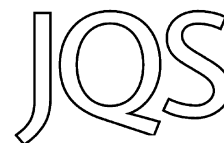


A multi-proxy study of Holocene environmental change recorded in alluvial deposits along the southern coast of the Pampa region, Argentina



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ABSTRACT: Analyses of fossil records of molluscs, stable isotopes of carbon and oxygen, diatoms and palynomorphs from alluvial deposits at Arroyo Claromecó, in the southern Pampa region of Argentina, provide an integrated reconstruction of rapid Holocene environmental change related to marine and palaeoclimate influences. The major events recorded include: (i) disturbances produced by marine influences in close proximity to the coast before ca. 7700 cal a BP; (ii) a short-term decrease in salinity associated with freshwater influx between ca. 7700 and 7400 cal a BP in response to eustatic adjustment as sea level rose; (iii) an increasing input of marine water related to the Holocene sea-level highstand and greater evaporative conditions between 7400 and 6450 cal a BP; and (iv) evaporative processes linked to a pronounced climatic variability that triggered changes in water chemistry during the last ca. 6000 cal a BP concurrently with the late Holocene sea-level fall. A comparison of coastal and continental stable isotope records from the Pampa region reveals that evaporation and a negative precipitation/evaporation (P/E) ratio balance strongly influenced water chemistry in the coastal region, and was as important an influence as marine water during the period of maximum sea-level highstand. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: diatoms; molluscs; palaeoecology; palynomorphs; stable isotopes.

Introduction

Fossil-rich alluvial and littoral deposits along the southern coast of the Pampa region house excellent multi-proxy archives for reconstructing past environmental conditions. Some of these alluvial deposits represent estuaries formed after ca. 7000 ¹⁴C a BP (ca. 7700 cal a BP) during the postglacial sea-level rise (Isla and Espinosa, 1998). Palaeoenvironmental reconstructions using fossil assemblages and lithostratigraphical studies from these estuarine deposits indicate that relative sea-level (RSL) changes influenced the sedimentary dynamics of rivers and streams flowing into the south-western Atlantic Ocean and thereby conditioned the structure and composition of plant communities, mollusc populations and diatom assemblages inhabiting the estuaries (De Francesco and Zárate, 1999; Espinosa *et al.*, 2003, 2012; Vilanova *et al.*, 2006, 2010; Vilanova and Prieto, 2012). Several Holocene RSL curves have been proposed for the Pampa coastline. Although there are discrepancies among the curves, all point to a maximum highstand ca. 6500–6000 ¹⁴C a BP (ca. 7400–6800 cal a BP) followed by a regressive trend to the present position (e.g. Isla and Espinosa, 1998; Cavalotto *et al.*, 2004).

A few previous studies have addressed taphonomic influences on the fossil record (Aguirre and Farinati, 1999; De Francesco and Zárate, 1999; Prieto *et al.*, 2004), or isotopic composition (Bonadonna *et al.*, 1995, 1999; Aguirre *et al.*, 1998, 2002) of fossil mollusc shells which in this paper

provide critical insights into interpretations of local and regional palaeoenvironmental conditions. The stable isotopic composition of fossil freshwater and brackish mollusc shells can be used to infer water temperature, precipitation patterns, evaporation, salinity, productivity and other important aspects of the palaeoenvironment (e.g. Leng and Marshall, 2004; McConnaughey and Gillikin, 2008).

An integrated view of palaeoecological conditions interpreted from several proxy indicators in the depositional sequence associated with RSL may provide new insights into the Holocene ecological and climatic history of the southern coastal Pampa region. Here we present a multi-proxy record from Arroyo Claromecó alluvial deposits that include mollusc taphonomy, C and O stable isotope analyses of gastropod shells, and diatom analyses. This study improves and complements a previous palaeoenvironmental framework derived from palynological analysis (Vilanova *et al.*, 2010). The study site provides an archive of both local and regional environmental changes during most of the Holocene, and due to its proximity to the coast, it is likely to be sensitive to changes in Holocene RSL, thereby allowing us to understand the processes that influence the salinity of coastal wetlands. Moreover, the reconstructed environments and inferred processes, especially those during the Holocene sea-level highstand, could be seen as an analogue of future scenarios produced by the ongoing sea-level rise related to global warming.

Study area

The Arroyo Claromecó (AC) drainage basin (~3017 km²) and the Quequén Grande (QG) and Quequén Salado (QS) river

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basins are situated in the *Pampa interserrana* (inter-range Pampa) area in southern Buenos Aires Province, Argentina (Fig. 1). AC is 60 km long and flows southward in a valley that varies in width between 500 m and 2–3 km (Carbone *et al.*, 2005). In its lower few kilometres AC flows through 1–3-m high sand dunes of the Southern Barrier 'Barrera Medanosa Austral' (BMA), before reaching the south-western Atlantic Ocean (Isla *et al.*, 2001) (Fig. 1). At its mouth, AC is an 88-m-wide and 1.5-m-deep coastal plain estuary (Bértola *et al.*, 2005).

The climate of the southern Pampa region varies from humid–subhumid in the north-east to dry–subhumid in the south-west (Carbone *et al.*, 2004) with an incipient water deficit south-westward across the region (Tonello and Prieto, 2010). The region sits along the northern border of the Southern Westerly Wind Belt (SWWB) and the north-easterly trade winds associated with the South American Monsoon System (SAMS) (Garreaud *et al.*, 2009). As a consequence, the climate is transitional oceanic temperate with marked thermal seasonality, multi-decadal variations, and winds predominantly from the north and north-west. Mean annual temperature is 13.9 °C and mean annual precipitation is

693 mm (Carbone *et al.*, 2004; Bértola *et al.*, 2005). The yearly mean rainfall oxygen isotopic composition ($\delta^{18}\text{O}$) varies from –4 to –6‰ from north to south across the Pampa region (Bonadonna *et al.*, 1999). The isotopic composition of river water and groundwater in the region (Fig. 1) is similar to the average isotopic composition of the region's rainfall (Bonadonna *et al.*, 1999; Quiroz Londoño *et al.*, 2008).

Stratigraphic context

The valley of AC is carved into a lower to upper Pliocene silty clay to sandy silt fluvial succession (Zárate, 2005), which is exposed discontinuously along the Arroyo bank. Late Pleistocene and Holocene alluvial deposits fill the present valley. From the Late Pleistocene to ca. 3500 ^{14}C a BP (ca. 3700 cal a BP) the water table was high and evidence for channel incision is absent. In contrast, between ca. 3500 and 2500 ^{14}C a BP (ca. 3700 and 3200 cal a BP) channel incision occurred with a consequent fall of the local water table. This late Holocene incision was probably in response to a fall in RSL (Vilanova *et al.*, 2010). In recent times, headward entrenchment and channel straightening in the lower reaches

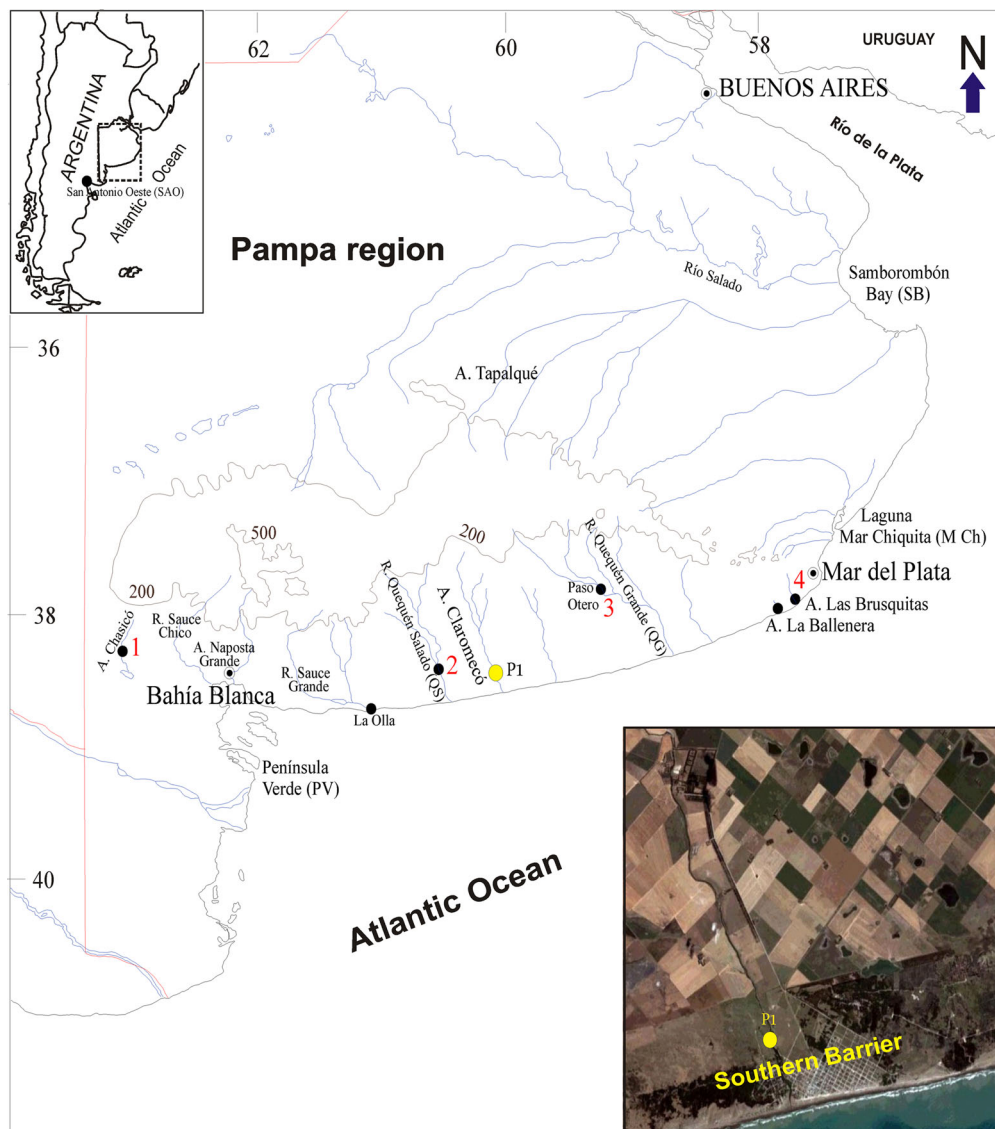


Figure 1. Location map showing the localities discussed in the text. Study area of Arroyo Claromecó. Numbers 1–4 refer to localities selected for stable isotope analyses comparison (Bonadonna *et al.*, 1999). SB, MCh, PV and SAO refer to localities where isotope data of modern *Heleobia australis* have been obtained (Aguirre *et al.*, 2002), and QR and QS refer to localities where stable isotope data of modern *Heleobia parchappii* have been obtained (Bonadonna *et al.*, 1995, 1999). This figure is available in colour online at wileyonlinelibrary.com.

of the valley isolated deposits of the late Holocene channel area and preserved them in an abandoned channel. The relatively rapid incision of the modern channel allowed preservation outside the incision zone of an extensive suite of multi-aged pre-incision deposits that record a detailed history of Holocene aggradation episodes. The stratigraphic relationships between the alluvial units at AC and radiocarbon dating have been published in detail by Vilanova *et al.* (2010). Five stratigraphic units have been documented in the area (Table 1); only four of them are present in the sequence selected for this study (Profile 1, Fig. 2).

Materials and methods

We studied a 493-cm-thick sedimentary sequence (Profile 1) situated 2 km from the coastline in the lower reaches of AC (Fig. 1). Sampling was carried out along a steep cutbank that exposes a thick section of floodplain deposits. Before sampling, the outermost 50 cm of the exposure was removed. The profile was sampled continuously at selected intervals (1–10 cm) according to lithological and stratigraphic changes (Fig. 2). Subsamples were collected for malacological, stable isotope and diatom analyses and for a previously reported palynological analysis (Vilanova *et al.*, 2010). A chronology was established using 13 conventional and accelerator mass spectrometry (AMS) radiocarbon analyses (Fig. 2; Table 2).

