Subzone LB-IIA (310–259 cm):

This subzone presents the highest diversity values in forams and ostracods and also the highest foraminifera abundances of the entire sequence. *Buccella peruviana* was the most abundant species of the total assemblage mainly in the lower part of this subzone being more than 40% and the only species at 290 cm level. *Ammonia tepida* and *Ammonia parkinsoniana* were also well represented. Smaller percentages (around 1%) of *Elphidium gunteri* and *Elphidium margaritaceum* were found. *Spirillina* sp. A (1%) was present in the uppermost level of this subzone. Ostracoda assemblages were composed mainly of *Cyprideis salebrosa* and *Limnocythere cusminskyae*. The level 300 cm was more diverse: *Limnocythere multiperforata*, *Limnocythere solum*, *Cytherura dimorphica*, *Pellucistoma elongata* and *Leptocythere* sp. were also present. The increasing abundances of charophyte gyrogonites, oogonia and proportions of *Limnocytheridae* along with the slight decrease in *C. salebrosa* were characteristic of the upper part of this subzone. *Subzone LB-IIB* (259–118 cm):

This comprised of 17 levels and is characterized by the absence of *B. peruviana*, absolute dominance of *L. cusminskyae* and the scattered presence of *A. parkinsoniana*, *A. tepida* and *C. salebrosa*. This subzone was divided in three subzones:

Subzone LB-IIB1 (259–183): This subzone presents the highest abundances of ostracods and charophytes. Among foraminifera, *Spirillina* sp. A was dominant (more than 55%) in the whole subzone, while *A. tepida* (less than 30%) and *A. parkinsoniana* (less than 15%) were found only in some levels. *L. cusminskyae* was accompanied by *Limnocytheridae* gen. et sp. indet. (up to 33%). *Sarocypridopsis aculeata*, *Potamocypris* sp. were found regularly and scarcely (less than 10%), while *C. salebrosa*, *Heterocypris incongruens* and *C. dimorphica* were also present in low percentages only in few levels. Charophyte gyrogonites and non-calcified oogonia were very abundant, and parts of their vegetative structures were also found even associated to the gyrogonites.

Subzone LB-IIB2 (183–128): In this subzone only ostracods were present with very fluctuating abundances. *L. cusminskyae* was dominant while *H. incongruens*, *Cypridopsis vidua*, and *S. aculeata* were present in some levels.

Subzone LB-IIB3 (128–118 cm): This subzone is comprised of one sterile level.

DISCUSSION

Faunal assemblage

Foraminiferal assemblages were represented by *Buccella peruviana*, *Ammonia parkinsoniana* and *Ammonia tepida* which were abundant at the lower middle part (subzone LB-IIA) of the succession, accompanied by smaller percentages of *Elphidium gunteri* and *Elphidium margaritaceum*. *Spirillina* sp. A dominated at the upper middle part (subzone LB-IIB1), being exclusive in some levels.

According to Murray (2006), *Buccella* inhabits lagoons and the inner shelf (0–100 m) in cold temperate waters. *B. peruviana* is one of the most abundant and frequent species of the inner shelf and its morphotypes have been recorded in brackish water environments with variations in salinity such as the Río de la Plata River (Argentina), Lagoa dos Patos (Brazil), Chui Creek (Uruguay), and coastal environments in the south of the Pampa coastal plain (Boltovskoy, 1957; Boltovskoy & Lena, 1974; Boltovskoy *et al.*, 1980; Alperin *et al.*, 2008; Cusminsky *et al.*, 2006; Marquez *et al.*, 2013). Recent analyses have determined that *B. peruviana* f. *campsi* and *B. peruviana* f. *frigida* represent different developmental stages of the same species, *B. peruviana* (Calvo-Marcilese & Langer, 2012).

