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Environmental history since 11,000 ^{14}C yr B.P. of the northeastern Pampas, Argentina, from alluvial sequences of the Luján River

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Abstract

Sedimentological, malacological, and pollen analyses from ^{14}C-dated alluvial sections from the Luján River provide a detailed record of environmental changes during the Holocene in the northeastern Pampas of Argentina. From 11,200 to 9000 ^{14}C yr B.P., both sedimentary and biological components suggest that the depositional environment was eutrophic, alkaline, and freshwater to brackish shallow water bodies without significant water circulation. During this time, bioclastic sedimentation was dominant and the shallow water bodies reached maximum development as the climate became more humid, suggesting an increase in precipitation. Short-term fluctuations in climate during the last stage of this interval may have been sufficient to initiate changes in the water bodies, as reduction of the volume alternated with periods of flooding. The beginning of the evolution of shallow swamps in the wide floodplain or huge wetlands was contemporaneous with a sea level lower than the present one. From 9000 and 7000 ^{14}C yr B.P., mesotrophic, alkaline, brackish, probably anoxic swamps existed. Between 7000 and 3000 ^{14}C yr B.P., anoxic calcareous swamps were formed, with subaerial exposure and development of the Puesto Berrondo Soil (3500–2900 ^{14}C yr B.P.). A trend to a reduction of water bodies is recorded from 9000 to ca. 3000 ^{14}C yr B.P., with a significant reduction after ca. 7000 ^{14}C yr B.P. A shift to subhumid–dry climate after 7000 ^{14}C yr B.P. appears to be the main cause. During this time, an additional external forcing toward higher groundwater levels was caused by Holocene marine transgression causing changes in the water bodies levels. The climate became drier during the late Holocene (ca. 3000 yr B.P.), when clastic sedimentation increased, under subhumid–dry conditions. Flood events increased in frequency during this time. From ca. A.D. 1790 to present, the pollen record reflects widespread disturbance of the vegetation during the European settlement.

Keywords: Sedimentology; Molluscs; Pollen; Environmental reconstruction; Holocene; Pampas; Argentina

Introduction

The alluvial deposits exposed in cutbanks along the Luján River are a classical paleontological and geological area recording late Quaternary evolution of the northeastern Pampas of Argentina. Ameghino (1880–1881, 1884, 1889) first proposed a sequence of hierarchical alluvial units defined on the basis of their paleontological content and lithology. Later, Frenguelli (1922, 1945a, 1945b) classified the units chronostratigraphically. These early publications reported that the alluvial sequences contained numerous species of late Pleistocene mammal fossils, molluscs and diatoms, and some plant remains. Although these alluvial sequences have been commonly used as type sections for correlating other Pampean exposures, an accurate chronology and the identification of the range of fossil remains present in the Luján River type area is still needed. Recently, Dangavs and Blasi (1995) carried out a sedimentological study of the units and correlated them with those described

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by Fidalgo et al. (1973) in the eastern Pampa. The documentation of other alluvial deposits in the Pampas and their use as proxy records of climatic change was demonstrated in recent studies (Zárate et al., 1998, 2000). Here we present a detailed sedimentological, malacological, and pollen analysis from the Holocene alluvial deposits of the Luján River. The age of the deposits was determined by ^{14}C ages from aquatic molluscs and bulk organic matter of buried soils. Based on these data, we reconstruct the Holocene environmental history of the northeastern Pampas of Buenos Aires Province. Timing and direction of these environmental changes are here compared with other paleoclimatic records of the Pampas.

Study area and stratigraphic context

The northeastern Pampas of Buenos Aires Province is a gently rolling plain drained by tributaries to the Paraná-de la Plata River, including Luján River (Fig. 1). Deep valley incision, still active, probably began during the late Holocene and extends to early Pleistocene bedrock (Dangavs and Blasi, 1995). For this reason, the character of this network is mainly exorheic without shallow lakes (“lagunas”) and stream ponds.

The Luján River is a permanent stream of moderate sinuosity. It is oriented SW–NE in the upper reaches, but 40 km upstream of the outlet it course turns toward the SE (Fig. 1), because of the rapid progradation (90–95 m/yr) of the Paraná delta onto the de la Plata River (Fucks and De Francesco, 2000). In the upper and middle reaches, the river is 40–50-m wide, with well-defined cutbanks (up to 5-m high), although in some places it is narrower. In the lower reach (below 5 m asl), the cutbanks are 2–3-m high, and the river valley opens into a wide floodplain.

The valley is located in the north portion of the rolling Pampa (León, 1991), a unit of the Pampa grasslands that consists of grassland dominated by species of the genera *Stipa*, *Piptochaetium*, and *Aristida* and where shrubs and subfruttices are dominant locally. Urban development and modern agriculture and husbandry have extensively modified the natural vegetation.

Present-day climate is humid mesothermal, with no or only a small water deficit. Precipitation regime is a transition to maritime winter rains (Prohaska, 1976). Mean annual precipitation is 1000 mm. Mean summer temperature (January) is 23 °C and mean winter temperature (July) is 10 °C.

Geology

The early Pleistocene Ensenada Formation constitutes the valley bedrock and crops out along the upper and middle reaches of the Luján River (Dangavs and Blasi, 1995). In downstream direction, between Mercedes and Lujan Cities, the river cutbanks are constituted successively and alternately, by different stratigraphical arrangements. In some 5–7-km-long reaches, the cutbanks expose Ensenada Formation overlain by the middle Pleistocene Buenos Aires Formation (Riggi et al., 1986), while in other reaches of similar length, the Ensenada Formation is overlain by late Pleistocene and Holocene deposits. The late Pleistocene and Holocene stratigraphic succession includes “Lujanense,” Puesto Callejón Viejo soil, “Platense fluvio-lacustre,” Puesto Berrondo soil, and reworked eolian and alluvial sediments (Fig. 2). Dangavs and Blasi (1995) correlated the “Lujanense” (Ameghino, 1889) with both the La Chumbiada Member (Dillon and Rabassa, 1985) and the Guerrero Member, and “Platense fluvio-lacustre” (Ameghino, 1889) with the Río Salado Member, all of them corresponding to the Luján Formation (Fidalgo et al., 1973).

In this region, the undulating early–middle Pleistocene paleosurface contains a succession of elongated NW–SE trending shallow depressions. These depressions, whose origin is still controversial, strongly control the modern channel pattern as well as the architecture of the alluvial deposits of the drainage nets in the region. Early and middle Pleistocene are exposed where streams incise the higher areas of the paleosurface while late Pleistocene–Holocene deposits are exposed in channels cut into the paleosurface depressions.

Twenty kilometers downstream from the Puente de la Tropa section, in the distal Luján River reach, estuarine deposits of the Destacamento Río Salado and Las Escobas Formations (Fidalgo et al., 1973) or “Platense estuárico,” croup out between the Ensenada Formation and modern alluvial sediments (Mazanares section, Fig. 1). These estuarine deposits were dated between 6370 and 3640 ^{14}C yr B.P. (obtained from *Erodona mactroides* and *Tagelus plebeius*; Figini, 1992; Fucks and De Francesco, 2003).

In the Pampa area, the deposition of the “Lujanense” began before the Last Glacial Maximum, probably between 40,000 and 30,000 ^{14}C yr B.P., and ended about 11,000–10,000 ^{14}C yr B.P. (Zárate et al., 2000). The “Platense fluvio-lacustre” was deposited between about 11,000–10,000 ^{14}C yr B.P. and 3400–2700 ^{14}C yr B.P. (Bonadonna et al., 1995; Johnson et al., 1998; Zárate et al., 2000). After this time, primary and reworked eolian and modern alluvial sediments accumulated in valley.