Malacological analysis

Ninety-two levels were sampled; each sample was subsampled into 50-cm³ subsamples. Subsamples were carefully washed and sieved using a 0.71-mm mesh (25 ASTM). Shells per sample were identified, counted and measured under a Nikon stereoscopic microscope.

All molluscs were identified to species level: *Heleobia parchappii* d'Orbigny, *H. australis* d'Orbigny, *Biomphalaria peregrina* d'Orbigny and *Succinea meridionalis* d'Orbigny (Gaillard and de Castellanos, 1976; Landoni, 1992). Fragments of Mytilidae were also recognized. Some specimens of

Heleobia that varied in their general shell shape from *H. australis* (e.g. less slender shells with more inflated whorls and deeper sutures) are reported as *Heleobia* spp. Very small shells with 1–1.5 whorls, including the apex, were reported as indeterminable shells. Density (individuals cm⁻³) for each species was calculated and tabulated.

Taphonomic analysis

The taphonomic analysis was restricted to *H. parchappii* and *H. australis*. Both are benthic gastropods of similar size and represent the dominant species in the sequence. Taphonomic attributes included (i) fragmentation, (ii) abrasion and (iii) presence or absence of calcium carbonate precipitation on the shell. Complete shells were separated from the shell fragments and any fragment that included the apex was considered a complete specimen (Kowalewski *et al.*, 1994). Total shell length was estimated only for those specimens where the apex and the last whorl were present.

Fragmentation and abrasion of the specimens was described using semi-quantitative taphonomic grades (Flessa *et al.*, 1993) and presented using ternary taphograms. Three taphonomic grades were used: good (grade 0 = best preservation), fair (grade 1 = intermediate) and poor (grade 2 = poorest) (Kowalewski *et al.*, 1994, 1995). Shell preservation was characterized as good when <5% of a sample's specimens were affected by each attribute, intermediate between 5 and 30%, and poor when >30% of the specimens were affected. Similarly, total shell fragmentation was measured using whole specimens and fragments of both species, except for those samples that contained only one species (6.5%). Taphonomic attribute analyses were adapted from Parsons and Brett (1991) and Kowalewski *et al.* (1994). The average taphonomic grade for each attribute was calculated for each sample to evaluate the variation of the combined attributes through the stratigraphic sequence and to determine what attribute contributed most to the taphonomic condition of each sample (Meldahl *et al.*, 1997). The total taphonomic grade was determined as the arithmetic sum of average taphonomic grade.

Table 1. Stratigraphic description of the Arroyo Claromec6 (AC) sequences.

Stratigraphic unit: age (¹⁴C a BP/cal a BP) and description

Unit 5: ca. 1600/1450 to present

Composed of aeolian sediments from the third generation of sand dunes of the BMA that mantles the top of the alluvial sequence along the west side of AC from the coastline up to 2 km inland. The sediments represent dune remobilization, which was significantly affected locally by human activities during modern times (Isla *et al.*, 2001).

Unit 4: ca. 3400 to ca. 500/3600–500

Alluvial sediments of the upper parts of the banks, next to the channel. A fining-upward unit mainly composed of fine sand deposited sporadically and intermittently during high flow events. Approximately contemporaneous with the palaeochannel infilling.

Unit 3: ca. 2500 to ca. 500/3200–500

Sediments infilling a palaeochannel which incised ca. 3500–2500 ¹⁴C a BP. This unit is not represented in the sedimentary profile studied in this work. The palynological (Vilanova *et al.*, 2010) and diatom (Hassan *et al.*, 2004) records from this unit were included in the discussion.

Unit 2

(Subunit 2d): ca. 5300–3500–2500/5900–3700–3200

Calcareous silty fine sand and clayey silt with thin interbeds of clay and tufa.

(Subunit 2c): 6200 to ca. 5300/7200–5900

Planar bedded dark grey and light brown clayey silt and black finely laminated clay, carbonate nodules and soft masses.

(Subunit 2b): 6540 to ca. 6200/7300–7200

Laminated clayey silts with fine stratification and intercalations of clay laminae.

(Subunit 2a): 6950–6540/7700–7300

Finely laminated dark brownish sandy silts.

Unit 1: Before 7000/7700

Fine-grained alluvial sediments, characterized by greenish grey, brown to yellowish brown sandy silts, with ferruginous mottles, carbonate concretions and root traces with oxidation haloes. In some part of the exposure the unit is reduced to grey, dark greyish brown and blue grey sandy silts. Only the upper 50 cm of this unit is exposed in the studied sequence. A palaeosol is developed in the upper part of this unit. Bulk organic matter samples from this soil yielded ages of 6080 ¹⁴C a BP from the Ab horizon and 7240 ¹⁴C a BP from the underlying Bw horizon (Fig. 2), providing age estimates for the length of pedogenesis and the time of burial.

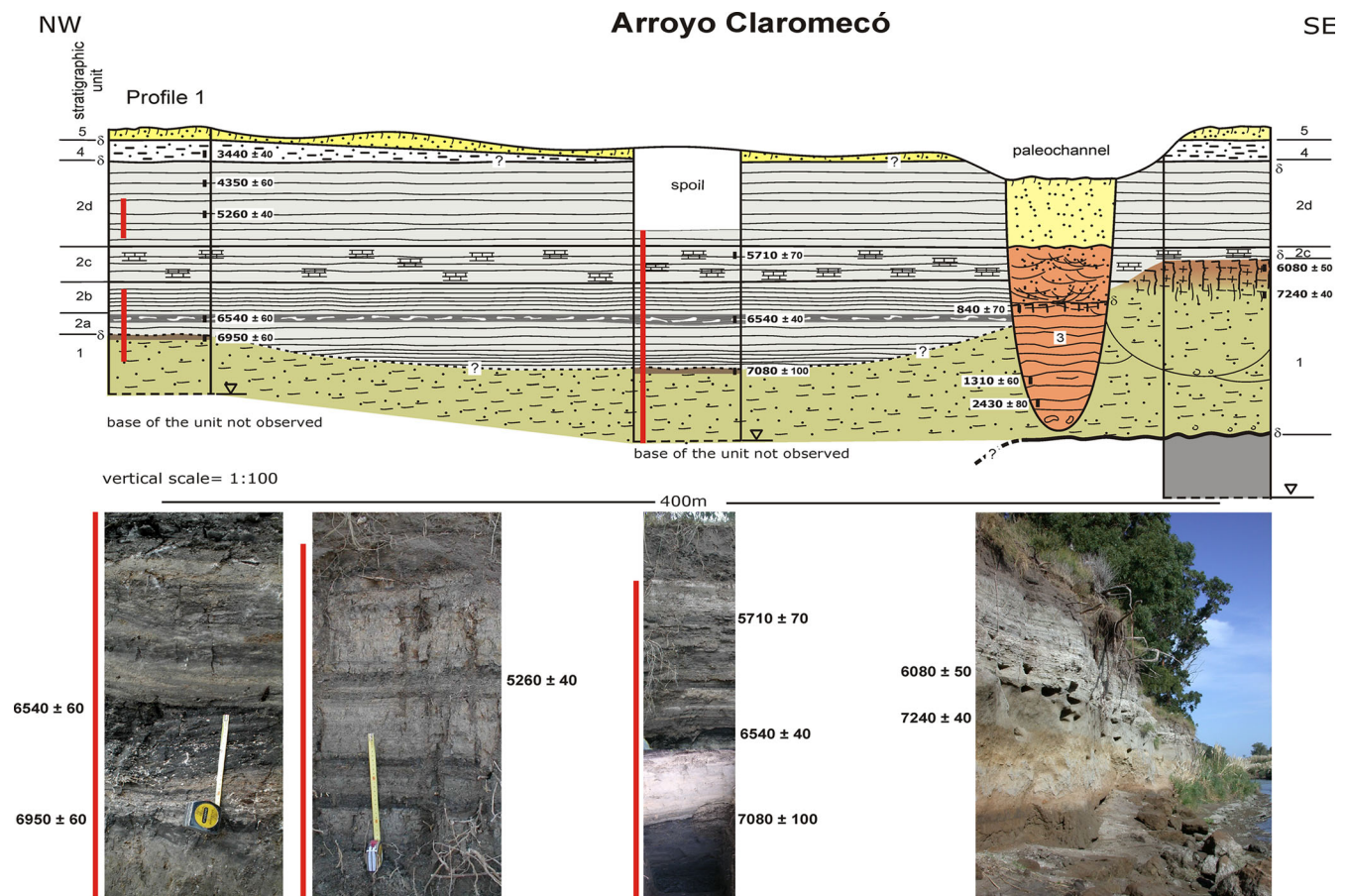


Figure 2. Generalized cross-section of the late Pleistocene and Holocene stratigraphy from Arroyo Claromec6 and stratigraphic unit correlations among profile 1 (P1) and the other sections at the site (Vilanova *et al.*, 2010; see Table 1 for stratigraphic unit descriptions). This figure is available in colour online at wileyonlinelibrary.com.

Calcium carbonate precipitation was observed macroscopically on some *H. parchappii* shells. The ratio of specimens with this precipitate to total shells was calculated for each level.

A nested design analysis of variance (ANOVA) was applied to the *H. parchappii* record to identify size differences between mollusc zones. Diagnostic plots were created to check for departures from the ANOVA model assumptions. Multiple comparisons were established with the Tukey test (Zar, 1999).

Stable isotope analysis

Carbon and oxygen stable isotope ratios ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) were determined for 84 gastropod shells (17 replicates) corresponding to the 54 stratigraphic levels in which *H. parchappii* and *H. australis* shells were ubiquitous, dominant and well preserved. *H. parchappii* occurred in almost all samples and was selected for the analysis from those levels where shells did not show a greatly shifted taphonomic condition. *H. parchappii* stratigraphically overlapped with

H. australis between 394 and 342 cm, which allowed comparison of the isotopic signatures of these species through this interval. Stable isotope analyses were also performed on shells of *S. meridionalis* in two levels from the bottom and top of the sequence. All shells were cleaned by sonicating in alcohol, and sampled by breaking off a portion of the aperture, pulverized, homogenized and sub-sampled for analysis.

Stable carbon isotope analyses were conducted at the Paul H. Nelson Stable Isotope Laboratory at the University of Iowa, Department of Earth and Environmental Sciences, and at the Keck Stable Isotope Laboratory at the University of Kansas. After being dried and pulverized with a mortar and pestle to ensure homogenization, the samples were dried overnight at 50 °C. Samples were digested using a Kiel III device interfaced with a Finnigan-MAT 252 isotope ratio mass spectrometer at Iowa and at Kansas interfaced with a Thermo Finnigan MAT 253 mass spectrometer. Samples were run with various internal and NIST standards and random in-house and inter-lab replicates confirmed a precision typically

Table 2. Radiocarbon dates and calibrated ages from the Profile 1 sequence at Arroyo Claromec6 (Vilanova *et al.*, 2010). Calibration was performed using CALIB 5.0.1 (Stuiver *et al.*, 2005).

Age (^{14}C a BP)	Calibrated age (cal a BP) ($\pm 2\sigma$)	Median probability	Depth (cm)	Material	Technique/laboratory no.
3440 \pm 40	3479–3723	3628	69–74	<i>H. parchappii</i>	AMS/Beta-242311
4350 \pm 60	4789–5044	4868	121–127	Organic matter	Conventional/Beta-183023
5260 \pm 40	5893–6031	5964	176–182	<i>H. parchappii</i>	AMS/Beta-180656
6540 \pm 60	7320–7439	7387	394–396	Charcoal	AMS/Beta-180654
6950 \pm 60	7610–7859	7733	430–435	Organic matter	Conventional/Beta-175780

better than 0.2‰. Stable carbon isotope values are reported relative to the V-PDB standard.