The genus *Ammonia* has a wide distribution and great morphological variability, bearing high salinity ranges. Several authors agree on the existence of a single species *A. beccarii* and different forms, varieties or ecophenotypes (Schnitker, 1974; Wang & Lutze, 1986; Walton & Sloan, 1990). Walton & Sloan (1990) recognized three basic forms of *A. beccarii*: f. *beccarii*, f. *parkinsoniana* and f. *tepida*. Molecular studies have suggested the separation of several of the forms attributed to *A. beccarii* in different species (Pawlowski *et al.*, 1995; Hayward *et al.*, 2004.). The specimens studied here were included in *A. parkinsoniana* and *A. tepida* (according to Calvo-Marcilese, 2011). *A. beccarii* f. *parkinsoniana* (considered in this study as *A. parkinsoniana*) has been recorded in environments with large variations of salinity or very low salinity (lower than 1 ‰) such as Quequén Grande River, Mar Chiquita Lagoon, and Río de la Plata River in Argentina, and Lagoa dos Patos in southern Brazil (Closs & Madeira, 1968; Boltovskoy & Boltovskoy, 1968; Boltovskoy & Lena, 1974; Lena & L'Hoste, 1975). *A. beccarii* f. *tepida* (considered in this study as *A. tepida*) is also common in estuaries, brackish and hyperhaline lagoons with sandy carbonate-rich sediments and salt marshes (Eichler *et al.*, 1995; Debenay *et al.*, 1998; 2001). In Araruama lagoon (Brazil), an increase in the proportion of *A. tepida* has been related to fresh water input and the enrichment in nutrients (Debenay *et al.*, 2001). In intertidal environments of the Pampa coastal plain, *A. parkinsoniana* and *A. tepida* are distributed in a very wide range of salinities, but appear in higher proportion in low marsh and subtidal environments (Calvo-Marcilese & Pratolongo, 2009; Marquez *et al.*, 2013).

The genus *Elphidium* is widely distributed along the inner shelf of Argentina and has been recognized worldwide (Boltovskoy, 1976; Murray, 2006). *E. gunteri* has been cited

for brackish environments, marshes, estuaries and coastal lagoons (Boltovskoy & Boltovskoy, 1968; Boltovskoy, 1976; Scott *et al.*, 1990; Cusminsky *et al.*, 2006; Marquez *et al.*, 2013). *E. margaritaceum* has been characterized by Alve & Murray (1999) as a stenohaline species and has been found living in the Baltic Sea, at stations with >24‰ salinity. It has been cited for the Argentine continental shelf, in bays, estuaries and littoral environments (Boltovskoy, 1954b, 1957; Boltovskoy *et al.*, 1980; Marquez *et al.*, 2013).

Modern species of *Spirillina* have been reported from algal vegetation of sublittoral bank environments (Western Australia), in lagoons of Barbuda (West Indies) and in shallow waters associated with *Macrocystis pyrifera* holdfasts in Magellan Strait (Davies, 1970 in Reolid *et al.*, 2008; Brasier, 1975, Hromic *et al.*, 2004). These forms live on seaweeds, crawling around by means of attaching pseudopodia while grazing on epiphytic diatoms and other microalgae (Berthold, 1976; Kitazato, 1988 in Reolid *et al.*, 2008). After a comprehensive review of known species of *Spirillina* and related genera, we think that *Spirillina* sp. A is a new species of this genus. It only is comparable to *Spirillina* sp. A reported by Boltovskoy & Boltovskoy (1968) in the lower section of Quequén Grande River at very low salinity values (< 1 ‰). Due to the abundance and the particular kind of assemblages in which this species was found, a future study in order to clarify its taxonomic status will be carried out.

In this study, *Spirillina* sp. A has been found forming monospecific assemblage at the upper middle part (subzone LB-IIB1) of the sequence. A 'monospecific' fauna (dominance ≥80%) occurs in sheltered, often brackish, intertidal or shallow-subtidal environments, never deeper than 25 m (Sen Gupta, 1999; Murray, 2006; Hayward, 2014). These stressed habitats may suffer: temperature extremes when the tide is out; extremes of dryness especially at higher sites that may not be inundated by the tides for several months on end; and sometimes, extremes of salinity, from weakly hyperhaline (40 psu) to hypohaline or even fresh water after heavy rain, when the tide is out (Hayward, 2014). We judge that *Spirillina* sp. A is species which probably inhabits stressed environments, primarily those stressed by low salinity.

