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Quaternary International 181 (2008) 123–138

Landscape evolution and climate changes in the Late Pleistocene–Holocene, southern Pampa (Argentina): Evidence from palynology, mammals and sedimentology

Mirta E. Quattrocchio[a,b,*], Ana M. Borromei[a,b], Cecilia M. Deschamps[c], Silvia C. Grill[a], Carlos A. Zavala[a,b]

[a]Departamento de Geología, Universidad Nacional del Sur, San Juan 670, 8000 Bahía Blanca, Argentina
[b]CONICET, Argentina
[c]CIC, Museo de La Plata, Paseo del Bosque s/n, 1900 La Plata, Argentina

Available online 4 March 2007

Abstract

The landscape evolution of the southwestern part of Buenos Aires Province (southern Pampa) is a good example for the understanding of continental deposits in arid–semiarid regions. In Buenos Aires Province, the last 9–3 Ma record is described as sequences composed of alternating loess and palaeosol units indicating climatic fluctuations between arid and cold (loess deposition), and warm and humid intervals (palaeosol development). The present drainage system flows across the Early Pliocene–Middle Pleistocene stratigraphic units. The stratigraphy and evolutionary history are analyzed using sequence-stratigraphic criteria; the interpretation of the climatic evolution of the area is based on pollen and mammal (mainly rodents) records. The Late Pleistocene sediments reflect arid to semiarid conditions. The Late Pleistocene/Holocene transition is characterized by development of palaeosols. The Early Holocene pollen records reflect the development of a vegetation community characteristic of coastal dunes. Sea level was still lower than today. Temperature and humidity reached its maximum during the mid-Holocene when the high diversity and abundance of marine dinocysts and acritarchs indicate a transgression. This event is associated with the gramineous steppe in the continent reflecting more temperate or local humid conditions, and with Brazilian mammal fauna. This relative rise of sea level lead to flooding the riverbeds producing deposition of gray muddy facies. Approximately at 3000 years BP the marine influence ended in the area. After 2610 years BP psammophytic herbaceous steppe development, as well as mammals, suggests arid to semiarid conditions. An interval of higher humidity is inferred at approximately 2000 years BP based on the development of gramineous steppe communities. A relative rise of temperature may be inferred by the southward expansion of the Brazilian mammal fauna.

1. Introduction

The paradigm of complexity, i.e. the systemic view of the world, is the most adequate theoretical reference to study the environment (Rojero, 2000). Accordingly, a multidisciplinary approach including different sources of evidence is the best way to study paleoenvironments. Continental deposits are often characterized by numerous unconformities and abrupt facies changes, but the land-based record offers spatial detail and sensitivity that the deep-sea record will never achieve. Paleoenvironmental studies of arid lands have to a degree been avoided due to their sparse vegetation and poor pollen production, high rates of deposition in most continental basins, predominantly clastic sediments, and abundance of carbonate and sulfate cements (Horowitz, 1992). Nevertheless, arid lands are more sensitive in registering environmental changes than temperate or tropical ones, thus enabling finer reconstruction of global trends. In this way, the southern Pampa in Argentina provides a good example about the importance of multidisciplinary studies of arid landscapes in reconstructing the evolution of past climates in the region.

*Corresponding author. Departamento de Geología, Universidad Nacional del Sur, San Juan 670, 8000 Bahía Blanca, Argentina.
E-mail address: mquattro@criba.ed.ar (M.E. Quattrocchio).

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doi:10.1016/j.quaint.2007.02.018