Diatom analysis

Twenty-one subsamples were selected for diatom analysis from the interval dating between 6950 and ca. 6200 ¹⁴C a BP (7700 and ca. 7000 cal a BP) (430 and 340 cm) to investigate palaeoenvironmental conditions during the Holocene sea-level highstand. Samples were prepared following standard techniques. From each diatom-bearing interval, a minimum of 300 diatom valves were counted under oil immersion (1000×). The identification of species was based on the local and standard diatom taxonomic literature. Diatom species were grouped in relation to salinity tolerances and life form, following the ecological classification of Vos and de Wolf (1988, 1993), Denys (1991/1992) and Hassan *et al.* (2009).

STATISTICA 6.0 (StatSoft, 2001), TILIA and TILIAGRAPH 5.0 software packages (Grimm, 2004) were employed for statistical analysis and plotting of the malacological, diatom and palynological data. Linear interpolation using TILIA was carried out to estimate age limits of the different zones as well as for the top and bottom age limits in the profile.

Results

Malacological and isotopic records

Seven mollusc assemblage zones are defined based on both the CONISS cluster analysis of mollusc density and the

taphonomic condition of *H. parchappii* and *H. australis* (Figs 3 and 4; Supporting information, Table S1). The variation in fragmentation and abrasion for *H. parchappii* and *H. australis* are presented as ternary taphograms (Fig. 5). The external surfaces of 0.34–20% of the *H. parchappii* shells were encrusted with calcium carbonate in the interval between 280 and 130 cm (Fig. 3). Throughout the sequence, the sizes of both *Heleobia* species were 4 mm or less, except for two levels (Fig. 4). The size of *H. parchappii* shells varied significantly among mollusc zones (nested design ANOVA, $F = 34.37$; $P < 0.001$).

H. parchappii isotopic data encompass the sequence from ca. 7700 ¹⁴C a BP (8200 cal a BP) to present and *H. australis* isotopic data cover the period from 6540 to ca. 6200 ¹⁴C a BP (7400–7000 cal a BP). Throughout the sequence, $\delta^{13}\text{C}$ values range between -7.46 and 1.71 ‰ and $\delta^{18}\text{O}$ between -3.18 and 4.54 ‰ (supporting Table S1). Both stable isotope ratios illustrate similar trends (Fig. 3) and are summarized for each mollusc zone (supporting Table S1).

Diatoms

The diatom record is represented by 87 taxa. Only the 42 most common diatom taxa (>2% of the entire assemblage) representing not <80% of the assemblage are illustrated (Fig. 6). Two diatom zones were defined using CONISS cluster analysis. The diatom ecological groups show that marine/brackish aerophilous, epiphytes and epipelon were dominant between 6950 and ca. 6800 ¹⁴C a BP (7700 and

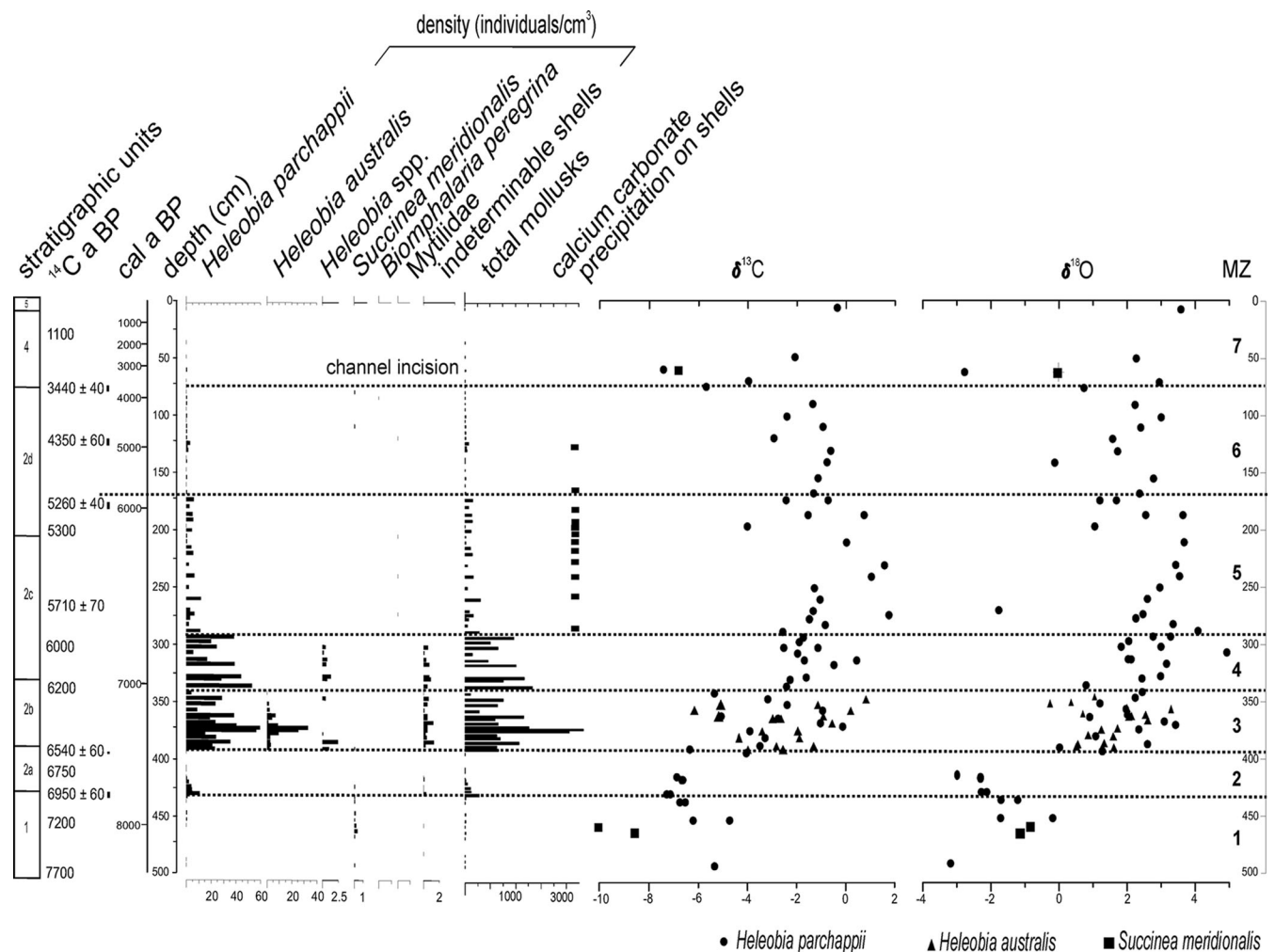


Figure 3. Mollusc densities, samples with calcium carbonate precipitation on shells, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of *Heleobia parchappii*, *H. australis* and *S. meridionalis*, and mollusc assemblage zones from profile P1.

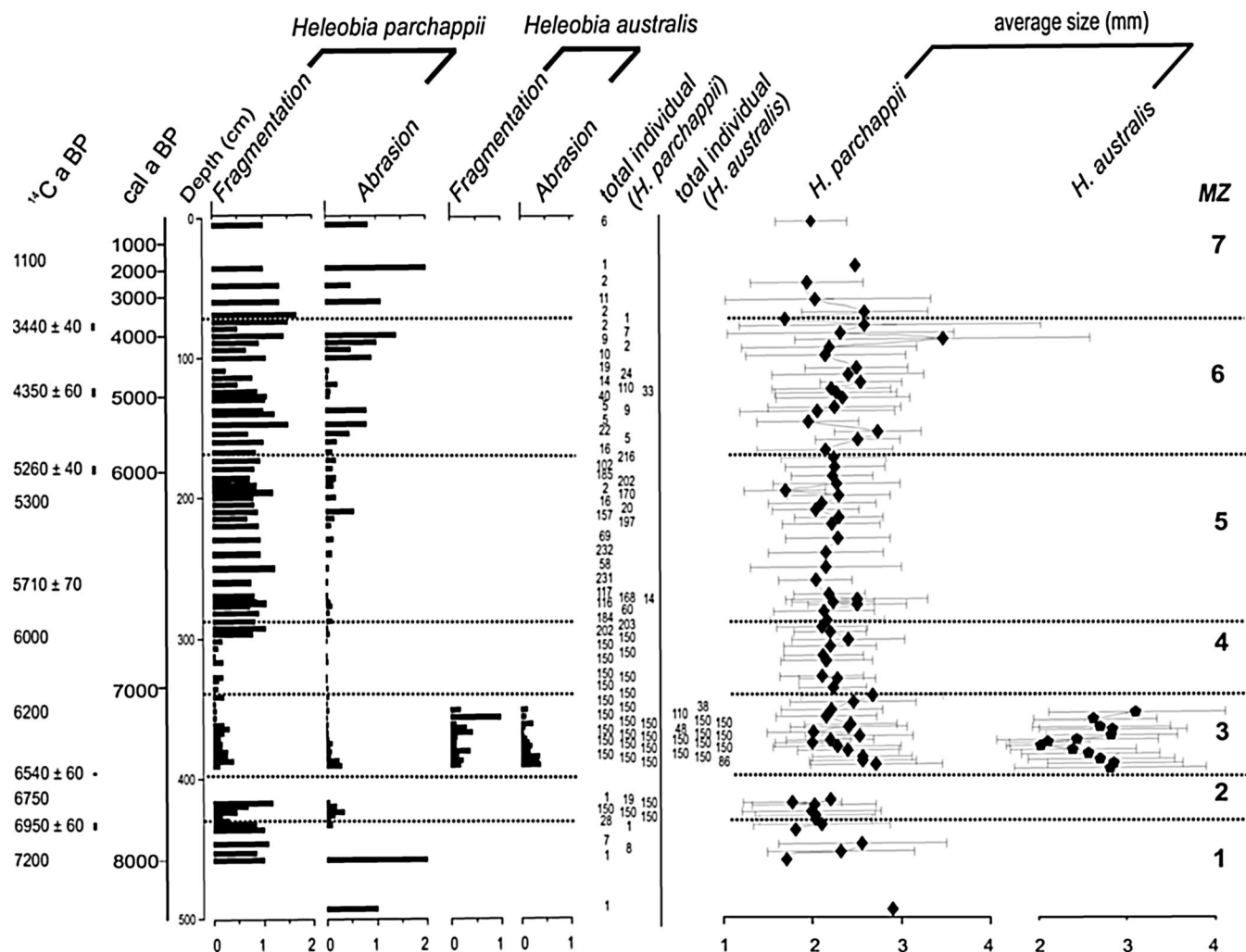


Figure 4. Average taphonomic grade and size variations of *Heleobia parchappii* and *H. australis* shells.

ca. 7600 cal a BP). Between ca. 6800 and ca. 6300 ^{14}C a BP (ca. 7600 and ca. 7300 cal a BP) peaks of marine/brackish and brackish/freshwater tycho plankton occur. From ca. 6300 to ca. 6200 ^{14}C a BP (ca. 7300 to ca. 7200 cal a BP) marine/brackish and brackish/freshwater epiphytes and epipelon dominate.