Methods

Dredging works along the middle reach of the Luján River produced a continuous exposure of more than 400 m. Sediment samples were collected from two outcrops [Puente de la Tropa site (34° 34′ 40″ S; 59° 08′ 14″ W) and Paso de Corro site (34° 33′ 17″ S; 59° 07′ 07″ W)] for sedimentological, malacological, and pollen analysis and radiocarbon dating (Figs. 1 and 2). Before sampling, the outermost exposed 50-cm were removed. Pollen and mollusc samples were taken at 5-cm intervals. A volumetric sampling (31.8 cm^3/sample) was carried out for mollusc analysis in each site. Eight samples of ca. 2 kg at different

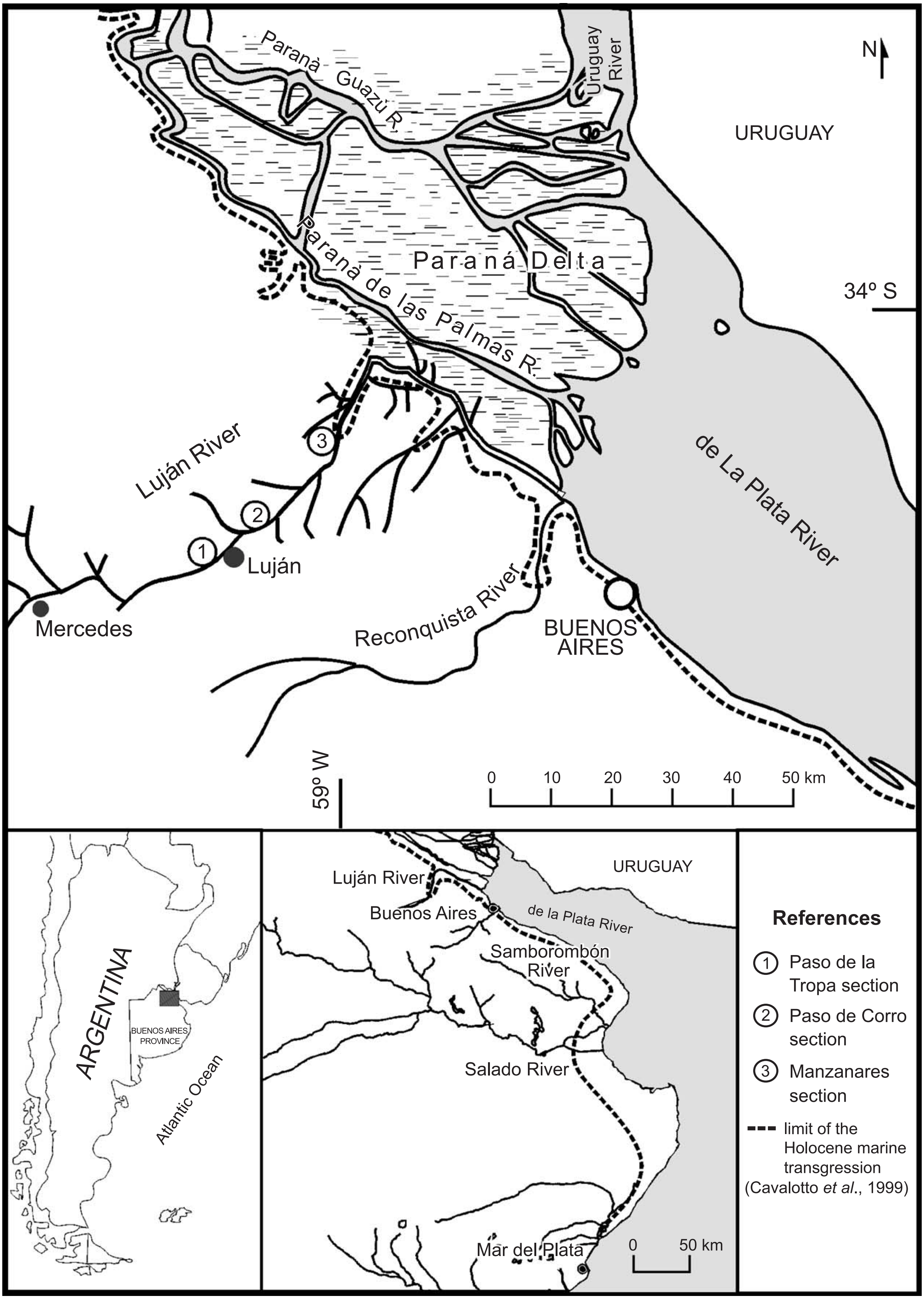

Fig. 1. Location map of the Luján River showing location of Puente de la Tropa, Paso de Corro, and Manzanares sections and geographic features.

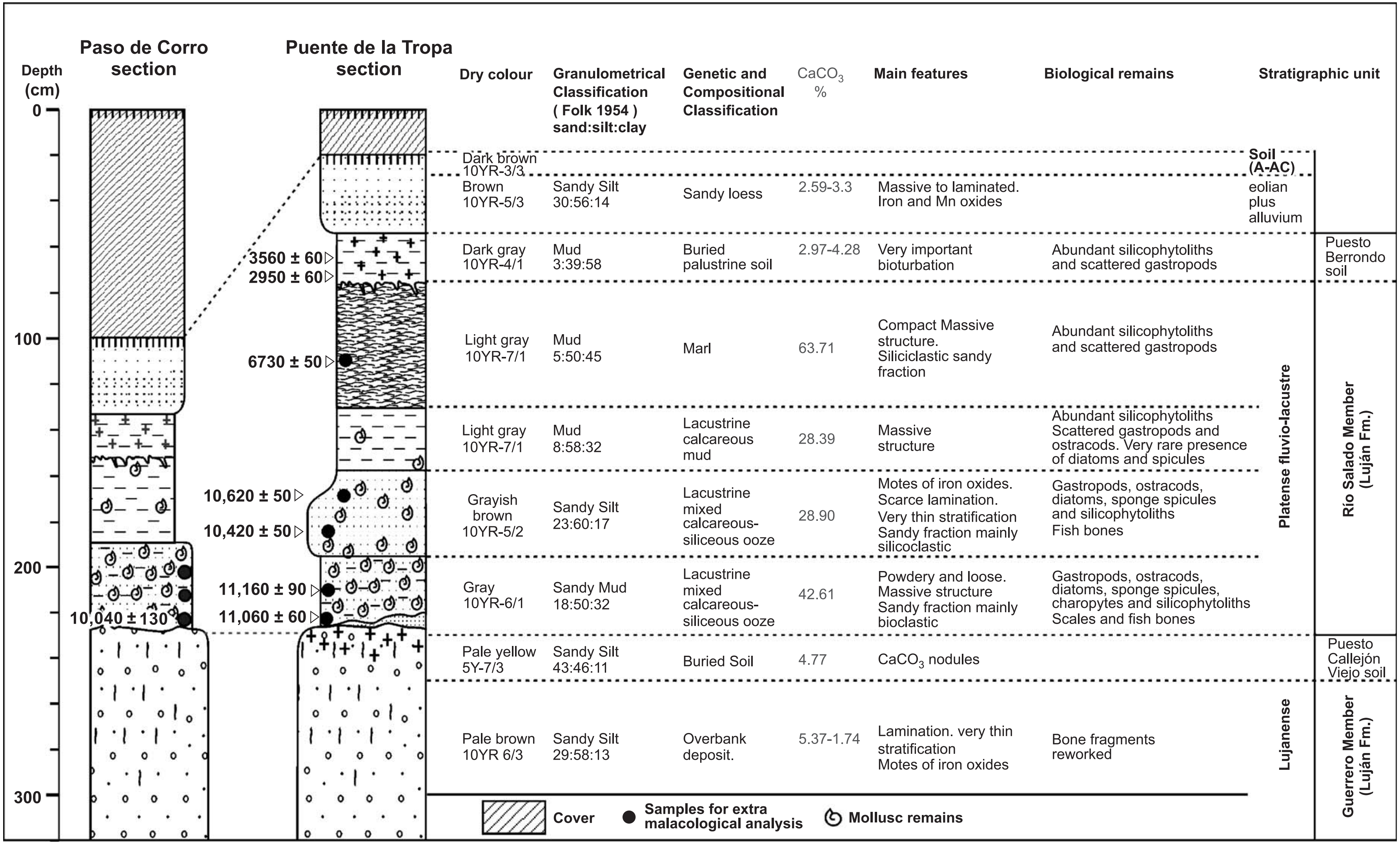

Fig. 2. Stratigraphic sequences at the Puente de la Tropa and Paso de Corro sections with the positions of all samples for extra malacological analyses, radiocarbon ages in ^{14}C yr B.P.

stratigraphic positions (five samples at the Puente de la Tropa and three samples at the Paso de Corro) were collected for extra malacological analyses (Fig. 2).