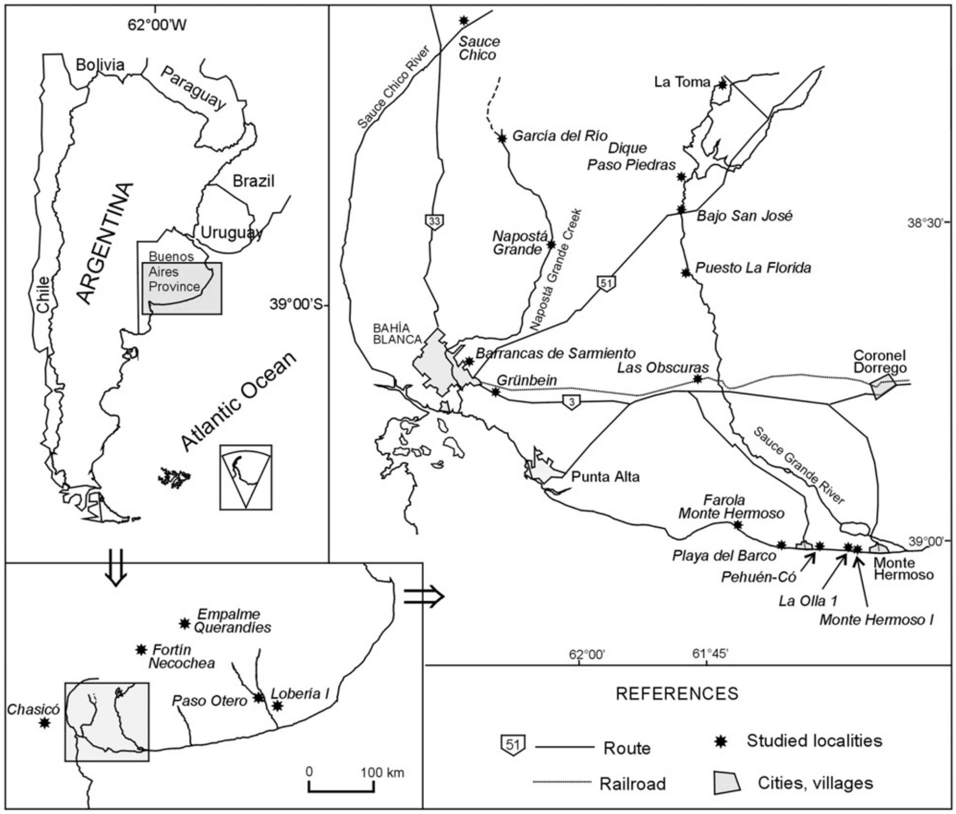

Fig. 1. Location map. Detailed area with localities mentioned in the text.

The aim of this paper is to provide a state of the art of the understanding of the Pleistocene and Holocene in the southwest Pampa (Argentina, Fig. 1), achieved from almost 20 years of mapping, stratigraphic studies and analyses of the fossil record. Paleontological studies include vertebrates, ostracods and palynomorphs. These results are presented in a chronosequence chart, which synthesizes the suggested space–time correlation of the events recognized (Fig. 2). A brief consideration of the Late Miocene–Middle Pleistocene biostratigraphy and paleoclimate is also given in order to provide the context in which Late Pleistocene–Holocene events probably took place.

2. Methodology

Detailed geological mapping of the area has revealed the existence of many localities (Fig. 1) displaying good exposures of Pleistocene and Holocene strata, allowing careful studies of pollen, ostracods and fossil vertebrates (Tables 1 and 2). Paleontological studies were supported and complemented by detailed sedimentological and facies analysis within a high-resolution sequence-stratigraphic framework, which provided information about the deposits from a genetic point of view (Zavala and Quattrocchio, 2001). This was especially significant alerting on possible paleoenvironmental control of the fossil content that must be taken into account when analyzing the presence and absence of taxa. The stratigraphic profiles of the studied localities were correlated within a chronostratigraphic chart (Fig. 2) that shows the space–time correlation of the events. This method is quite useful when stratigraphic units are not continuous, such as Quaternary fluvial ones, which were considered unconformity bounded units representing the events occurred in the basin, with temporal and genetic meaning (Deschamps, 2005). In Fig. 2, some of the studied localities, covering the whole time interval represented in the area, were ordered in a hypothetical E–W line crossing the Arroyo Napostá Grande and Río Sauce Grande basins and the highlands between them. The thick black lines indicate the levels exposed at each locality. The biostratigraphic analysis was presented in a previous paper in which the stratigraphic provenance of the remains was shown in the corresponding stratigraphic profiles; bio- and chronostratigraphic units were defined based on fossil mammals (Deschamps, 2005); ages/stages follow Cione and Tonni (2001) and Verzi et al. (2004b).

The paleoenvironmental interpretations based on fossil mammals were made according to their ecological requirements in the cases in which they have modern representatives, or on the basis of paleobiological studies in extinct lineages. In both cases, data were taken from the literature (Deschamps, 2003, and literature therein).

Fossil pollen records (Table 2) were interpreted in terms of environmental information using the modern