Discussion

Local and regional palaeoenvironmental reconstruction

Five major periods of environmental change are suggested by integrating interpretations from each proxy (Fig. 7):

1. Before ca. 7700 cal a BP (7000 ^{14}C a BP) the absence or low densities of *H. parchappii* with a variable taphonomic grade suggests restrictive conditions, such as turbid water or a lack of permanent aquatic environments that prevented the development and maintenance of stable populations. The presence of abraded shells suggests sporadic transport by flowing water. The development of some shallow freshwater–brackish water bodies along the floodplain is suggested by the expansion of halophytic vegetation and the substantial reduction of grasslands (Fig. 8). This interpretation is also supported by the presence of *Succinea meridionalis*, a terrestrial snail associated with aquatic environments (Landoni, 1992) that has been found living on *Spartina densiflora* in salt marshes in the Pampa coastal area (Espinosa *et al.*, 2003). *S. meridionalis* $\delta^{13}\text{C}$

and $\delta^{18}\text{O}$ values are lower than those from modern snails recovered from coastal dunes (Bonadonna *et al.*, 1999), a difference that may be related to wetland habitat conditions. During this period, average $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ are higher than values of modern *H. parchappii* shells (Fig. 9a, b) suggesting seawater intrusion may have modified the isotope composition of both environmental waters and mollusc shells. During this time RSL was similar to today (Isla and Espinosa, 1998). Prior to ca. 8000 cal a BP elsewhere along the southern Pampa coastline halophytic salt marsh vegetation (Prieto *et al.*, 2000) developed in a brackish lagoon (Espinosa *et al.*, 2012) in the lower reaches of the QG river and an area prone to sporadic supratidal flooding developed at the La Olla site (Blasi *et al.*, 2013) (Fig. 1). These records suggest that the lower reaches of valleys along the pre-7700 cal a BP southern Pampa coastline supported wetland halophytic vegetation supported by elevated salinity and periodic incursion of marine water.

2. The period from ca. 7700 to 7400 cal a BP (7000–6500 ^{14}C a BP) is associated with an increase in the size and depth of the water bodies, as evidenced by a relative increase in abundance of *H. parchappii* and the disappearance of *S. meridionalis*; the latter was forced to move to the new littoral zone. The good taphonomic condition of *H. parchappii* shells indicates a non-transported assemblage. The dominance of marine/brackish aerophilous diatoms from supratidal environments (Vos and de Wolf, 1993), accompanied by epiphytes and epipelon

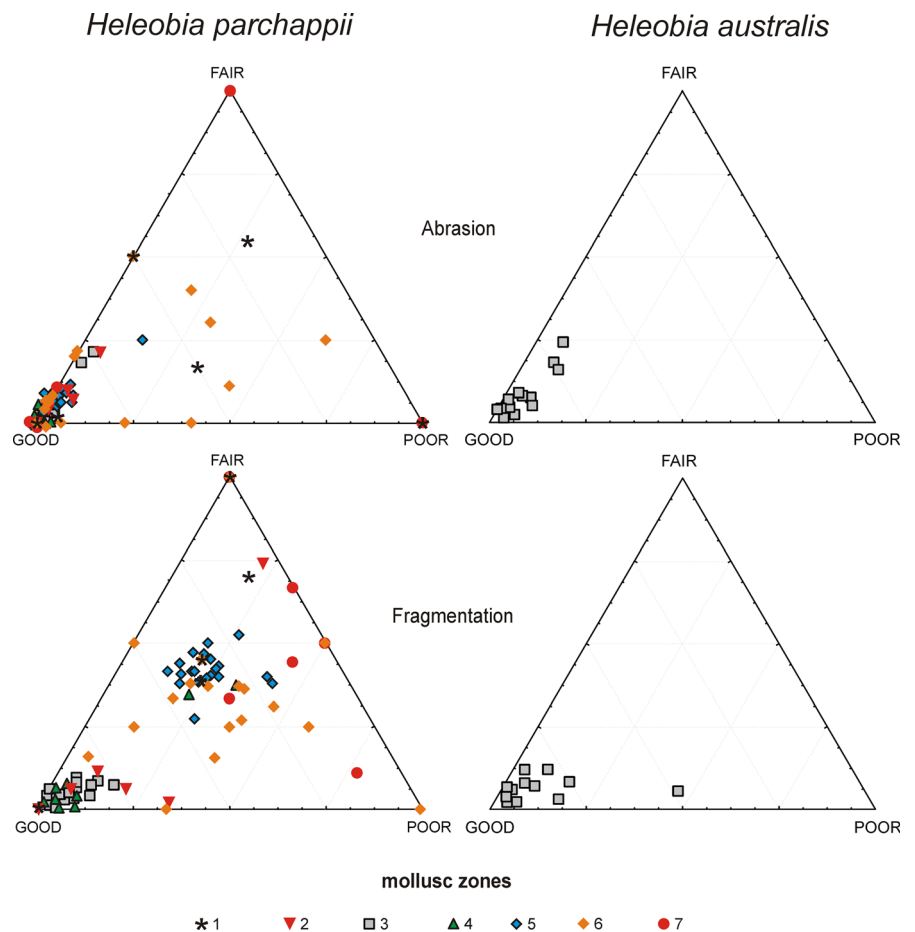


Figure 5. Ternary taphograms showing variations among samples for taphonomic attributes of *Heleobia parchappii* and *H. australis* shells. This figure is available in colour online at wileyonlinelibrary.com.

diatoms, suggests an irregularly flooded shallow coastal environment with aquatic plants (Fig. 6). The high values of Chenopodiaceae and occurrence of *Limonium brasiliense* suggest the development of upper salt marsh vegetation (Vilanova and Prieto, 2012) (Figs 7 and 8). *H. parchappii* $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are relatively light during this interval (supporting Table S1), reflecting the existence of a more wet/humid and productive environment in comparison with the rest of the Holocene record (Fig. 9a). The higher than previous moisture conditions reflect freshwater influx and a decrease in salinity that resulted as the wetland transitioned from brackish to fresher conditions. These conditions agree with the direction of environmental change indicated by the diatom and palynological records (Figs 6 and 8). Indeed, a peak of brackish/freshwater tychoplankton diatoms (Fig. 6) at ca. 7500 cal a BP indicates more water depth and less salinity. The change in the water depth and salinity coincide with the replacement of salt marsh vegetation by a hydrophytic community (Figs 7 and 8) in a brackish–freshwater marsh. *H. parchappii* populations disappeared soon after 7600 cal a BP, because of decreased dissolved oxygen content in the waters, but reappeared ca. 7400 cal a BP when the water body became more well-oxygenated (Tietze *et al.*, 2011). This shift in dissolved oxygen may be related to an increase in authigenic organic matter trapped by abundant sedges in these wetlands, as suggested by the high pollen concentration in this zone (subunit 2a, Fig. 7).

Overall, the proxies reveal short-term shifts in environmental conditions related to a salinity decrease produced by freshwater influx. This shift could be a regional eustatic adjustment to rising RSL as similar changes were found at estuaries of Arroyo La Ballenera (Stutz *et al.*, 2002) and the

QG River (Prieto *et al.*, 2000), and at the La Olla site (Blasi *et al.*, 2013) where brackish–freshwater marshes and mixohaline marsh in the upper intertidal–lower supratidal zone, respectively, developed about this time. The RSL rise fostered the formation of barrier-bars that may have occasioned local-scale damming at stream mouths, impoundment and expansion of freshwater–brackish wetlands progressively confined behind those barriers. These barriers could be related to the first generation of littoral dunes of the BMA that formed between ca. 8000 and 7400 cal a BP (Blasi *et al.*, 2013). It is also possible that the freshening conditions may reflect a regional climatic shift that increased freshwater input, as the high amount of Cyperaceae pollen in this zone may reflect higher freshwater input related to increased precipitation. Quantitative pollen–climate relationships for the Pampa region show that Cyperaceae pollen is positively correlated with precipitation (Tonello and Prieto, 2008).

3. Between ca. 7400 and 6000 cal a BP (6500–5250 ^{14}C a BP) a series of short-term environmental changes (centennial scale) are recorded.

- 3.1. Between ca. 7400 and 7200 cal a BP (6500–6200 ^{14}C a BP) the highest densities of *H. parchappii* in the sequence indicate favourable conditions for the establishment of this opportunistic species, such as a large and well-oxygenated water body with abundant submerged vegetation. This scenario is also supported by an increase of brackish/freshwater tychoplankton and epiphyte diatoms (Fig. 6) plus the occurrence of brackish aquatic *Ruppia* sp. and phytoplankton (*Spirogyra*, *Botryococcus* and *Peridinioideae*) (Figs 7 and 8). A continuous record of intermediate and larger shells of *H. australis* and *H. parchappii* with

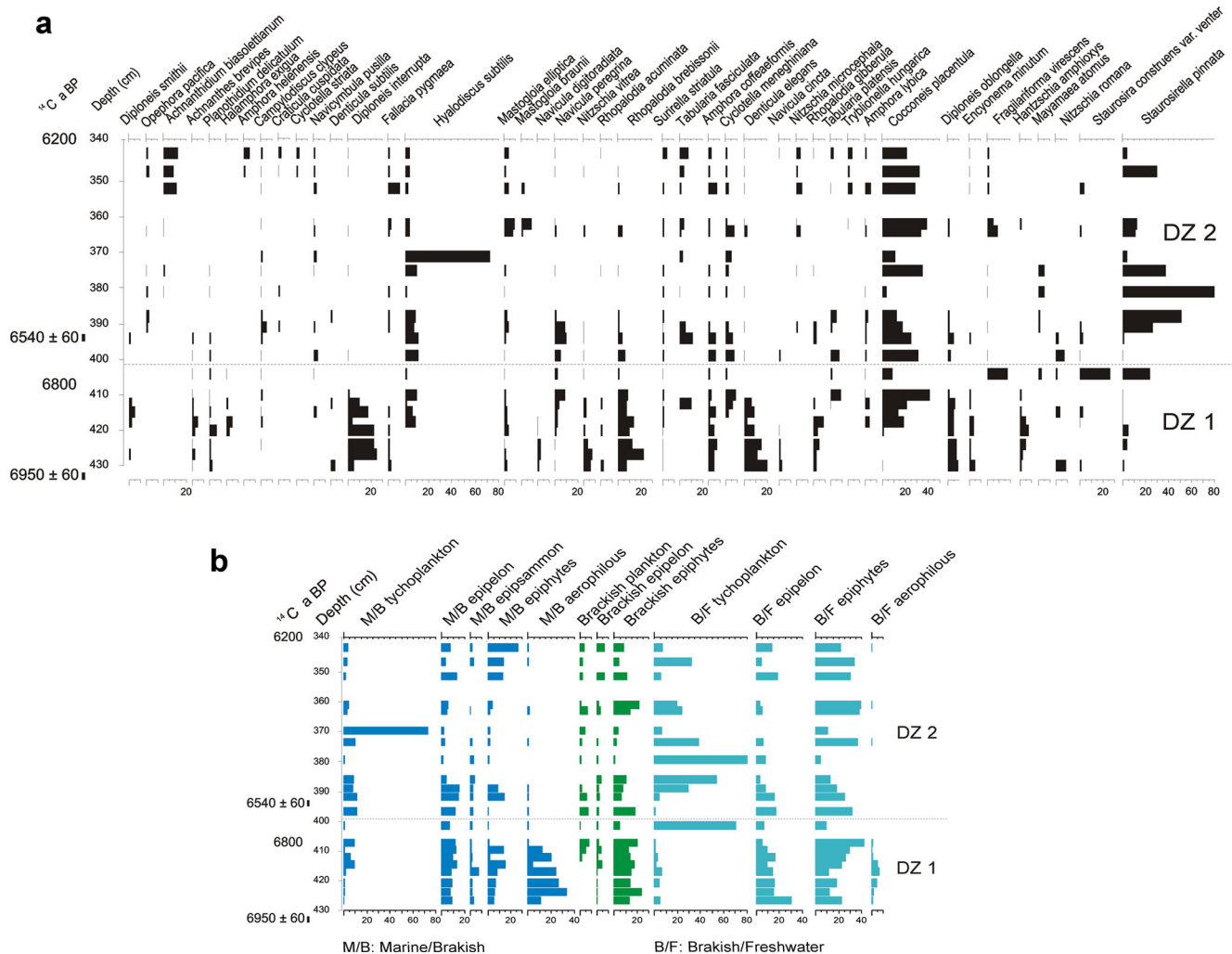


Figure 6. (a) Relative abundance of the dominant diatom species. (b) Diatom ecological groups with diatom zones in Profile 1. This figure is available in colour online at wileyonlinelibrary.com.