Sediments

Grain size analyses were performed following standard procedures. Organic matter was removed by digestion with hydrogen peroxide and carbonate removed with dilute HCl. The latter treatment was not performed on those samples in which a significant portion of the sand fraction consisted of carbonate detritus such as shell and other skeletal fragments. For dispersion, Na-hexametaphosphate was used. Grain size analysis was made for the sand size fraction by wet sieving using selected set-screens at 1-ϕ intervals, and for silt and clay size by the pipette method (Carver, 1971). Standard petrographic procedures were used to determine sand composition. Carbonate content was calculated using the acid-neutralization method as well as the gravimetric method with some samples (Allison and Moodie, 1965).

Molluscs

All samples were sieved (# 25 ϕ), carefully washed (avoiding breakage of shells), and dried overnight. All molluscs in each sample were counted and size determination made with an ocular micrometer in a Wild M5A stereoscopic microscope. Percentages of different types and density (individual/cm^3) were calculated. Gastropod nomenclature is based on de Castellanos and Fernández (1976), de Castellanos and Landoni (1981), Fernández (1973), Fernández and de Castellanos (1973), Gaillard and de Castellanos (1976), Landoni (1992), and Rumi (1991).

Before the radiocarbon analysis on *Heleobia parchappii*, shells from extra samples were randomly subsampled to analyze the abundance of species, and both size–frequency distributions and shell fragmentation to determine whether samples could have been subject to taphonomic alteration (De Francesco and Zárate, 1999). Shell fragmentation of *H. parchappii* was calculated according to Parsons and Brett (1991).

Pollen

Pollen samples were prepared using standard pretreatment techniques, including KOH (10%), HCl, heavy liquid separation by $ZnCl_2$, HF (48%), and acetolysis (Faegri and Iversen, 1989). Before treatment, five tablets of *Lycopodium* spores were added to each sample for the calculation of pollen concentration in grains per gram of sediment (Stockmarr, 1971). Identification of pollen was based on the reference collections at the Paleoecology and Palynology Laboratory of the Universidad Nacional de Mar del Plata.

Pollen, spore, and mollusc data were plotted using TILIA and TILIAGRAPH software (Grimm, 1991).

Results

Stratigraphy and sedimentology

Three stratigraphic units are recognized along the cutbanks at the upper–middle reaches of the Luján River, from the Mercedes city to near Manzanares section (Fig. 1). These units are clearly differentiated by their grain size, bedding, and bounding surfaces (Fig. 2). The oldest unit is the "Lujanense," which is composed of laminated sand to sandy silt deposited in channel and floodplain environments. The lithological and mineralogical composition of this unit has been described in detail by Dangavs and Blasi (1995) and abundant remains of mammal fossils have been recovered throughout it (Tonni et al., 1999). The Puesto Callejón Viejo soil, a hydromorphic soil with ferruginous mottles, carbonate nodules, and abundant clay is developed in the uppermost part of the "Lujanense." This paleosol is traceable for several kilometers along the valley of the Luján River and has been identified in similar stratigraphic position in other valleys of the northern Pampas (Fidalgo et al., 1973), and southern and central Pampas (Zárate et al., 2000).

The "Platense fluvio-lacustre" unit conformably overlies the "Lujanense." This is a 180-cm-thick fining-upward sequence mainly composed of muddy marls with marked bioturbation, iron oxide accumulation, and calcium carbonate nodules. Although this unit is usually tabular, some exposures perpendicular to the river are lenticular and show that the "Platense fluvio-lacustre" is inset against and partially buries the "Lujanense". The contact with the underlying Puesto Callejón Viejo soil is abrupt and smooth in all sections. The "Platense fluvio-lacustre" unit ends with a distinct paleosol (Puesto Berrondo soil), which is unconformably overlain by primary and reworked eolian sandy silt and modern alluvial deposits modified by development of the modern soil (A–AC profile).

Calcium carbonate content of the "Platense" varies between 14% and 64%, reaching higher values in organogenic sandy muds and muddy marl (Fig. 2). The highest percentages are found in samples rich in carbonate shells (bioclasts), while in the muddy marl levels powdery calcium carbonate is result of chemical precipitates.

Biological opal (phytoliths, diatoms, and spicules) was identified in both sandy muds and muds of the "Platense." Phytoliths are represented by fan-shaped and elongated morphotypes, which are characteristic in Poaceae tribes such as Bambuseae, Oryzeae, Chlorideae, and Paniceae (Bertoldi de Pomar, 1971).

Malacological analysis

Four freshwater gastropod species (*H. parchappii*, *Biomphalaria tenagophila*, *Pomacea canaliculata* and *Lymnaea viatrix*), and two terrestrial gastropod species (*Succinea meridionalis* and a member of the terrestrial family Systrophiidae) were identified (Fig. 3). In all previous papers (e.g., Camacho, 1966; Frenguelli, 1945a,b), the latter taxon was assigned to *Scolodonta semperi* (Table 1). However, the specific identification of Systrophiidae is not possible now because this taxon probably includes more than one species (S. Miquel, personal communication, 2000).

Concentration (individuals/cm^3) and abundance (%) of species are reported (Figs. 4 and 5). In addition, size–frequency distributions of *H. parchappii* from extra sample analyses are also shown (Fig. 6). These analyses were not made on the sample at 105–115-cm depth in the Puente de la Tropa section due to the small number of shells and because most of the specimens were broken.

Ecological information on the freshwater and terrestrial gastropods is somewhat limited (de Castellanos and Fernández, 1976; Landoni, 1992). The same freshwater gastropod species live today in a wide variety of permanent water bodies of the Buenos Aires province.

H. parchappii is an invader species (Cazzaniga, 1981) that lives commonly on submerged vegetation (Cazzaniga, 1982; Gaillard and de Castellanos, 1976; Landoni, 1992). It has also been found in other substrates like calcrete, gravel, and silt (Darrigran, 1995, De Francesco and Isla, 2003). Despite being very widespread in freshwater environments, this species can develop and maintain stable populations in brackish waters with mean salinity values between 17‰ and 23‰ (De Francesco and Isla, 2003). Most of the South American species of *Heleobia* live almost exclusively in clean, transparent, and well-oxygenated water. Stagnant water without circulation is a limiting factor (Weyrauch, 1963). No populations of *H. parchappii* are now living in the Luján River.

B. tenagophila lives mainly in lentic bodies with transparent water, in areas containing submerged aquatic vegetation and at depths of less than 2 or 3 m. Water chemistry is often sodium–calcium carbonate type, with neutral to slightly acid pH (Rumi, 1991).

P. canaliculata mostly inhabits deeper sites (lentic or lotic) with stagnant water or low water velocity, high content of suspended material, and low Na$^+$/(K$^+$+Mg$^+$) ratios (Martín et al., 2001). They can survive in very dry conditions or at low river water levels and in water with variable salinity (de Castellanos and Fernández, 1976). Water temperature is one of the most important ecological factors in this species life cycle. An increase in water temperature can notably shorten its life span by lowering the age of the first reproduction (Estebenet, 1989).

Table 1
Freshwater and terrestrial molluscs previously identified by other authors and their correlation with those identified at Puente de la Tropa and Paso de Corro sections (Luján River)

Ameghino (1880–1881)	Frenguelli (1945b)	This paper
Palludestrina parchapii *Palludinella parchappei*	*Littoridina parchappi*	*Heleobia parchappii*
Ampullaria canaliculata	*Ampullaria canaliculata*	*Pomacea canaliculata*
Planorbis montanus	*Planorbis peregrinus*[a]	*Biomphalaria tenagophila*[a]
Not found	*Lymnaea viatrix*	*Lymnaea viatrix*
Not found	*Succinea meridionalis*	*Succinea meridionalis*
Not found	*Scolodonta semperi*[b]	Systrophiidae spp. Indet[b]
Not found	*Ancylus culicoides*	Not found
Helix	Not found	Not found

[a] We have not found *Planorbis peregrinus* (=*Biomphalaria peregrina*) in the studied sequences. It is likely that Frenguelli (1945b) confused *Biomphalaria peregrina* with *B. tenagophila* due mainly to their morphologic similarity.

[b] Systematic change is discussed in the text.