Charophytes were better represented at medium levels (subzones LB-IIA and LB-IIB1) of the sequence. Most of charophytes species are limited to water bodies with clear, alkaline waters and low nutrient budget (García, 1994; Apolinarska *et al.*, 2011). It is remarkable that *Spirillina* and charophytes were associated in most levels. This joint presence could allow us to infer for *Spirillina* also clear water preferences along with a possible epiphytic way of living.

Ostracod assemblages presented relatively low diversity. In the lower middle part (LB-IIA) of the sequence, *Limnocythere cusminskyae* and *Cyprideis salebroso* were the main components of the assemblages. Upwards, Limnocytheridae species, in particular *L. cusminskyae*, were dominant. *C. salebroso* is able to bear great salinity variations and is commonly associated with brackish environments, like estuaries or coastal lagoons (Ornellas & Würdig, 1983; Dias Brito *et al.*, 1988), but also inhabits lentic environments

without marine connection (Ramírez, 1967; Laprida, 2006). *L. cusminskyae* lives in permanent lagoons or lotic waters (Laprida, 2006). According to Laprida (2006) and Laprida *et al.* (2014) this species prefers freshwater-oligohaline and highly alkaline waters, where it may be dominant, whereas D'Ambrosio (2014) considers this species (named as *Limnocythere staplini*) as an indicator of saline conditions taking into account that, even though it was found living in a wide salinity range (0.2 to 44.3 g l⁻¹) at Llanquihue basin, was dominant in the more saline biotope.

Other taxa associated to *L. cusminskyae*-*C. salebroso* assemblage were *Parakrithella hanai*, *Cytherura dimorphica*, *Leptocythere* sp., *Pellucistoma elongata* and two other species of *Limnocythere*: *L. multiperforata* and *L. solum*. These last two species have been recorded in Quaternary sediments of different localities of Buenos Aires Province in association with brackish-water Ostracoda remains (Ferrero, 2006, 2009). The others are marine species but often occurring in brackish environments. *C. dimorphica* and species of *Leptocythere* sp. have been recorded living in Mar Chiquita coastal lagoon (p.o.) and in tidal flats of Bahía Blanca estuary (Martínez, 2005). *P. elongata* is a phytal species found in Río de la Plata and several littoral localities of Buenos Aires and Chubut Provinces (Whatley *et al.*, 1997, 1998) and *P. hanai* was described by Hartmann (1962) for littoral environments of Chile and recorded by Whatley *et al.* (1997, 1998) in coastal environments of Argentina between 38°S and 42°47'S.

Along the sequence, *Limnocythere* dominated assemblages can be divided in two types based mainly on the presence of a unidentified species of Limnocytheridae. In the first, Limnocytheridae gen. et sp. indet. was the second component of the assemblage. This taxon has not found living but has been recorded in other Holocene sequences of the Pampas plain in paleoenvironments recognized as brackish with low salinity (Ferrero, 2006). Other components of this association were *Sarscypridopsis aculeata* and *Potamocypris* sp. *S. aculeata* is cosmopolitan, it mainly occur in brackish-water (oligohaline) but also lives in pure fresh-water (Meish, 2000), while *Potamocypris* is recognized as a freshwater genus occurring both in permanent and non-permanent water-bodies. In the second type, *L. cusminskyae* is accompanied by *Heterocypris incongruens* and *Cypridopsis vidua*. Both species are cosmopolitan and eurytopic, with wide tolerance ranges of pH, temperature and salinity, preferring well oxygenated waters (Külköylüoğlu & Vinyrad, 2000; Külköylüoğlu, 2003; Laprida, 2006; D'Ambrosio, 2014). Cusminsky *et al.* (2005) recorded this species in seeps, spring and creek pools and, in low frequencies, in permanent waters and also in ephemeral lakes.