good taphonomic condition indicate autochthonous–parautochthonous assemblages, similar to assemblages of these species that occurred between ca. 7525 and 6100 cal a BP in the lower reaches of the QG River (De Francesco and Zárate, 1999). The alternating densities and variable sizes of *H. parchappii* (Figs 3 and 4) suggest salinity fluctuations and mesohaline conditions (Cazzaniga, 1982). During this period, a downstream deposit of intertidal and neritic mollusc shells indicates estuarine conditions at the Arroyo mouth, suggesting a much larger estuary than today at the mid-Holocene sea-level highstand (Vilanova *et al.*, 2010). The *H. australis* record also indicates that the marine influence also reached a greater distance upstream during this interval. This species inhabits low-energy environments, such as estuarine and coastal lagoons (Carcedo and Fiori, 2012), or marine-influenced salt marshes with limited freshwater input (Canepuccia *et al.*, 2007). The species' abundance in estuaries decreases with increasing salinity and tidal exposure (De Francesco and Isla, 2003). Taking into account that shells of *H. australis* have a lower relative density (Fig. 3), it is possible that populations of this species living near the inner boundary of their distribution in the estuary were transported inland by tides or via a buoyancy dispersal strategy (Cazzaniga and Fiori, 2006). The increase in Poaceae (Fig. 8), probably

reflecting *Spartina* spp., may have provided a favourable habitat for mollusc populations (Canepuccia *et al.*, 2007). The good taphonomic condition of both gastropod species along with an uneven degree of preservation (Fig. 5) indicates minimal reworking and local transport in a low-energy environment. The coexistence of *H. parchappii* and *H. australis* suggests that both species might have developed in the same habitat given that *H. parchappii* is adapted to wide salinity variations (Bonadonna *et al.*, 1995) and/or evaporative conditions. The latter is reflected in the broad range of shell $\delta^{18}\text{O}$ values (Fig. 7). Coexisting assemblages of *H. parchappii* and *H. australis* have been recorded in other alluvial and littoral sequences from the coastal Pampa region dating to the period between 8200 and ca. 2200 cal a BP (e.g. Bonadonna *et al.*, 1995; De Francesco and Zárate, 1999; Aguirre *et al.*, 2002; Vilanova and Prieto, 2012). The presence, abundance and taphonomic conditions of these assemblages seem to be related to the distance of the sampled site from the contemporaneous coastline. Furthermore, as in AC, diminutive *Heleobia* species are also recorded at other localities where *H. parchappii* was the most abundant mollusc species in the assemblage. All these similarities suggest that the AC record reflects a regional environmental response to estuary development during the Holocene sea-level highstand. The highstand caused

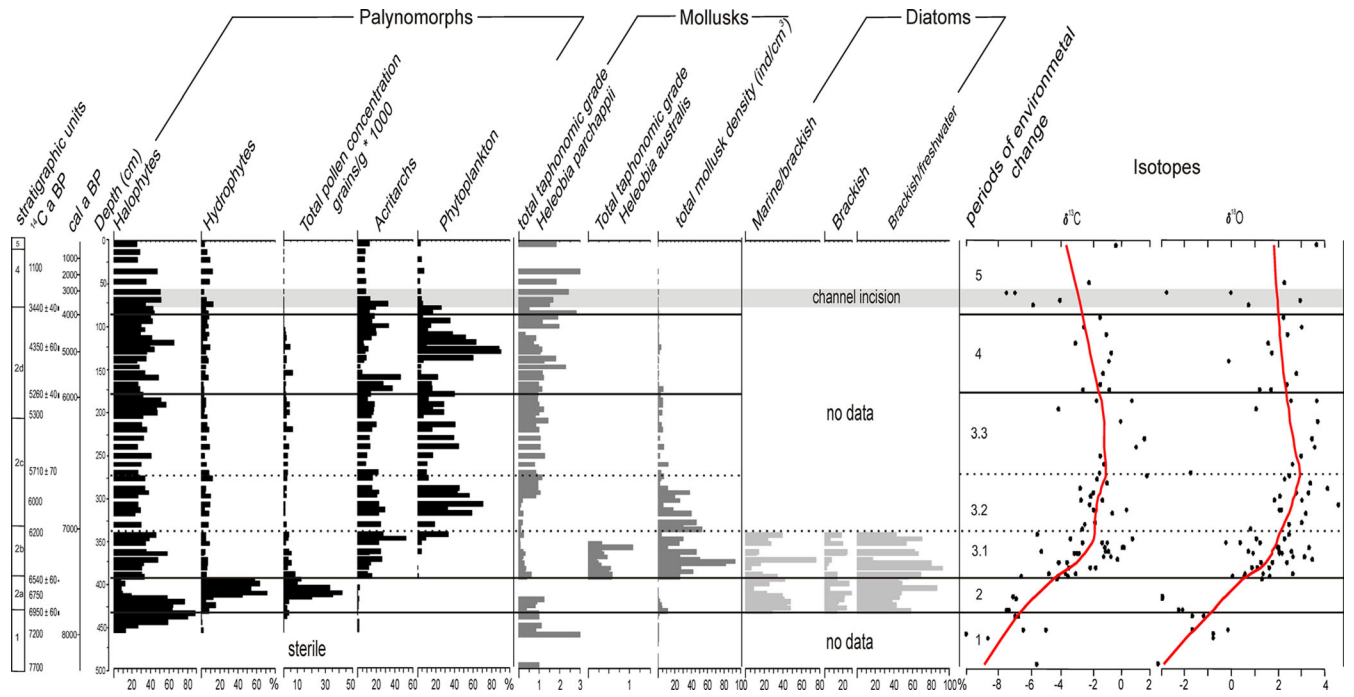


Figure 7. Summary diagram of pollen groups, total pollen concentration, non-pollen palynomorph groups, total taphonomic grade for *Heleobia parchappii* and *H. australis*, total mollusc density, diatom ecological groups, periods of environmental changes, and O and C stable isotope ratios. The fitted line is a LOESS (Hammer *et al.*, 2001) smoother (span: 0.20; order: 1) to highlight the long-term trend.

widespread inundation of the lower reaches of valleys flowing to the sea that waterlogged and buried soils (Table 1) on floodplains as natural levees were overtopped (Vilanova *et al.*, 2010).

At ca. 7200 cal a BP the system gradually became more energetic, as suggested by an increase in fragmentation of *H. australis* shells. The highest densities of *H. australis* and *H. parchappii* occur at ca. 7300 cal a BP. Specimens from this interval are also the most diminutive in the sequence (Fig. 5), probably because of an increase in the concentration of bicarbonate which may be harmful to the development of this species (Peretti, 2005). This interpretation is consistent with the changing alkalinity and salinity conditions in the water body inferred from palynological spectra that show an abrupt

decrease of freshwater taxa and increase in phytoplankton and acritarchs (Fig. 9). The diatom record indicates fluctuations in water depth beginning with an increase in marine input at 7300 cal a BP when the marine/brackish *Hyalodiscus subtilis* dominates, followed by marine/brackish and brackish/freshwater epiphytes and epipelon as the environment shallowed at ca. 7200 cal a BP.

During this period, *H. parchappii* $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values exhibit a broad range and a dramatic shift, increasing almost three-fold over previous values (Figs 7 and 9a). The broad range in values reflects the mixing of fresh and marine waters and probably also the occurrence of evaporative processes, resulting in a predominance of mixohaline/mesohaline water. Because this is a marginal marine setting, the mixing of fluvial and marine waters may have played a greater role in affecting carbonate $\delta^{18}\text{O}$ values than did changes in the P/E ratio (Peros *et al.*, 2007). Seawater ($\delta^{18}\text{O} \approx -2\text{‰}$ VSMOW) is usually much heavier than the local precipitation; therefore, the incursion of seawater significantly shifts the $\delta^{18}\text{O}$ of coastal wetlands to heavier values (Peros *et al.*, 2007). *H. australis* $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values (Figs 3 and 9c) also range broadly in this interval, probably reflecting the mixing of fresh and marine waters. Such mixing events would produce synchronous increases in both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values. Nevertheless, the fact that most $\delta^{18}\text{O}$ values from *H. australis* shells in this interval are higher than values from shells of living organisms from the Pampa region suggests that increased evaporation probably influenced the isotopic composition of the water body (Fig. 9c). The positive trends in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of both *H. parchappii* and *H. australis* reflect a salinity increase and the predominance of mixohaline water. However, it is difficult to determine whether the $\delta^{18}\text{O}$ value increase in this interval resulted from seawater incursion due to storm activity, RSL rise, a

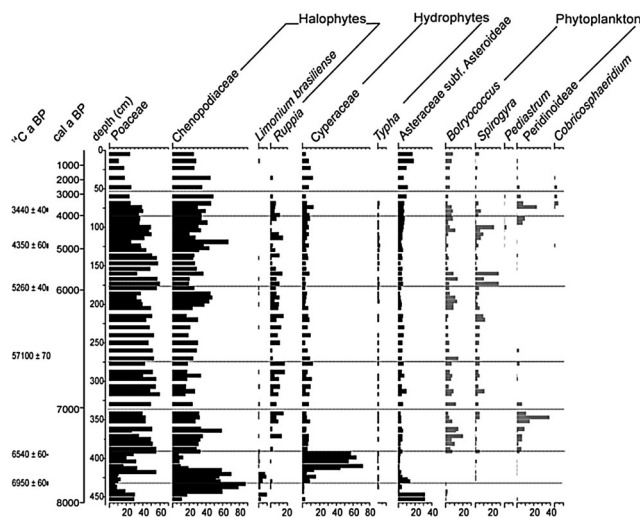


Figure 8. Synthetic palynological diagram from Profile 1 (only the taxa cited in the discussion are shown). Pollen and non-pollen palynomorphs are presented along a time scale (adapted from Vilanova *et al.*, 2010).