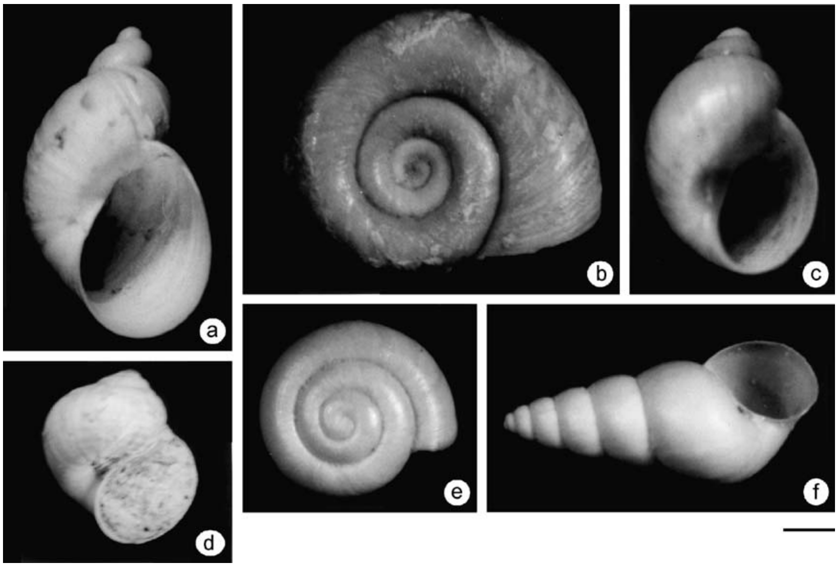

Fig. 3. Gastropods found in Puente de la Tropa and Paso de Corro sections. (a) *Succinea meridionalis*; (b) *Biomphalaria tenagophila*; (c) *Lymnaea viatrix*, scale bar = 1.45 mm; (d) *Pomacea canaliculata*, scale bar = 0.43 cm; (e) Systrophiidae, (f) *Heleobia parchappii*, scale bar = 0.73 mm.

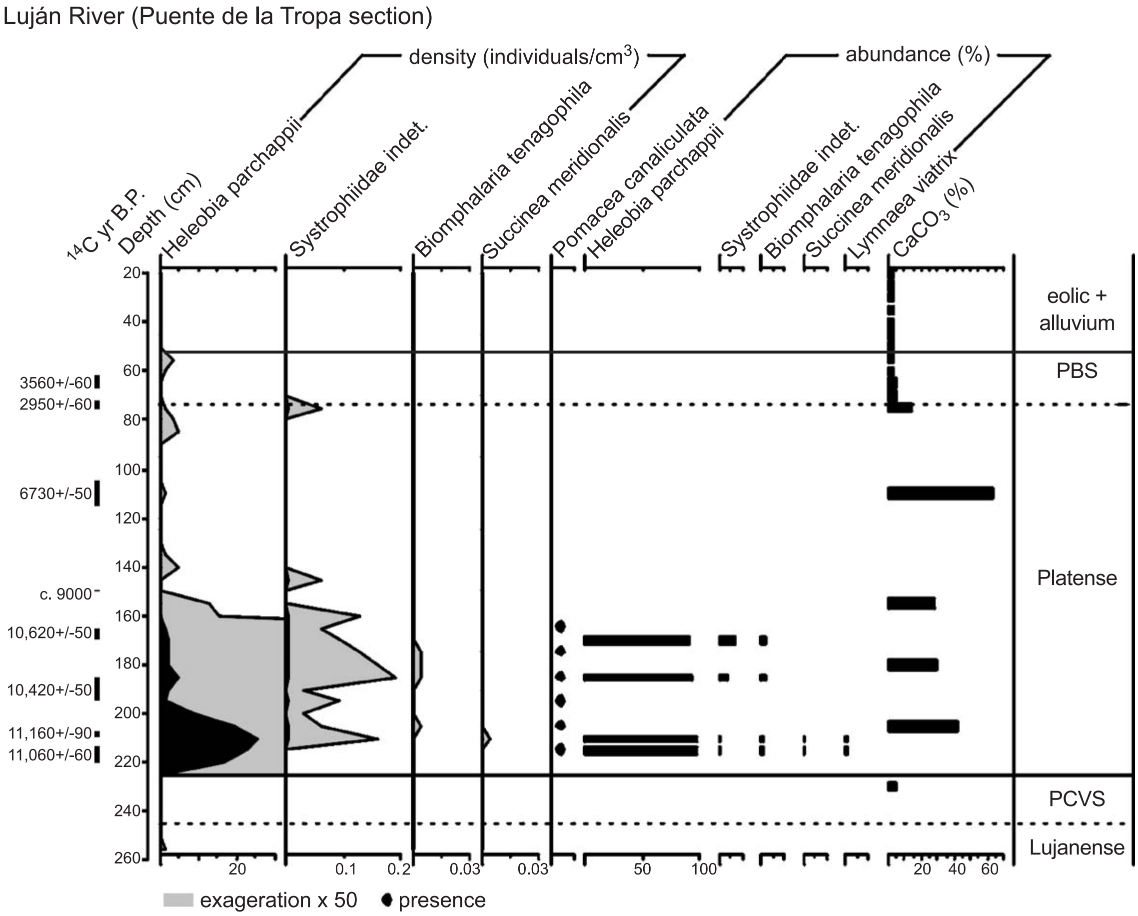

Fig. 4. Density and abundance of gastropods, and percentages of $CaCO_3$ in Puente de la Tropa section, Luján River. PBS = Puesto Berrondo soil. PCVS = Puesto Callejón Viejo soil.

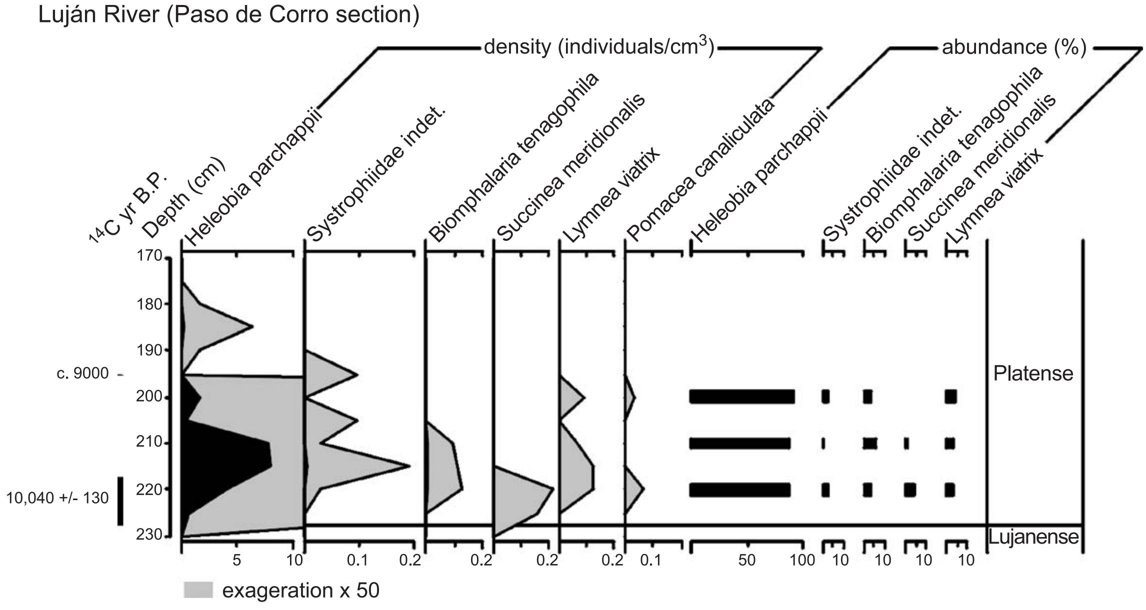

Fig. 5. Density and abundance of gastropods in Paso de Corro section, Luján River.