The low diversity and abundance of foraminifera and the composition of foraminifera and ostracod assemblages recovered along Las Brusquitas outcrop allow us to infer the development of a brackish marginal marine environment at this locality. Brackish environments with similar diversity values have been inferred in several sites of the Pampa coastal plain (Laprida & Bertels-Psotka, 2003; Calvo-Marcilese

& Pratolongo, 2009; Calvo-Marcilese *et al.*, 2011, 2013; Marquez & Ferrero, 2011).

Even though agglutinated foraminifera have been found in different biotopes of the east coast of South America (Lena & L'Hoste, 1975; Boltovskoy *et al.*, 1980; Scott *et al.*, 1990; Calvo Marcilese & Pratolongo, 2009), their absence is a common feature of most of the Holocene sequences studied in the same region including Las Brusquitas outcrop. This fact may be primarily caused by taphonomic processes. Microbial degradation of the organic cements is suggested by various authors as an important mechanism of agglutinated loss (Goldstein & Watkins, 1999; Berkeley *et al.*, 2007). However, some species relatively more robust appear to be more resistant to degradation, producing patterns of selective preservation (Goldstein & Watkins, 1999; de Rijk & Troelstra, 1999; Debenay *et al.*, 2004; Hayward *et al.*, 2004). Calvo-Marcilese *et al.* (2013) argue that other possible reason of the absence of agglutinated fauna, along Holocene sections of Bahía Blanca estuary, may be related to their specificity to occupy niches especially within the salt marshes, considering their sampled sites as unsuitable to find such foraminifera.

The state of preservation of the shells (poor fragmented materials) and also, adult/juvenile ostracod ratios would indicate low energy environments prevailing. Oxidation processes at lower levels of the section were very clear. Oxidation of calcareous shells, in marine environments lagoon, was probably related to the presence of roots, precipitation of iron ions and a high content of organic matter (Ritter & Erthal, 2011). In the middle and towards the top of the sequence, the state of preservation improved, evidenced by the shells without significant taphonomic signs.

Paleoenvironmental evolution of Las Brusquitas Creek

Four main paleoenvironmental stages were recognized based on foraminifera, ostracod and charophyte assemblages:

Stage A (zone LB-I), deposited between 7500-7200 and 6300-6200 cal yr BP (6400 ¹⁴C-5400 ¹⁴C yr BP): Foraminifera absence and the scarce presence of juveniles of *L. cusminskyae*, *Leptocythere* sp. and charophyte gyrogonites indicate a non-marine environment, probably with oligohaline water. The low concentration of microfossils could be explained by a high sedimentation rate during an early stage of the last marine transgression.

Stage B (subzone LB-IIA), deposited between 6300-6200 and 6000-5700 cal yr BP (5400 ¹⁴C - 5200 ¹⁴C yr BP): This stage, mainly characterized by the presence of the typical inner shelf foraminifera, *B. peruviana* and the euhaline ostracod, *C. salebrosa* corresponds to brackish-estuarine environments with moderate energy levels. Around 6300-6200 cal yr BP (5400 ¹⁴C), the more diverse Ostracoda assemblage, formed by a 60% of marine species, and the highest abundance of *B. peruviana* allow us recognized the level of major marine influence of Las Brusquitas outcrop. These interpretations are consistent with those made by other authors based on similar assemblages (Laprida *et al.*, 2007; Cusminsky *et al.*, 2009; Calvo-Marcilese *et al.*, 2011; Marquez & Ferrero, 2011). This is in accordance with previous geological and geomorphological studies, which