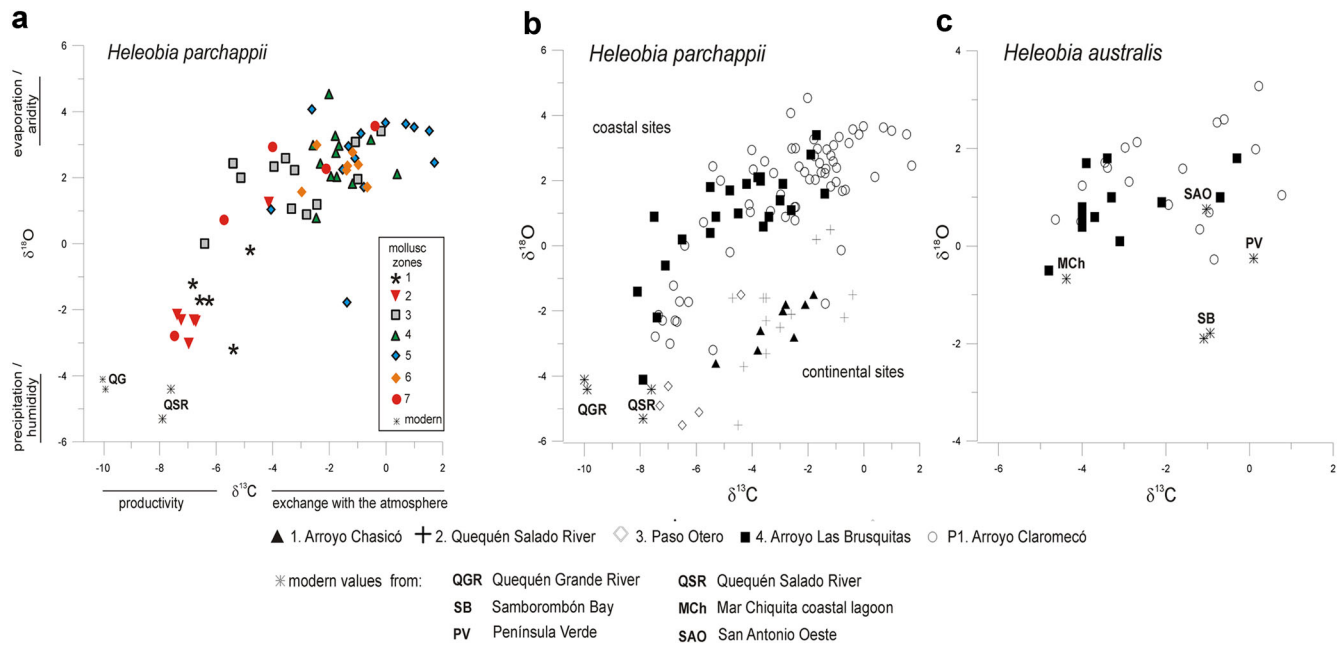


Figure 9. (a) Plots of $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ for the Holocene *Heleobia parchappii* from profile P1 at Arroyo Claromecó, mollusc zones and modern isotopic data. (b) $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ for all *H. parchappii* from modern data and Holocene fossil sequences (Table 3). (c) Plots of $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ of *H. australis* from modern data and fossil sequences (Table 3). This figure is available in colour online at wileyonlinelibrary.com.

change in P/E ratio or some other factor (Peros *et al.*, 2007).

During this period, halophytic vegetation and brackish water bodies were also developing at other locations in the region, such as at Arroyo Las Brusquitas (ALB) (Vilanova *et al.*, 2006) and Arroyo La Ballenera (Stutz *et al.*, 2002). Moreover, increased extension of other estuaries took place during this period, such as in the QG River where the estuary reached up to 12 km inland from the present mouth (Espinosa *et al.*, 2012).

- 3.2. *Between 7200 and 6450 cal a BP (6200–5750 ^{14}C a BP), *H. parchappii* dominates the assemblage and varies widely in abundance, while *H. australis* disappears from the assemblage. This marks the beginning of isolation from the sea and the development of a shallow-water brackish environment with highly variable salinity and chemical conditions as RSL declined following the Holocene highstand. An accompanying decrease in relative environmental energy at this time is indicated by the good preservation of *H. parchappii* shells (Figs 4 and 5). About 6450 cal a BP the assemblage has equal proportions of shells with fair, good and poor preservation, suggesting a change to more energetic conditions. *H. parchappii* $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values show a trend towards less negative values before 6450 cal a BP and positive values after that date (Fig. 7). The range of $\delta^{13}\text{C}$ values narrows but $\delta^{18}\text{O}$ values remain similar to those of the previous period that reflect increasing salinity, consistent with brackish condi-*

tions indicated by high values of acritarchs and the peak pollen values of the aquatic plant *Ruppia* sp. (Figs 7 and 8). These salinity conditions may have been a result of persistent tidal influence, given that the specimens of *Heleobia* spp. in this interval could be individuals of *H. australis*. Tidal influences as well as climatic conditions that fostered an evaporative environment could both be significant factors influencing the shell isotopic record of this period.

In summary, between 7400 and 6450 cal a BP all proxies suggest increasing marine water input and physical–chemical changes related to an increase in RSL, along with some evaporative effects. Regionally, in Arroyo La Ballenera, the marine influence fostered a halophytic community along with the maximum records of *Ruppia*, a dominance of marine–brackish benthic and epiphytic diatoms, and the greatest abundance of *H. australis* (Stutz *et al.*, 2002). Similarly, in ALB brackish and epiphytic diatom assemblages indicate a shallow brackish environment (lagoon) and associated vegetation at this time (Vilanova *et al.*, 2006). Consequently, despite some temporal offset, similar vegetation communities, mollusc populations and diatom assemblages changed across the region during this period as a consistent regional response to marine influence and increased evaporation.

- 3.3. *From ca. 6450 to 6000 cal a BP (5750–5250 ^{14}C a BP) a significant change in the composition of mollusc assemblages occurred. This change was characterized by an abrupt decrease in the density of*

Table 3. Localities used for *H. parchappii* and *H. australis* stable isotope data comparison and ^{14}C and calibrated age ranges (Fig. 1 for location).

Sequence	Latitude/longitude	Age range (^{14}C a BP)	Calibrated age range (cal a BP) (2σ)	References
Arroyo Chasicó	38°15'S, 62°45'W	<10 230 ± 70 to 2260 ± 40	11 596–12 119 to 2117–2337	Bonadonna <i>et al.</i> (1999)
Quequén Salado River	38°45'S, 60°45'W	10 840 ± 380 to ca. 8500	11 601–13 460 to ca. 9464–9541	Bonadonna <i>et al.</i> (1999)
Paso Otero	38°07'S, 59°00'W	8670 + 560/–520 to 5730 ± 280	8376–11 168 to 5893–7172	Bonadonna <i>et al.</i> (1999)
Arroyo Las Brusquitas	38°14'S, 57°46'W	6380 ± 60 to 2040 ± 80	6710–6990 to 1830–2300	Bonadonna <i>et al.</i> (1995), Vilanova <i>et al.</i> (2006)

H. parchappii and a scattered occurrence of fragmented marine Mytilidae shells, both of which reflect the development of a water body with fluctuating depth and salinity. Variable amounts of Poaceae, halophytic vegetation and phytoplankton (Figs 7 and 8) indicate that salinity and other water chemistry conditions were highly variable (Vilanova *et al.*, 2010). In ALB, abundant *H. parchappii* shells and the absence of *H. australis* indicate reduced tidal influence (Vilanova *et al.*, 2006). The trend towards heavier $\delta^{13}\text{C}$ values and positive $\delta^{18}\text{O}$ values established in the previous period continued. The $\delta^{13}\text{C}$ attained the highest Holocene values (1.7‰) and $\delta^{18}\text{O}$ reached almost 4‰. However, about 6200 cal a BP the oscillating values of both stable isotope ratios coincide with the appearance of tufa deposits. This suggests changes in water chemistry probably related to a negative balance in the P/E ratio. The presence of carbonate precipitate on *H. parchappii* shells during this period (Fig. 3) may similarly reflect climatic influences, such as high evaporation rates, CO_2 loss due to high surface water temperature, or a reduction of rainfall and post-depositional carbonate enrichment. The heavy $\delta^{13}\text{C}$ values in this interval probably reflect changes in catchment vegetation cover and water body productivity, which in turn control dissolved inorganic carbon (DIC) incorporated in mollusc shells. The more positive $\delta^{18}\text{O}$ values reflect increased evaporative effects probably related to dry/semi-arid climatic conditions. Likewise, in ALB, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are relatively high in this period, in particular $\delta^{18}\text{O}$ (2.5‰), indicating the establishment of a lagoonal environment and isotopic enrichment due to evaporation (Bonadonna *et al.*, 1995; Vilanova *et al.*, 2006). Overall, the primary factor causing the broader range of isotopic values was most likely evaporative processes and consequent changes in water chemistry at a regional scale.

4. Between 6000 and 4000 cal a BP (5250–3500 ^{14}C a BP) depth, pH and conductivity of the water body fluctuated widely. The variable conditions explain the very low densities of *H. parchappii* and the occurrence of a few shells of *S. meridionalis* and *B. peregrina* around 4000 cal a BP. A moderate energy setting is suggested by variations in the taphonomic condition of *H. parchappii*, although the average taphonomic grade indicates parautochthonous assemblages (Fig. 5). The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values have broad ranges. High $\delta^{18}\text{O}$ values suggest evaporation and desiccation processes that fostered brackish (saline/alkaline) conditions. The palynological record indicates repeated fluctuations between grassland and halophytic vegetation in response to variations in water level and physical–chemical conditions (Vilanova *et al.*, 2010). Climatic variability progressively became the main regional environmental forcing, while marine effects decreased.
5. The period from ca. 4000 cal a BP (3500 ^{14}C a BP) to the present is characterized by a regional RSL fall and concurrent hydrological variability producing alternating flooding and desiccation events (Vilanova, 2005). During this period, flooding events deposited sediment, including fragmented and corroded *H. parchappii* shells on higher parts of the floodplain. Average taphonomic grades for both attributes and lower density values indicate that most of these shells are transported and reworked (Figs 4 and 9). Shell concentrations are the lowest recorded in the sequence, suggesting probable taphonomic biases in the assemblage. The exclusive presence of *H. parchappii* may

indicate mesohaline waters (Tietze and De Francesco, 2010). The decreasing number of phytoplankton together with the presence of *Cobricosphaeridium* and the disappearance of *Typha* and *Ruppia* suggest desiccation of the wetland (Fig. 8). Over this interval, the pollen record reveals the dominance of halophytic and psammophytic vegetation (Fig. 8). These grassy communities occurred in a narrow palaeochannel dated to ca. 3600–720 cal a BP whose incision occurred sometime between ca. 3700 and 3200 cal a BP (Fig. 2). Diatom assemblages from the palaeochannel deposits indicate a slightly brackish environment with abundant aquatic vegetation and eutrophic conditions lacking a marine connection. After ca. 720 cal a BP the assemblage suggests an increase in desiccation in relation to drier environmental conditions and/or palaeochannel infilling by the incursion of coastal dunes and sand sheets (Hassan *et al.*, 2004). The broad range of shell isotope values from this interval reflects high environmental variability, although it must be kept in mind that shells may have been redeposited from nearby locations during infrequent flooding. Infrequent flooding is suggested by sporadic and intermittent sediment deposition and incipient soil formation during this interval, which created gaps in the record. Overall, isotope values support the existence of drier environmental conditions, as shown in the $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ plot (Fig. 9a). *S. meridionalis* $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotope ratios are similar to modern values (Bonadonna *et al.*, 1999) and are slightly heavier with respect to values during the period >8000–7400 cal a BP, all of which suggest drier conditions than before. This interpretation agrees with higher $\delta^{18}\text{O}$ values in ALB at ca. 2200 cal a BP, which were interpreted as isotopic enrichment due to evaporation (Bonadonna *et al.*, 1995; Vilanova *et al.*, 2006). Sand dunes that constitute the present landform configuration of the BMA encroached on the site after ca. 500 cal a BP. These sand dunes formed all along the south-eastern Pampa region, marking a regional response to climate change and RSL fall to its present position.

Regional comparison of Holocene climatic and environmental conditions based on inland and coastal isotope records of the Pampa region

To highlight the regional character of AC records and the environmental evolution associated with eustatic and climatic forcing factors we compare stable isotope records from inland and coastal areas of the Pampa region. The AC records from *H. parchappii* and *H. australis* fossil shells are compared with both modern and fossil shells of these same species, the former collected from modern estuaries and the latter retrieved from outcrops along several rivers in the Pampa region (Fig. 9b,c; Table 3). The shells were systematically sampled following lithostratigraphic criteria and analysed using similar laboratory methods, permitting a reliable comparison. The data allow us to establish differences and similarities in the Holocene climate of inland and coastal settings in the southern Pampa, which today has a semi-arid to subhumid–humid climatic gradient (Fig. 1).