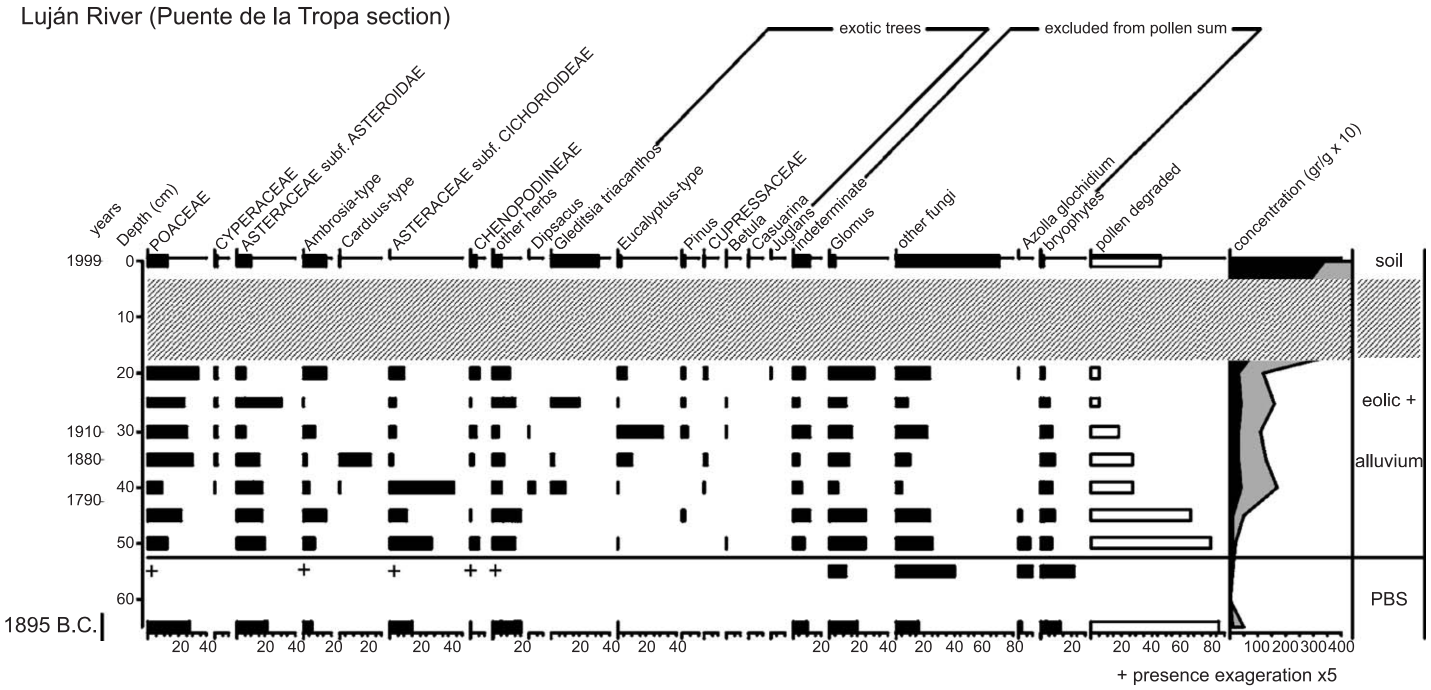

Fig. 6. Pollen diagram in percentages and concentration for Puente de la Tropa section. Dashed = cover. PBS = Puesto Berrondo soil.

Table 2
Suggested correlation among historical events and pollen at the Puente de la Tropa section

Sediment horizon (cm)	Marker	Suggested date (A.D.)	Likely historical cause
30	First record of *Pinus* and *Betula* pollen	1910–1930	Founding of Ameghino and Rivera public parks
35	Beginning of *Eucalyptus*-type pollen and peak in *Carduus*-type	1880–1882	Forestation with 1300 *Eucalyptus* specimens
40	First *Dipsacus* and *Gleditsia triacanthos* pollen and peak of Asteraceae subf. Cichorioideae	1790–beginning of 19th century	Development of agriculture and population

L. viatrix lives in different lentic or lotic environments. Among lotic environments, it lives only in backwater (de Castellanos and Landoni, 1981). Different species of Lymnaediae normally live in clean water, preferentially without turbulence, at different depths and with the presence of silt and aquatic plants, although they can swim to the surface when they need to breath (Landoni, 1992). They require water rich in calcium, developing especially in alkaline waters (de Castellanos and Landoni, 1981). Like *P. canaliculata*, *L. viatrix* survives dry periods by burying themselves in silt or in detritic sediments, or by secreting a mucous substance that closes the aperture.

S. meridionalis is a terrestrial gastropod that has been associated to aquatic environments (Landoni, 1992). However, this species can inhabit a wide range of terrestrial environments (d'Orbigny, 1835–1847).

Pollen analysis

Results are shown in Figure 6. Pollen sum ranges between 124 and 483 grains. Bryophyte spores, fungal spores, *Azolla* glochidia, and indeterminate pollen grains were not included in the pollen sum. Pollen assemblages also contain degraded pollen grains. The percentages of poorly preserved pollen grains were calculated as percentages out of the sum. Samples below 65 cm contain very few or no pollen and spores. Individual levels may show mixed pollen assemblages due to pollen percolation, reflected, e.g., by fluctuations in pollen concentration/degraded pollen and the presence of single degraded pollen grains of *Pinus*, *Betula*, and Myrtaceae in the lower part of the profile. However, the entire sequence shows a consistent chronology of events (Table 2). There is no correlation between percentages of $CaCO_3$ and both degraded pollen percentage and pollen concentration values. Probably, the most important factor responsible for pollen degradation is microbial activity.

Radiocarbon dating and chronology

Radiocarbon dates were obtained on bulk organic carbon (two samples of soil organic matter) and inorganic carbon of biological remains (six samples of *H. parchappii* shells) (Table 3; Fig. 2). Radiocarbon dates were performed by conventional beta counting and accelerator mass spectrometry (AMS).

Size–frequency distributions of *H. parchappii* show the same positively skewed curve found in living specimens (Cazzaniga, 1982) with persistence of small individuals and a wide range of sizes (Fig. 7). This, in addition to a moderately low fragmentation, indicates the absence of a post mortem transport and assures that fossil shells were found in situ providing a firm basis for assessing reliability in radiocarbon dates. Moreover, samples show values of $\delta^{13}C$ lying within ranges obtained for living *H. parchappii* sampled in the Pampas by Bonnadonna et al. (1999). Only one sample did not show $\delta^{13}C$ of typical freshwater shells (Table 3), suggesting high excess carbonate in the water, coincident with the highest value of $CaCO_3$ in the profile (Fig. 2). This might indicate that a reservoir effect of unknown magnitude exists in the shell date. A reservoir

Table 3
Radiocarbon data from Puente de la Tropa and Paso de Corro sections, Luján River

Depth (cm)	Lab. No.	^{14}C date ± σ ^{14}C yr B.P.	$\delta^{13}C/^{12}C$ (‰)	Calibrated dates[a] cal yr B.P.	Material dated
Puente de la Tropa section (34° 34′ 40″ S; 59° 08′ 14 W)					
62–67	Beta-118013	3560 ± 60	−25.0	Cal B.C. 2030–1735	Soil organic matter
72–75	Beta-127752	2950 ± 60	−25.0	Cal B.P. 3325–2935	Soil organic matter
105–115	Beta-127751	6730 ± 50	+1.6	Cal B.P. 7360–7170	*Heleobia parchappii*
165–170	Beta-120516	10,620 ± 50	−7.3	Cal B.P. 12,925–12,605 Cal B.P. 12,495–12,350	*Heleobia parchappii*
185–195	Beta-118463	10,420 ± 50	−7.4	Cal B.P. 12,815–11,950	*Heleobia parchappii*
207–212	Beta-118461	11,160 ± 90	−7.4	Cal B.P. 13,435–12,895	*Heleobia parchappii*
213–220	Beta-118462	11,060 ± 60	−7.8	Cal B.P. 13,180–12,890	*Heleobia parchappii*
Paso de Corro section (34° 33′ 17″ S; 59° 07′ 07″ W)					
217–227	Beta-133459	10,040 ± 130	−5.0	Cal B.P. 12,330–11,190	*Heleobia parchappii*

[a] Ages calibrated to a "calendar" time scale using the CALIB 3.0 program (Beta Analytic, written communication, 2000). Age ranges are ± 2σ.