indicate that at that time the sea rose and reached a maximum transgression between 6500 and 5000 yr BP (Isla, 1989; Fasano, 1991). At the end of this stage an increase of relative abundance of *Ammonia* spp. and *Elphidium* spp. plus a decrease in *B. peruviana* and *C. salebrosa* suggest that the environment evolves towards more restricted conditions. Assemblages formed by species of normal marine environments, such as *B. peruviana*, with a high content of brackish water species such as *Elphidium* spp. and *Ammonia* spp., were interpreted as a gradual sea level fall and/or coastal progradation and a change to a more estuarine condition (Laprida *et al.*, 2007; Marquez & Ferrero, 2011; Calvo-Marcilese *et al.*, 2013). The final phase of stage B coincides with the first steps of the regressive event at 6000 yr BP, when the sea level began to fall (Isla *et al.*, 1996; Violante & Cavallotto, 2004).

Stage C (LB-IIB1), deposited between 6000-5700 and 2300-2000 cal yr BP (5200-2200 ¹⁴C yr BP): The absence of *B. peruviana* and *C. salebrosa* and the dominance of *Spirillina* sp. A and Limnocytheridae spp. indicate the evolution to more continental environments. The development of clear-water lagoon with abundant submerged vegetation may be inferred based upon the abundance of charophytes remains, not only calcified and non-calcified oogonia but also vegetative remains. The dominance of *L. cusminskyae* along with the presence of *S. aculeata* and Limnocytheridae gen. et sp. indet. may be related to oligohaline waters. *L. cusminskyae* dominated assemblages may indicate relatively low conductivity and also high alkaline waters. At c. 4400-4200 cal yr BP (c. 3900 ¹⁴C yr BP), a rise in the diversity of both fauna groups as well as the presence of marine/brackish species, denote a sporadic increase of marine connection probably originated by extraordinary tides or storms.

Stage D (zone LB-IIB2), deposited between 2300-2000 and 2000-1700 cal yr BP (2200 ¹⁴C-2000 ¹⁴C yr BP): the absence of foraminifera and ostracod assemblages reflects the establishment of a continental environment not influenced by the proximity of the sea. Furthermore, the dominance of *L. cusminskyae* together with the wide fluctuation in abundances of microfossils can indicate oscillations in water levels probably related to desiccation periods and salinity variations due to evaporation. Charophyte absence can be associated to low water levels and turbidity. The results of this stage are in accordance with a progressive evolution towards more restricted environments due to the establishment of a sand dune barrier, as proposed by several authors (Schnack *et al.*, 1982; Fasano *et al.*, 1982; Fasano, 1991; Violante, 1992; Violante & Parker, 1992). Finally, after c. 2200-1700 cal yr BP (2000 ¹⁴C yr BP), the record was buried by dune sands partially modified by soil development.

Comparison with other proxies

Studies on pollen, diatoms, and mollusks as well as isotope analysis have been previously carried out by several authors in Las Brusquitas outcrop (Figure 6). Our results and interpretation are broadly agreed with their ones, only a few concordances, discrepancies or adjustment among the different lines of evidences are pointed out here.

Figure 6. Summarized paleoenvironmental settings at Las Brusquitas outcrop.

From pollen and diatoms (Vilanova *et al.*, 2006) brackish to freshwater paleoenvironments and salt to brackish marshes are inferred. On this basis we expected to find agglutinated foraminifera fauna, however this was absent. Debenay *et al.* (2001) were surprised to find a very low proportion of agglutinated fauna in the lagoon of Araruama (Brazil), even in organic rich sediments and lower salinity waters. The authors found no explanation for the dearth of this fauna. In Las Brusquitas outcrop we suggest two possible reasons why we didn't find agglutinated foraminifera; agglutinated loss due to taphonomic processes or that the described marshes were not so widespread or uniformly distributed, resulting in the lack of their specific niches in the sampled record.

From the mollusks (Prieto *et al.*, 2003) and the isotope analysis ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) (Bonadonna *et al.*, 1995) were also inferred brackish environments (estuarine and coastal/marine brackish, respectively) that evolve freshwater. This change is also evident from the analysis using foraminifera and ostracods combined.