H. parchappii shells from AC and ALB have similar ranges of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, consistent with their location near the coastline. Both valleys were subjected to marine influence and evaporative effects during the period ca. 7400–2200 cal a BP. In contrast, the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ ranges at these two localities are different from the ranges at QS River, Arroyo Chasicó (ACh) and Paso Otero (PO). The latter sites share similar ranges of values, consistent with the fact that all of

them are in a more continental location and all but PO are located to the west, an area with an incipient water deficit. Shells of *H. parchappii* from PO have the lightest $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of all these sites, attributed to wetter conditions and increasing rainfall around 9750 cal a BP (Bonadonna *et al.*, 1995, 1999). The $\delta^{13}\text{C}_{\text{CaCO}_3}$ and $\delta^{18}\text{O}_{\text{CaCO}_3}$ of ACh show the same trends, suggesting a climatic amelioration with increasing temperature and precipitation during the early Holocene (Zech *et al.*, 2009).

H. australis $\delta^{18}\text{O}$ values from AC and ALB are heavier than modern values from Mar Chiquita (MCh) and Samborombón Bay (SB). This difference reveals the predominance of marine influence and greater evaporative effects at AC and ALB with respect to present conditions at MCh and SB. Most $\delta^{13}\text{C}$ values at AC and ALB fall between modern values at MCh and SB, possibly because of a mixture of fresh and marine waters combined with a supply of lighter carbon in DIC of continental origin. Some values (especially from AC) are near 0 and +1‰, which are similar to values from northern Patagonia San Antonio Oeste (SAO) and southern Pampa estuaries Península Verde (PV), possibly suggesting a different meteoric signal and/or exchange with atmospheric CO_2 . Both SAO and PV are in an area where yearly rainfall is less than at AC and the P/E ratio is negative (Tonello and Prieto, 2010). Nevertheless, it is clear that both AC and ALB are affected by evaporation processes that produced $\delta^{18}\text{O}$ enrichment.

Trends of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ co-vary over time, suggesting that carbon incorporated into the shells was not substantially derived from metabolic carbon but from DIC in the water. This agrees with the documented association of shell isotopic composition with DIC in freshwater (fluvial) environments (Bonadonna *et al.*, 1999, and references therein). After ca. 6000 cal a BP, isotope data point to the dominance of dry air masses and semi-arid conditions with infrequent flooding events. This agrees with the trends of drier conditions during the mid-Holocene and pronounced climatic instability and higher evaporation at the beginning of the late Holocene suggested by isotopic data from further north in the Pampa (Bonadonna *et al.*, 1999; Zech *et al.*, 2009). Our interpretations are also coherent with trends of precipitation decrease quantitatively estimated for the late Holocene south-western Pampa region (Tonello and Prieto, 2010) and drying suggested by episodes of aeolian reactivation across the Pampa region during the mid- and late Holocene (Zárate and Tripaldi, 2012).

Palaeoclimatic evolution in a regional and extraregional context

Previous studies suggest a more arid climate during the mid-Holocene and increased precipitation during the late Holocene in comparison with the modern rainfall regime in the Pampas, and the mid-latitude region on the leeside of the Andes between 37 and 42°S (e.g. Grimm *et al.*, 2001; Schäbitz, 2003; Mancini *et al.*, 2005; Marcos *et al.*, 2012; Razik *et al.*, 2013). North-eastern and central Patagonian palynological records dating to the middle Holocene indicate low precipitation values and arid climatic conditions, in agreement with the general trends recorded at AC. These conditions may reflect relatively abrupt shifts in the position of the SWWB, superimposed on slower solar insolation changes (Bentley *et al.*, 2009). The SWWB shifted northward during the mid-Holocene (Razik *et al.*, 2013). This situation produced more frequent incursions of dry south-westerly to southerly air masses into the north-east extra-Andean (Schäbitz, 2003) and south-western Pampa regions. This could have produced the semi-arid conditions and evapora-

tive conditions that we interpret at AC, at least since ca. 6000 cal a BP. Maximum dry conditions developed at the centre of the arid/semi-arid region (ASR) during this time and the Arid Diagonal north of 42°S became established (Mancini *et al.*, 2005). Our data confirm the eastward displacement of the ASR during the mid-Holocene proposed by Mancini *et al.* (2005). More frequent incursions of southerly to south-westerly winds along the coast of south-east South America drove the Sub-antarctic Shelf Water (SSW) further north (Razik *et al.*, 2013). SSW flow was probably also intensified by a broadening shelf as sea level rose to the Holocene maximum between 7400 and 6450 cal a BP. Middle Holocene drying extended into north-western Patagonia, where Iglesias *et al.* (2012a, b) interpreted that the mid-Holocene precipitation gradient was steep enough to preclude the eastward expansion of *Austrocedrus* sp. Finally, Mancini *et al.* (2005) found that the forest-steppe ecotone also lay west of its present position, pointing to region-wide drying.

After about 4000 cal a BP the SAMS intensified over south-east South America inducing more intense north-easterly trade winds. El Niño Southern Oscillation (ENSO) variability also increased significantly (Razik *et al.*, 2013). Both changes fostered climatic variability, including intensification of precipitation and variable hydrological conditions reflected in the post-4370 cal a BP record at AC. In north-eastern Patagonia most of the palynological records suggest a weakening of westerly winds and the penetration of moist Atlantic air from the north-east and greater local moisture availability (Schäbitz, 2003; Marcos *et al.*, 2012). In north-western Patagonia present-day mixed *Nothofagus dombeyi* and *Austrocedrus chilensis* forests developed at ca. 4500–3000 cal a BP, probably in response to increased effective moisture. Greater moisture availability was probably related to the continued northward shift and strengthening of the SWWB, as well as the intensification of ENSO-related climate variability that caused short-term oscillations in humidity (e.g. Iglesias *et al.*, 2012a, b; Markgraf *et al.*, 2013).

Conclusions

The consistency of changes in malacological, stable isotope, diatom and palynomorph records contained in Pampean alluvial sequences demonstrates that these proxies are sensitive indicators of rapid Holocene environmental changes in grassland landscapes. This study enhances our understanding of the palaeoenvironmental framework of the AC area by yielding new information on palaeosalinity, water depth, geochemical conditions and palaeoenvironments with direct relevance to regional marine influence and palaeoclimate during the mid and late Holocene. This new information reflects not only local-scale variations but also regional response to forcing factors such as RSL variations as well as drier and more variable climatic conditions with respect to the modern climatic setting. This dual range of response is also indicated by similar changes in the lower reaches of valleys along the south and south-eastern coastal Pampa region occurring almost concurrently. In particular, we found that climatic variability recorded in AC is coherent with the climatic history of both the Pampa region and the mid-latitudes between 37 and 42°S on the leeside of the Andes.

The main events characterizing the palaeoecological response include: (i) marine influence in close proximity to the coast disturbing marginal environments before ca. 7700 cal a BP; (ii) a short-term decrease in salinity associated with freshwater influx between ca. 7700 and 7400 cal a BP in response to eustatic adjustment of the basins as sea level

rose; (iii) an increasing input of marine water related to the Holocene sea-level maximum coupled with greater evaporative conditions between 7400 and 6450 cal a BP; and (iv) evaporative processes linked to pronounced climatic variability that triggered changes in water chemistry during the last ca. 6000 cal a BP concurrent with RSL fall.

The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analyses of *Heleobia parchappii* and *H. australis* shells informed us with regard to evaporative processes and marine influence with more certainty than previous studies, in particular related to the maximum Holocene sea-level highstand. The regional comparison of isotope records clearly shows that coastal settings have a different isotopic signal than continental settings and revealed that evaporation and the negative P/E ratio balance at AC always influenced water chemistry to some degree, being as important as marine water influence during the period of maximum sea-level highstand. After ca. 6000 cal a BP the isotope data support interpretations that dry events and semi-arid conditions were dominant across the region.

Supporting Information

Additional supporting information can be found in the online version of this article:

Table S1. Mollusc assemblage zones and associated stable isotope ratios from Profile 1, Arroyo Claromecó.

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Abbreviations: AC, Arroyo Claromecó; ACh, Arroyo Chasicó; ALB, Arroyo Las Brusquitas; ANOVA, analysis of variance; ASR, arid/semi-arid region; BMA, Barrera Medanos Austral; DIC, dissolved inorganic carbon; ENSO, El Niño Southern Oscillation; P/E, precipitation/evaporation; PO, Paso Otero; QG, Quequén Grande; QS, Quequén Salado; RSL, relative sea level; SAMS, South American Monsoon System; SSW, Sub-antarctic Shelf Water; SWWB, Southern Westerly Wind Belt.

References

- Aguirre ML, Farinati EA. 1999. Taphonomic processes affecting late Quaternary mollusks along the coastal area of Buenos Aires Province (Argentina, Southwestern Atlantic). *Palaeogeography, Palaeoclimatology, Palaeoecology* **149**: 283–304.
- Aguirre ML, Leng MJ, Spiro B. 1998. Variation in isotopic composition (C, O and Sr) of Holocene *Mactra isabelleana* (Bivalvia) from the coast of Buenos Aires Province, Argentina. *Holocene* **8**: 613–621.
- Aguirre ML, Zanchetta G, Fallick AE. 2002. Stable isotope composition of *Littoridina australis* from the coast of Buenos Aires province, Argentina, during Holocene climatic fluctuations. *Geobios* **35**: 79–88.
- Bentley MJ, Hodgson DA, Smith JA, et al. 2009. Mechanisms of Holocene palaeoenvironmental change in the Antarctic Peninsula region. *Holocene* **19**: 51–69.
- Bértola G, Cortizo L, Juárez V, et al. 2005. *Determinación de la problemática de las playas y médanos de los partidos de Tres Arroyos y San Cayetano, Buenos Aires*. CIC y CGCC, Universidad Nacional de Mar del Plata.
- Blasi A, Politis G, Bayón C. 2013. Palaeoenvironmental reconstruction of La Olla, a Holocene archaeological site in the Pampean coast (Argentina). *Journal of Archaeological Science* **40**: 1554–1567.
- Bonadonna FP, Leone G, Zanchetta G. 1995. Composición isotópica de los fósiles de gasterópodos continentales de la provincia de Buenos Aires. Indicaciones paleoclimáticas. In *Evolución Biológica y Climática de la Región Pampeana Durante Los Últimos Cinco Millones de Años. Un Ensayo de Correlación con El Mediterráneo Occidental*, Alberdi MT, Leone G, Tonni EP (eds). Monografías del Museo Nacional de Ciencias Naturales: Madrid; 77–104.
- Bonadonna FP, Leone G, Zanchetta G. 1999. Stable isotope analyses on the last 30 ka molluscan fauna from Pampa grassland, Bonaerense region, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology* **153**: 289–308.
- Canepuccia AD, Escapa M, Daleo P, et al. 2007. Positive interactions of the smooth cordgrass *Spartina alterniflora* on the mud snail *Heleobia australis*, in South Western Atlantic salt marshes. *Journal of Experimental Marine Biology and Ecology* **353**: 180–190.
- Carbone ME, Piccolo MC, Perillo GME. 2005. Morphology and physical parameters of the Claromecó creek estuary, Argentina. *Thalassas* **21**: 55–63.
- Carbone ME, Piccolo MC, Scian BV. 2004. Análisis de los períodos secos y húmedos en la cuenca del Arroyo Claromecó, Argentina. *Papeles de Geografía* **40**: 25–35.
- Carcedo MC, Fiori SM. 2012. Long-term study of the life cycle and growth of *Heleobia australis* (Caenogastropoda, Cochliopidae) in the Bahía Blanca estuary, Argentina. *Ciencias Marinas* **38**: 589–597.
- Cavalotto JL, Violante RA, Parker G. 2004. Sea-level fluctuations during the last 8600 years in the de la Plata river (Argentina). *Quaternary International* **114**: 155–165.
- Cazzaniga NJ. 1982. Notas sobre hidróbidos Argentinos. 5. Conquiliometría de *Littoridina parchappii* (d'Orbigny, 1835) (Gastropoda: Rissooidea) referida a su ciclo de vida en poblaciones australes. *Iheringia Série Zoologia* **61**: 97–118.
- Cazzaniga NJ, Fiori SM. 2006. Daily activity pattern of *Heleobia parchappii* (Gastropoda: Hydrobiidae) under laboratory conditions. *Journal of Freshwater Ecology* **21**: 65–70.
- De Francesco CG, Isla FI. 2003. Distribution and abundance of hydrobiid snails in a mixed estuary and a coastal lagoon, Argentina. *Estuaries* **26**: 790–797.
- De Francesco CG, Zárate MA. 1999. Análisis tafonómico de *Littoridina* (Gastropoda: Hydrobiidae) en perfiles holocenos del río Quequén Grande (provincia de Buenos Aires): significado paleobiológico y paleoambiental. *Ameghiniana* **36**: 297–310.
- Denys L. 1991/1992. *A check-list of the diatoms in the Holocene deposits of the western Belgian coastal plain with a survey of their apparent ecological requirements*. Professional Paper, 246. Belgian Geological Survey.
- Espinosa M, De Francesco CG, Isla F. 2003. Paleoenvironmental reconstruction of Holocene coastal deposits from the Southeastern Buenos Aires Province, Argentina. *Journal of Paleolimnology* **29**: 49–60.
- Espinosa M, Hassan G, Isla F. 2012. Diatom-inferred salinity changes in relation to Holocene sea-level fluctuations in estuarine environments of Argentina. *Alcheringa* **36**: 373–386.
- Flessa KW, Cutler AH, Meldahl KH. 1993. Time and taphonomy: quantitative estimates of time-averaging and stratigraphic disorder in a shallow marine habitat. *Paleobiology* **19**: 266–286.
- Gaillard MC, de Castellanos ZA. 1976. Moluscos Gasterópodos, Hydrobiidae. In *Fauna de agua dulce de la República Argentina*, Ringuet RA (ed.). FECIC: Buenos Aires; **15**: 1–39.
- Garreaud RD, Vuille M, Compagnucci R, et al. 2009. Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology* **281**: 180–195.
- Grimm EC, Lozano-García S, Behling H, et al. 2001. Holocene vegetation and climate variability in the Americas. In *Interhemispheric Climate Linkages*, Markgraf V (ed.). Academic Press: San Diego; 325–365.
- Grimm EC. 2004. *TILIA Software*. Illinois State Museum, Research and Collection Center: Springfield, IL.
- Hammer Ø, Harper DAT, Ryan PD. 2001. PAST: paleontological statistics software package for education and data analysis. *Palaeontologica Electronica* **4**: pp.lp. <http://palaeo-electronica.org/2001-1/past/issue-01.html>.
- Hassan G, Espinosa MA, Isla FI. 2004. Análisis paleoambiental de una secuencia del Holoceno tardío del arroyo Claromecó (Provincia de Buenos Aires, Argentina) basado en diatomeas. *Ameghiniana* **41**: 161–170.