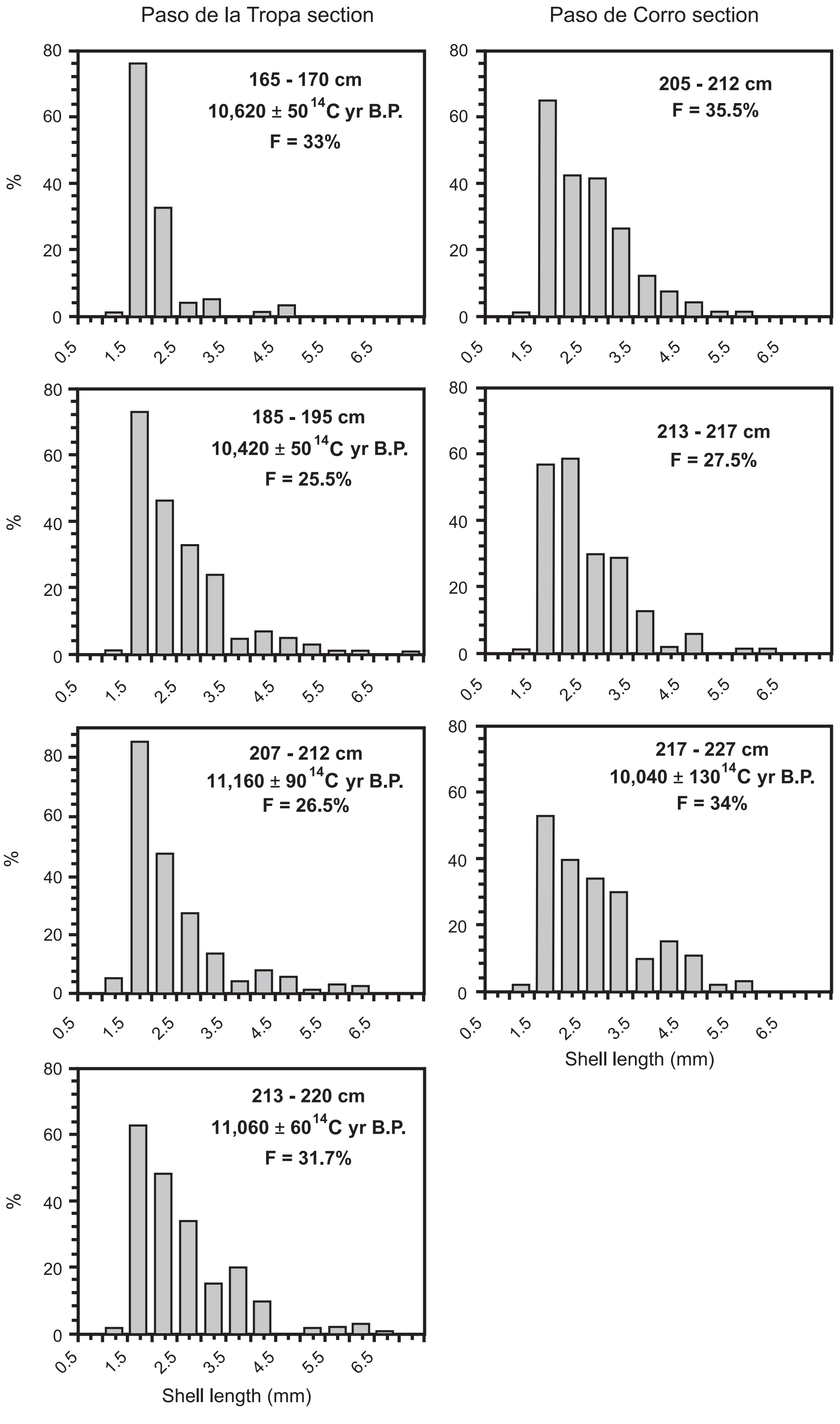

Fig. 7. Size–frequency distribution of *Heleobia parchappii* and radiocarbon data. The Kolmogorov–Smirnov two-sample test (Zar, 1984) indicated statistical differences only in the curve of level 170 cm at the Puente de la Tropa section ($d_{\max} = 0.36$; $P < 0.001$). None of the other distribution showed a significant difference ($d_{\max} = 0.005–0.075$; $P > 0.10$). F = fragmentation.

effect for modern gastropod shells (*Chilina* sp.) in the central Pampa of ca. 1100 yr was estimated (Figini et al., 1995). But because this genus was not used in this study, the carbonate ages obtained have not been corrected for reservoir effect.

Paleosol age reversals (Table 3) might be due to translocation of younger organic materials into lower strata, because of bioturbation processes after soil formation. Because ^{14}C ages of soil organic matter are generally younger than the true age of soil formation (Wang et al., 1996), we can infer that soil development began before the age indicated by ^{14}C analyses.

No numerical ages have been obtained from the reworked eolian and alluvial sediments above the Puesto Berrondo soil; its deposition is bracketed between before A.D. 1790 and recent times, based on the pollen record (Table 2).

The available radiocarbon dates place the temporal range for the "Platense fluvio-lacustre" unit at 11,200–2900 ^{14}C yr B.P. in the Luján River valley, but the uncertainties related to residence time for soil organic matter and possible reservoir effects for shells may affect the chronology.

Discussion

Local environmental history during the Holocene and vegetation change related to the impact of European settlement

The deposition of the sequences was initiated during the late Pleistocene with a fluvial reactivation that caused the erosion of the early–middle Pleistocene substratum and the accumulation of the "Lujanense" as channel and floodplain facies of the paleo-Luján River (Dangavs and Blasi, 1995). Toward the end of the late Pleistocene, the Puesto Callejón Viejo soil developed in the upper part of the "Lujanense" during a period of reduced sedimentation rate and ephemeral flows (Zárate et al., 2000). The precise timing of the period during which the Puesto Callejón Viejo soil formed is not known. Around 11,200 ^{14}C yr B.P., "Platense fluvio-lacustre" deposits began to bury the Puesto Callejón Viejo soil along the axis of drainages. The alloctonous silicoclastic components of the "Platense fluvio-lacustre" were deposited from uniform quite-water suspension while the non-terrigenous carbonate mud was coevally precipitated from stagnant freshwater bodies. Both sedimentary and biogenic components suggest that the depositional environment was eutrophic shallow water bodies without significant water circulation.

The rhythmic succession of silicoclastic muds and bioclastic silty sand show a gradual vertical passage and suggests systematic variations in the water bodies regime, water depth, and consequent migration of the water bodies level related to changes in environmental conditions. These fluctuations are also reflected in biological indicators such as the density and abundance of molluscs, and with the size–frequency distribution and fragmentation of *H. parchappii*, and provide a basis for reconstructing physical and hydrological changes, including changes in water depth of the water bodies.

The modern pattern of the Salado River and the Samborombón River basins (Fig. 1) could be use as an analogue of the "Platense" deposition. Both fluvial systems shows an incised and confined channel cut through highs on the early–middle Pleistocene paleosurface without development of flood plain and alternating reaches, where the channel flows through paleosurface depressions and is confined by levees that flank and separate from a wide flood plain (L. Pierrard, personal communication, 2003). During seasonal floods, water overtops the levees onto the low flood plain. The floodbasins beyond the levees on both sides of the river harbor wetlands, small shallow lakes, large interconnected shallow lakes, and permanent or seasonal swamp. These areas remain flooded for long time during wet periods and dry up during dry periods.

From 11,200 to ca. 3000 ^{14}C yr B.P., four changes related to the evolution of lentic water bodies occurred. Between 11,200 and ca. 10,500 ^{14}C yr B.P., shallow swamps or large wetlands formed along the floodplains as the groundwater level rose along the Luján River. This is suggested by the great diversity of gastropods similar to that found in present shallow lakes and wetlands of the Pampas (*P. canaliculata*, *B. tenagophila*, and *L. viatrix*) and by the abrupt increase of the opportunistic species *H. parchappii* giving rise to extensive auchthoctonous concentrations. All of these taxa indicate development of shallow and clear freshwater water bodies (2–3-m deep) with aquatic submerged vegetation. This agrees with the absence of *S. meridionalis*, which is probably related to an increase in the size of the water body, forcing the snails to move to the new littoral zone.