At c. 4441 – 4082 cal yr BP (3900 ^{14}C yr BP), from the presence of a few *H. australis* and fragments of Mytilidae it was inferred that the tidal influence was still present, but limited only to extraordinary ones (Prieto *et al.*, 2003). This ephemeral condition might be registered with the analysis of foraminifera and ostracods evidencing their sensitivity to environmental changes and the importance of carrying out paleoenvironmental studies integrating this group.

Vilanova *et al.* (2006) described around to 2200-1700 cal yr BP (*c.* 2000 ^{14}C yr BP, saline condition due to desiccation or an unusually high tide range. Our results also indicate saline conditions but the absence of any marine element plus the dominance of *L. cusminskyae* make us prefer the first explanation.

Holocene sea-level in the coastal region of the Pampa plain

Paleoecological and paleoenvironmental studies from various coastal sites of the Pampa plain suggest changes in the sea level and marine influence during the Holocene. The effect of the sea-level fluctuations occurred at different times and magnitudes according to the characteristics of each basin: depth, distance from shoreline, geomorphology and freshwater input (Isla *et al.*, 1986).

On the coast of the Pampa plain, the largest marine influence occurred, from north to south, after 7600-7500 cal yr BP in Luján River (6700 ^{14}C yr BP), prior to 6200-6000 cal yr BP (5400 ^{14}C yr BP) in the core south of Punta Rasa (Prieto *et al.*, 2004; Laprida *et al.*, 2007), between *c.* 9100-10200 and 8500-8000 cal yr BP (8700 and 7500 ^{14}C yr BP) for the Mar Chiquita lagoon area, around 7750-7300 cal yr BP for Punta Hermengo (6700 ^{14}C yr BP), between *c.* 7800-7400 cal yr BP and 6700-6400 cal yr BP (6800 and 6100 ^{14}C yr BP) for the La Ballenera Creek, and between *c.* 6900-

7300 and 6200-5900 cal yr BP (6200 and 5300 ^{14}C yr BP) for Quequén Grande River (Ferrero, 1996; Espinosa, 2001; Espinosa *et al.*, 2003; Hassan *et al.*, 2011; Marquez & Ferrero, 2011; Fayó & Espinosa, 2014). In the Bahía Blanca estuary, the largest marine influence was recorded between *c.* 6300-6400 and 5900-5800 cal yr BP (5600 and 5200 ^{14}C yr BP) in Napostá Grande Stream (Calvo-Marcilese *et al.*, 2013). On the other hand, Gómez *et al.* (2005, 2006) and Cusminsky *et al.* (2009) recognized negative oscillations of the Last Glacial Maximum at 6400 yr BP, 4200 yr BP and 2900 yr BP during the transgressive hemicycle BP in the PS2B2 core (Figure 7).

In Las Brusquitas Creek, the maximum of marine influence reaches to 6300-6200 cal yr BP (*c.* 5400 ^{14}C yr BP) after that age the sea began to fall. However, at *c.* 4400-4200 cal yr BP (*c.* 3900 ^{14}C yr BP), a slight increase was observed, reflecting sporadic marine influence. The environmental changes in Las Brusquitas Creek are consistent with the evolution of the coastline of the Pampa plain in relation to sea level changes.

CONCLUSIONS

From the study of calcareous proxies, can be inferred shallow and low energy marginal marine palaeoenvironments in Las Brusquitas Creek. In a first stage, between 7500-7200 and 6300-6200 cal yr BP, it could be recognized the development

Figure 7. Location of sites discussed in the text of the Pampa coastal plain.

of a non-marine environment. Around 6300-6200 cal yr BP marine influence rose and the environment changed to brackish-estuarine with moderate energy levels. Sometime before c. 6000-5700 cal yr BP sea-level drop giving rises to the development of clear-water lagoon, probably oligohaline, with abundant submerged vegetation. In a final stage (from 2300-2000 to 2000-1700 cal yr BP), a continental environment not influenced by the proximity of the sea was established.