- Hassan G, Espinosa MA, Isla FI. 2009. Diatom-based inference model for paleosalinity reconstructions in estuaries along the northeastern coast of Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology* **275**: 77–91.
- Iglesias V, Whitlock C, Bianchi MM, et al. 2012a. Climate and local controls of long-term vegetation dynamics in northern Patagonia (Lat 41°S). *Quaternary Research* **78**: 502–512.
- Iglesias V, Whitlock C, Bianchi MM, et al. 2012b. Holocene climate variability and environmental history at the Patagonian forest/steppe ecotone: Lago Mosquito (42°29'3.89" S, 71°24'14.57" W) and Laguna del Cóndor (42°20'47.22"S, 71°17'07.62"W). *Holocene* **22**: 1254–1264.
- Isla FI, Cortizo LC, Turno Orellano HA. 2001. Dinámica y evolución de las barreras medianosas, provincia de Buenos Aires, Argentina. *Revista Brasileira de Geomorfologia* **2**: 73–83.
- Isla FI, Espinosa MA. 1998. Modelo sedimentario de colmatación de pequeños estuarios dominados por limo, provincia de Buenos Aires. *VII Reunión Argentina de Sedimentología, Actas*, Salta, Argentina; 24–36.
- Kowalewski M, Flessa KW, Aggen JA. 1994. Taphofacies analysis of recent shelly cheniers (beach ridges), northeastern Baja California, Mexico. *Facies* **31**: 209–242.
- Kowalewski M, Flessa KW, Hallam DP. 1995. Ternary taphograms: triangular diagrams applied to taphonomic analysis. *Palaios* **10**: 478–483.
- Landoni NA. 1992. Inventario de los moluscos de agua dulce de la provincia de Buenos Aires. In *Situación Ambiental de la Provincia de Buenos Aires. Recursos y Rasgos Naturales en la Evaluación Ambiental*, López HL, Tonni EP (eds). Comisión de Investigaciones Científicas: La Plata; 1–53.
- Leng MJ, Marshall JD. 2004. Palaeoclimate interpretation of stable isotope data from lake sediment archives. *Quaternary Science Reviews* **23**: 811–831.
- Mancini MV, Paez MM, Prieto AR, et al. 2005. Middle Holocene climatic variability reconstruction from pollen records (32–52° S, Argentina). *Quaternary International* **132**: 47–59.
- Marcos MA, Mancini MV, Favier Dubois CM. 2012. Middle–Late Holocene environmental changes in NE Patagonia inferred by palynological records and their relation to human occupation. *Holocene* **22**: 1271–1281.
- Markgraf V, Iglesias V, Whitlock C. 2013. Late and postglacial vegetation and fire history from Cordón Serrucho Norte, southern Patagonia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **371**: 109–118.
- Mc Connaughey TA, Gillikin DP. 2008. Carbon isotopes in mollusk shell carbonates. *Geo-Marine Letters* **28**: 287–299.
- Meldahl KH, Flessa KW, Cutler AH. 1997. Time-averaging and postmortem skeletal survival in benthic fossil assemblages: Quantitative comparisons among Holocene environments. *Paleobiology* **23**: 207–229.
- Parsons KM, Brett CE. 1991. Taphonomic processes and biases in modern marine environment. In *The Processes of Fossilization*, Donovan SK (ed.). Columbia University: New York; 23–65.
- Peretti V. 2005. *Factores ambientales y distribución de moluscos en las lagunas del centro-este de La Pampa*. Unpublished Thesis, Universidad Nacional de La Pampa.
- Peros MC, Reinhardt EG, Schwarcz HP, et al. 2007. High-resolution paleosalinity reconstruction from Laguna de la Leche, north coastal Cuba, using Sr, O, and C isotopes. *Palaeogeography, Palaeoclimatology, Palaeoecology* **245**: 535–550.
- Prieto AR, Blasi AM, De Francesco CG, et al. 2004. Environmental history since 11,000 14 C yr BP of the northeastern Pampas, Argentina, from alluvial sequences of the Luján River. *Quaternary Research* **62**: 146–161.
- Prieto AR, Stutz S, Vilanova I. 2000. Cambios de la vegetación entre los 7.000 y 6.000 14C a. A.P. en la actual barrera arenosa Austral, Provincia de Buenos Aires. XI Simposio Argentino de Paleobotánica y Palinología. Resúmenes: 95. Tucumán. *Ameghiniana* **37**(4): Suplemento: 61.
- Quiroz Londoño OM, Martínez DE, Dapeña C, et al. 2008. Hydrogeochemistry and isotope analyses used to determine groundwater recharge and flow in low-gradient catchments of the province of Buenos Aires, Argentina. *Hydrogeology Journal* **16**: 1113–1127.
- Razik S, Chiessi CM, Romero OE, et al. 2013. Interaction of the South American Monsoon System and the Southern Westerly Wind Belt during the last 14 kyr. *Palaeogeography, Palaeoclimatology, Palaeoecology* **374**: 28–40.
- Schäbitz F. 2003. Estudios polínicos del cuaternario en las regiones áridas del sur de Argentina. *Revista del Museo Argentino de Ciencias Naturales* **5**: 291–299.
- StatSoft. 2001. *STATISTICA for Window, ver. 6.0*. StatSoft, Inc.: Tulsa, OK.
- Stuiver M, Reimer PJ, Reimer RW. 2005. *Calib 5.0.1*. <http://calib.qubc.uk/calib/>.
- Stutz S, Espinosa MA, De Francesco CG, et al. 2002. Historia ambiental del arroyo La Ballenera (provincia de Buenos Aires) durante el último ciclo transgresivo-regresivo. Análisis de diatomeas, polen, moluscos y sedimentos. *VIII Congreso Argentino de Paleontología y Bioestratigrafía*. Actas: 51. Corrientes, Argentina.
- Tietze E, De Francesco CG. 2010. Environmental significance of freshwater mollusks in the Southern Pampas, Argentina: to what detail can local environments be inferred from mollusk composition? *Hydrobiologia* **64**: 133–143.
- Tietze E, De Francesco CG, Núñez MV. 2011. What can gastropod assemblages tell us about freshwater environments?. In *Gastropods: Diversity, Habitat and Genetics*, Bianchi A, Fields J (eds). Nova Science Publishers: New York; 1–34.
- Tonello MS, Prieto AR. 2008. Modern vegetation–pollen–climate relationships for the Pampa grasslands of Argentina. *Journal of Biogeography* **35**: 926–938.
- Tonello MS, Prieto AR. 2010. Tendencias climáticas para los pastizales pampeanos durante el Pleistoceno tardío–Holoceno: estimaciones cuantitativas basadas en secuencias polínicas fósiles. *Ameghiniana* **47**: 501–514.
- Vilanova I. 2005. *Dinámica de cambio de la vegetación y variabilidad climática desde el Pleistoceno tardío en el actual sector costero bonaerense (35°–45° S)*. Doctoral Thesis, Universidad Nacional de Mar del Plata, Argentina.
- Vilanova I, Prieto AR. 2012. Historia de la vegetación de las llanuras costeras de la Bahía Samborombón (~35,5° S), Argentina, desde 7800 14 C años. *Ameghiniana* **49**: 303–318.
- Vilanova I, Prieto AR, Espinosa MA. 2006. Palaeoenvironmental evolution and sea-level fluctuations along the southeastern Pampa grasslands coast of Argentina during the Holocene. *Journal of Quaternary Science* **21**: 227–242.
- Vilanova I, Prieto AR, Stutz S, et al. 2010. Holocene vegetation changes along the southeastern coast of the Argentinian Pampa grasslands in relation to sea-level fluctuations and climatic variability: Palynological analysis of alluvial sequences from Arroyo Claromecó. *Palaeogeography, Palaeoclimatology, Palaeoecology* **298**: 210–223.
- Vos PC, de Wolf H. 1988. Methodological aspects of paleo-ecological diatom research in coastal areas of the Netherlands. *Geologie en Mijnbouw* **67**: 31–40.
- Vos PC, de Wolf H. 1993. Reconstruction of sedimentary environments in Holocene coastal deposits of the southwest Netherlands; the Poortvliet boring, a case study of palaeoenvironmental diatom research. *Hydrobiologia* **269/270**: 297–306.
- Zar JH. 1999. *Biostatistical Analysis*. Prentice Hall: Englewood Cliffs, NJ.
- Zárate M. 2005. El Cenozoico tardío continental de la provincia de Buenos Aires. In *Geología y Recursos Minerales de la Provincia de Buenos Aires de Barrio R, Etcheverry R, Caballé M, Llambías E* (eds). Relatorio 16° Congreso Geológico Argentino: La Plata; 139–158.
- Zárate MA, Tripaldi A. 2012. The aeolian system of central Argentina. *Aeolian Research* **3**: 401–417.
- Zech W, Zech M, Zech R, et al. 2009. Late Quaternary paleosol records from subtropical (38°S) and tropical (16°S) South America and paleoclimatic implications. *Quaternary International* **196**: 107–120.