Between 10,500 and ca. 9000 ^{14}C yr B.P., a decrease of water levels alternating with periodic flooding events is suggested by alternating densities of *H. parchappii* and Systrophiidae. A drop in water level is indicated by the abrupt decrease in the density of *H. parchappii* and the relative increase of the terrestrial Sytrophiidae. However, the water levels were still relatively high as indicated by the abundance of *B. tenagophila*, *L. viatrix*, and *P. canaliculata* (Figs. 4 and 5). The replacement of sandy muds by sandy silts suggests conditions of more hydrodynamic energy due to greater turbulence of littoral currents. This shift to a littoral marginal facies may have occurred because of climatic or geomorphologic change in the basin with the swamp reduction.

Between 11,200 and ca. 9000 ^{14}C yr B.P., the dominant diatoms, *Hyalodiscus subtilis* and *Synedra platensis* (Table 4), suggest the development of a freshwater alkaline water body with clear and shallow, oligo-mesohalobious water, and slightly brackish environments (Frenguelli, 1945b).

Table 4
Diatom data from Puente de la Tropa section updated in terms of nomenclature, habitat, salinity, and pH from Frenguelli (1945b)

Species	225–170 cm	170–110 cm	Habitat	Salinity	pH
Achnantes brevipes var. *intermedia* (Kutz) Cleve	r	–	E	M	A
Amphora ovalis Kutz.	e	–	B	OI	A
Anomoeoneis sphaerophora fa. sculpta (Ehr.) Krammer	–	r	B	M	A
Caloneis bacillum (Grunow) Cleve	r	e	Aer.	OI	A
Campylodiscus clypeus Ehr.	r	–	B	M	–
Cyclotella meneghiniana Kutz.	r	–	P	OH	A
Denticula valida Grunow	o	a	B	OH	–
Diploneis argentina Frenguelli	o	r	B	M	–
D. ovalis (Hilse) Cleve	e	–	Aer.	OI	A
Fragilaria fonticola Hust.	r	r	?	OI	–
Gomphonema longiceps Ehr.	r	–	E	H	I
Hantzchia amphioxys (Ehr.) Grunow	e	r	Aer.	OI	I
Hantzchia amphioxys var. *xerophila*	–	r	Aer.	OI	I
Hyalodiscus subtilis Bailey	d	r	B	M	–
Melosira italica (Ehr.) Kutz.	r	r	P	H	I
Navicula cuspidata var. *lanceolata* Grunow	r	–	Aer.	OI	A
N. megacuspidata var. *pampeana* (Freng.) Luch. Ver.	r	–	?	OH	–
N. mutica var. *cohni* (Hilse) Grun.	–	e	Aer.	OH	I
N. peregrina (Ehr.) Kutz.	r	–	B	M	–
Nitzchia brebissonii W. Smith	r	c	B?	OH	–
N. stagnorum Rabh.	–	r	B?	OI	–
N. vitrea Norman	r	r	B	M	–
Pinnularia borealis Ehr.	–	e	Aer.	OI	I
Rhopalodia gibberula var. *argentina* (Brun.) Freng.	o	r	E	OH	I
R. gibba (Kütz.) Müller	r	e	E	OH	Al
R. gibberula (Ehr.) Müller	r	o	E	OH	I
R. gibberula var. *protracta* Grunow	–	e	E	OH	I
R. musculus (Kütz.) Müller	o	–	E	M	I
Surirella euglypta Ehr.	–	r	?	OI	–
S. rorata Frenguelli	e	–	P	M	–
S. striatula Turpin	r	–	B	M	–
Synedra platensis Freng.	c	e	E	OH	–
S. ulna (Nitzch) Ehr.	r	e	P	OI	I
Terpsinoe musica Ehr.[a]	r	o	E	OH	–

d: dominant; a: abundant; c: common; o: occasional; r: rare; e: very rare; –: barren.
E: epiphytic; B: benthic; P: planktonic; Aer: aerophilous.
M: mesohalobous; OH: oligohalobous halophilous; OI: oligohalobous indifferent.
H: halophobous; A: alkaliphilous; Al: alkalibiontic; I: indifferent.
[a] Not mentioned in Frenguelli (1945b).

A further reduction in the water level occurred between ca. 9000 and 7000 ^{14}C yr B.P., as indicated by the absence of *P. canaliculata* and *L. viatrix*. Lower water levels might have resulted in a reduction in oxygen content, preventing the development of *H. parchappii*. The low number of *H. parchappii* with size range distribution significantly smaller than those of previous levels suggests a reworked assemblage. An increase in water temperature is suggested by the disappearance of *P. canaliculata*, the higher frequency of *Terpsinoe musica* (Table 4), and the presence of macrosilicophytoliths of megathermic Poaceae (Burkart, 1969). The development of an oligohalobious swamp with stagnant and turbid water is also suggested by the dominance of diatoms such as *Denticula valida* and *Nitzchia brebissoni* (Frenguelli, 1945b) (Table 4). A similar trend is indicated by sedimentological changes, which show the development of a calcareous mud in an alkaline, brackish, and probably anoxic swamp environment. Extra-basin sediment input was minimal as indicated by the low proportion of sand and ash in the deposits. This suggests that the basin's land surface was well protected by vegetation cover, fostering low suspended load in runoff and an absence of eolian input.

Between ca. 7000 and 3000 ^{14}C yr B.P., a calcareous swamp developed. Marl deposition during this time may have the resulted from high evaporation rates or CO$_2$ loss owing to high surface water temperature in a shallow, eutrophic, and hard water environment (Bogs, 1992). The disappearance of *H. parchappii* about 3600–2900 ^{14}C yr B.P. and the development of the Puesto Berrondo soil suggest that at that time, water flow became ephemeral with seasonal pools leading to a desiccation of the swamp under subhumid dry conditions. This is also suggested by the development of an herbaceous steppe of Poaceae and Asteraceae and the presence of *Azolla*, a floating water fern, which develops in ponds and backwaters, and grows on wet substrates that border slow-moving watercourses. The low values of δ^{13}C in two soil samples (Table 3) suggest a vegetation of predominantly C$_3$ plants. In the southern, central, and northern Pampas region, relative land surface stability is indicated by development of the Puesto Berrondo soil that began between 5000 and 4000 ^{14}C yr B.P. (Zárate et al., 2000).

Probably, the Puesto Berrondo soil persisted into the late Holocene when deposition of eolian–alluvian sediments began and buried the soil. These deposits are laminated in some levels, because of local water reworking, suggesting alternating desiccation and flooding events. Plant communities are represented by a herbaceous steppe. According to Dangavs and Blasi (1995), a climate change during the final late Holocene probably triggered the reactivation of the drainage network, valley incision, and bigger contribution of eolian input.

Pollen spectra from the upper 60 cm of the section show that partial replacement of herbaceous steppe by disturbance species began (Fig. 6) because of European settlement at ca. A.D. 1790 (Garavaglia, 1999). This is recorded by the decline of grass and the rise of Asteraceae subf. Cichorioideae and the presence of *Dipsacus* and *Carduus*-type. Cichorioideae pollen is regarded as an indicator of soils that have been tilled over several years. *Dipsacus* is a disturbance species that was introduced by Spanish conquerors in the late 16th century and was used to comb wool. Thistle (*Carduus*-type) became abundant throughout the Pampas following the introduction of exotic livestock, which facilitated its dispersal. There is historical evidence of the abundance of thistles on the NE Pampas after A.D. 1790 (Rapoport, 1996). *Gleditsia triacanthos*, an exotic tree species invader, appears after A.D. 1810. This plant was used among others as natural fences since the early 19th century. Subsequently, *G. triacanthos* naturalized and expanded aggressively.

Soil development and stabilization is indicated by the decline of *Ambrosia*-type and Asteraceae subf. Cichorioideae pollen and the increase in grass pollen and pollen concentration. The peak of *Carduus*-type reflects changes of land use at ca. A.D. 1880, probably related to the establishment and expansion of exotic arboreal vegetation. The increase in *Eucalyptus* pollen suggests a date after ca. A.D.1880, perhaps related to the plantation of 1300 *Eucalyptus* in Luján City between A.D.1880 and 1882. Moreover, between A.D. 1854 and 1910, many gardens and public squares were forested and numerous fruit trees were cultivated in the surroundings of Luján City. *Pinus*, Cupressaceae, *Casuarina*, *Juglans*, and *Betula* represent these activities in the pollen assemblages. In the last decades of the 20th-century agriculture, livestock and industry have further modified the Pampa grasslands. *Ambrosia* and *G. triacanthos* pollen dominate in the modern sample, reflecting widespread disturbance and a situation totally different from the pre Hispanic grassland.