The new chronologies provided by this work allowed adjusting two important events in the evolution of the Pampa coastal plain: firstly, the maximum transgressive to 6300-6200 cal yr BP (5400 ^{14}C) and secondarily a sporadic increase of marine connection to 4400-4200 cal yr BP (c. 3900 ^{14}C yr BP).

This work, based on the combined study of foraminifera, ostracod and charophyte assemblages, is a new contribution to the understanding of paleoenvironmental evolution of marginal marine environments in the region. More data about *Spirillina* sp. A and its living conditions will be useful to improve the knowledge of these kinds of environments. The response of these group assemblages to environmental changes was shown to be very sensitive and complementary with other proxies.

ACKNOWLEDGMENTS

This study is a contribution to the projects PICT 2010-0082, PICT 2014-1271, PIP 00819, PIP 00021, EXA 587/12 and Comahue University Project B166. The results are part of the doctoral thesis of Melina Marquez. We thank A. Prieto and I. Vilanova for collaborating in the sampling and for providing us with useful information. We are grateful to both reviewers for their suggestions and comments which enriched this study.

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Received in October, 2015; accepted in March, 2016.

Appendix 1. Faunal reference list.

Faunal reference list

Class Foraminiferida Loeblich y Tappan (1992)

Cornuspira planorbis Schultze, 1854

Miliolinella subrotunda (Montagu, 1803) = *Vermiculum subrotundum* Montagu, 1803

Spirillina sp. A

Bolivina sp.

Haynesina depressula (Walker & Jacob, 1798) = *Nautilus depressulus* Walker and Jacob, 1798

Nonion pauperatum (Balkwill & Wright, 1885) = *Nonionina pauperata* Balkwill y Wright, 1885

Nonion sp.

Nonionella sp.

Buccella peruviana (d'Orbigny, 1839) = *Rotalina peruviana* d'Orbigny, 1839

Ammonia parkinsoniana (d'Orbigny, 1839) = *Rosalina parkinsoniana* d'Orbigny, 1839

Ammonia tepida Cushman, 1926

Criboelphidium excavatum (Terquem, 1875) = *Polystomella excavata* Terquem, 1875

Criboelphidium poeyanum (d'Orbigny, 1826) = *Polystomella poeyana* d'Orbigny, 1826

Elphidium gunteri Cole, 1931

Elphidium margaritaceum Cushman, 1930

Elphidium sp.

Class Ostracoda Latreille, 1806

Chlamydotheca incisa (Claus, 1893) = *Pachycypris incisa* Claus, 1892

Heterocypris incongruens (Ramdohr, 1808) = *Cypris incongruens* Ramdohr, 1808

Cypridopsis vidua (O. F. Müller, 1776) = *Cypris vidua* Müller, 1776

Sarscypridopsis aculeata (Costa, 1847) = *Cypridopsis aculeata* Costa, 1847

Potamocypris sp.

Candona sp.

Darwinula? sp.

Cyprideis multidentata Hartmann, 1955

Cyprideis salebrosa Bold, 1963

Parakrithella hanai Hartmann, 1962

Cytherura dimorphica Bertels & Martínez, 1997

Leptocythere sp.

Callistocythere litoralensis (Rossi de García, 1966) = *Perissocytheridea litoralensis* Rossi de García, 1966

Limnocythere multiperforata (Whatley & Cholich, 1974) = *Pampacythere multiperforata* Whatley & Cholich, 1974

Limnocythere solum (Whatley & Cholich, 1974) = *Pampacythere solum* Whatley & Cholich, 1974

Limnocythere cusminskyae Ramón-Mercau, Plastani & Laprida, 2014

Limnocytheridae gen. et sp. indet.

Pellucistoma elongata Whatley, Moguilevsky, Toy, Chadwick & Ramos, 1997

Xestoleberis sp.