Regional environmental history during the Holocene

The environmental history of the Luján River provides a record of the functional state of the aquatic system in the northeastern Pampas during the last 11,000 ^{14}C yr. This system underwent physical–chemical changes during its evolutionary development, driven mainly by climatic changes that produced changes in limnetic plant and animal metabolism. The initial bioclastic-dominated sedimentation diminished progressively until it was replaced by chemical-dominated sedimentation toward the end of the “Platense” deposition. Assuming that no catastrophic events occurred and that the sedimentary records are continuous, primarily bioclastic sediment (gastropods) accumulation at a rate of 6 cm/100 yr occurred between 11,200 and 9000 ^{14}C yr B.P. From 9000 to 3000 ^{14}C yr B.P., the sedimentation rate decreased to 1.1 cm/100 yr, when chemical sedimentation dominated over clastic input and the water bodies became shallower and calcareous. The low detrital input reflects a well-developed vegetation cover in the basin and landscape stability throughout the catchment area. A final episode of clastic deposition produced by delivery of sand and silt to drainageways by floods and eolian processes was a response to agricultural disturbance in the catchment during the last ca. 500 yr.

During the early part of the Holocene, humid conditions prevailed in the Pampas. These conditions began sometime between 10,000 and 11,000 ^{14}C yr B.P. as indicated by a marked decrease of the eolian input and development of the Puesto Callejón Viejo soil (Muhs and Zárate, 2001). From 11,200 ^{14}C yr B.P. to ca. 9000 ^{14}C yr B.P., bioclastic sedimentation was dominant as shallow in-stream ponds or wetlands reached maximum development. This suggests a more humid climate and an increase in precipitation. Short-term fluctuations in climate during the last stage of this interval may have been sufficient to initiate changes in the water bodies, as reduction of the volume alternated with periods of flooding. In the central and south–southwest part of the Pampa grasslands, pollen records indicate that this interval was marked by the replacement of dry steppe by humid grasslands and the rapid evolution of pond environments, suggesting a shift toward subhumid–humid climatic conditions (Prieto, 2000). This change is also indicated by a gradual increase in bioclastic sedimentation (diatoms, gastropods) in alluvial sequences of the southern Pampas (Zárate et al., 2000). In the central Pampas, pollen records represent a hydrosere succession that suggests the transformation of ponds into swamps at ca. 8000 ^{14}C yr B.P. and the establishment of humid grasslands (Prieto, 1996) while isotopic data indicate that around 9000 ^{14}C yr B.P. climatic and meteorological conditions comparable with those of present times became established (Bonnadonna et al., 1999). Similar climatic conditions between ca. 8500 and 3500 ^{14}C yr B.P. have been inferred by Iriondo (1999) from geomorphological and sedimentological records in the northwestern and northern Pampa region.

The appearance of shallow in-stream ponds or wetlands was contemporaneous with a sea level lower than present. According to Argentine Shelf data, sea level was −95 m at ca.

Table 5
Relation between proxy data and environmental changes

^{14}C yr B.P.	Sedimentary environments Main processes	Molluscs	Diatoms	Pollen
	Modern soil	No data	No data	Widespread disturbance of the vegetation
A.D.1700	Reworked eolian and alluvial sediments			Herbaceous steppe Ponds and backwaters
3000	Soil development Anoxic calcareous swamp Dominant abiotic carbonate precipitates Minor detrital siliciclastic grain accumulations	Water flow ephemeral with seasonal pools		No data
7000	Alkaline, anoxic swamp/ Extra basin sediment input minimal. Abiotic carbonate precipitates Low silty and clay terrigenous detrital siliciclastic sedimentation/ Low carbonate shells and biogenic silica accumulation/	Reduction in water levels and oxygen content. Increase in water temperature and turbulence. Shell fragmentation	Oligohalobous swamp, stagnant and turbid water/ Increase in temperature/	
9000	Shallow water bodies. Greater turbulence of littoral currents Littoral marginal facies/ Sandy terrigenous detrital siliciclastic sedimentation Carbonate shells and biogenic silica accumulation/	Decrease of water levels and periodic flooding. Water levels still high. Auchthoctonous shell concentrations.	Freshwater alkaline water body Clear and shallow oligo mesohalobious water/ Slightly brackish environments/	
10,500	Maximum development of eutrophic shallow swamps in floodplains or wetlands/ Dominance of carbonate shells and biogenic silica accumulations. Silty and clay terrigenous siliciclastic sedimentation/	Shallow and clear water bodies (2 – 3-m deep). Auchthoctonous shell concentrations/		
11,200	Soil development	Scarce gastropods		

11,000 ^{14}C yr B.P. and rose to −27 m at 8800 ^{14}C yr B.P. (Guilderson et al., 2000). Consequently, the paleovalley of the de la Plata River was very restricted laterally (Cavallotto et al., 1999) and the Luján River outlet was in a different position. Under such an eustatic regime, the accommodation rate in the sedimentary basin was high but the sedimentation rate was low due to low sediment yield in the vegetated basin. During this period of low erosion rate, soil development (Puesto Callejon Viejo soil) was widespread in valleys and interfluvial areas.

In the Luján River area, a trend toward a reduction of water bodies is recorded from 9000 to ca. 3000 ^{14}C yr B.P., with a significant reduction after ca. 7000 ^{14}C yr B.P. as suggested by marl formation and disappearance of shallow lake gastropod species. This suggests development of a subhumid−dry climate after ca. 7000 ^{14}C yr B.P. in which evapotranspiration exceeded precipitation.

During the middle Holocene, an additional external forcing on the lower reaches of the Luján River was caused by marine transgression, with sea level reaching present sea level around 7000 ^{14}C yr B.P., and a maximum height of +6.5 m at 6000 ^{14}C yr B.P. in the northeastern and eastern Pampas (Cavallotto et al., 1999) (Fig. 1). As a consequence of the rise of the sea level, the alluvial valley of the de La Plata River was flooded and enlargement of its estuary occurred. A 10-km-wide by 20-km-long estuary developed in the lower reach of the Luján River during this time (Iriondo, 1993). During this marine transgression, the “Platense estuarine” deposits accumulated. Between 6000 and 5000 yr B.P., the sea level fell from +6.5 to +5 m and remained stable until 3500 ^{14}C yr B.P. (Cavallotto et al., 1999). This sea level fall favored delta progadation of the Paraná River, a change from estuarine to fluvial environmental in the de la Plata River (Cavallotto et al., 1999), and the progressive shifting of the Luján River channel toward its present position.

The climate became drier in the late Holocene, when clastic sedimentation resulting from eolian input increased. The presence of reworked material suggests that common short-term climatic shifts were frequent during this time. Although the regional climatic record of the late Holocene is not well known, the pollen records suggest subhumid–dry climatic conditions (Prieto, 1996) with several episodes related to increases in precipitation (Stutz et al., 2002) and faunal assemblages that indicate arid to semiarid conditions (Tonni et al., 1999). From ca. A.D. 1790 to present, the pollen record of the Luján River area documents vegetation changes resulting from the introduction of exotic herbivores and exotic plants during European settlement, and a widespread disturbance occurring during the 20th century.

Conclusion

The interpretation of alluvial stratigraphy and sediment bodies is a problematic area of late Quaternary environmental reconstruction due to many factors that influenced stream behavior and alluvial stratigraphic sequences. For instance, base level was generally varying at the same time as the climate; vegetation and hydrology were also undergoing change. In spite of these potential complexities, the Luján River record indicates that approximately synchronous changes in sediment, molluscs, diatoms, and alluvial processes during the Holocene are in good agreement (Table 5) and suggest that climate was the major forcing mechanism of regional fluvial system behavior. Keeping in mind that the radiocarbon dates have not been corrected for a possible reservoir effect and that the age represented by organic matter dated on paleosols is a minimum age than the true age of soil formation, the correlation between the paleoenvironmental changes inferred from different proxy records of the Pampa region and from those of the Luján River area indicate similarity in the timing and magnitude of Holocene climatic and landscape evolution from northeast to southwest across the Pampas.

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