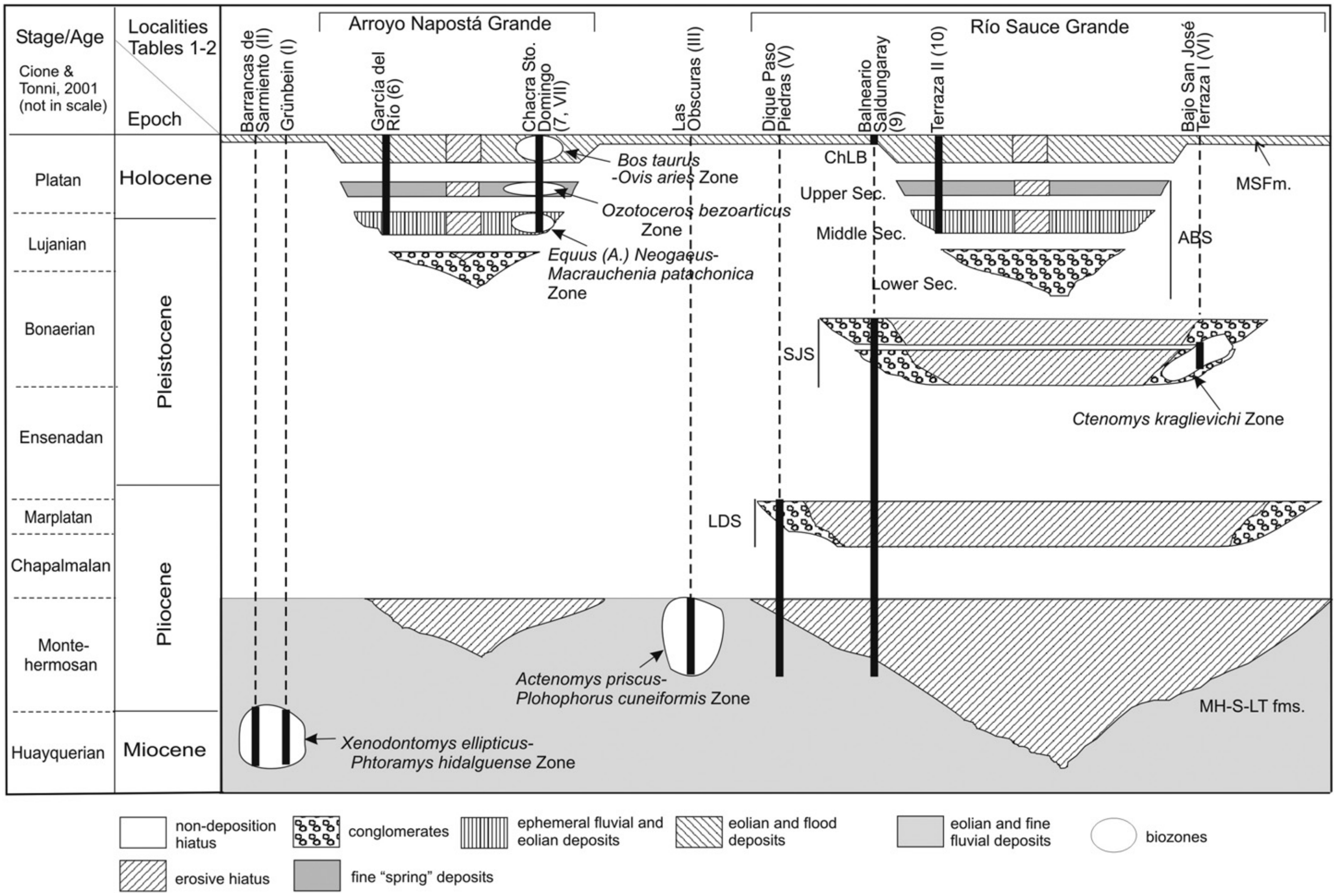

Fig. 2. Chronostratigraphic chart, showing space–time correlation of the events, and biozones based on mammals. Modified from Deschamps (2005). ABS, Agua Blanca Sequence; ChLB Fm., Chacra La Blanqueada Formation; LDS, La Delta Sequence; MH–S–LT fms., Monte Hermoso–Saldungaray–La Toma formations; MSFm, Matadero Saldungaray Formation; SJS, San José Sequence.

pollen–vegetation–climate relationship as analogue. Modern pollen rain samples (Prieto, 1996) and pollen traps (Borromei and Quattrocchio, 1990) were used in the interpretation of fossil sequences. Palynological analysis involved the recognition of plant communities, their fluctuations through time and the specification of pollen assemblage zones. The concept of ''palynofacies'' (Combaz, 1964) was used, integrated to that of sedimentary facies, to determine the environment of deposition. Relative sea level changes were evaluated taking into account the microplankton preserved in marine deposits, as well as changes of coastal vegetal communities.

The radiocarbon dates have not been corrected for a possible reservoir effect and as mentioned by Prieto et al. (2004), the age represented by organic matter dated on palaeosols is a minimum age rather than the true age of soil formation.

3. Present climate, vegetation and fauna

Pampa grasslands include humid temperate prairies (humid Pampa) and dry steppes of moderate continental climate (dry Pampa) (Prieto, 2000). The southwestern part of Buenos Aires Province (dry Pampa) is crossed year-round by SW–NE moving air masses (Burgos, 1968). This region is influenced predominantly by Atlantic and South Pacific anticyclones. In winter, the sub-Antarctic low pressure advances equatorwards and the southern westerlies reach this region with cold and dry air. The southwestern Pampa is delimited by the isohyets of 700–800 mm in the east and 500–600 mm in the west. The average temperatures are between 21 °C in summer (January) and 7 °C in winter (July) (Burgos, 1968). The area is classified as subhumid-dry (C_1) with incipient water deficit, according to the Thornwhaite climatic classification (Burgos and Vidal, 1951). The area is located in the Pampeana Province, Austral District according to the phytogeographical regions of Cabrera (1976). Verettoni and Aramayo (1976) recognized several plant communities in the studied area. Gramineous steppe occurs on the plains. Grasses include the dominant *Stipa papposa* and *Bromus brevi*, which associate with herbs and shrubs including *Cynodon hirsutus*, *Baccharis ulicina*, *Parthenium hysterophorus*, *Verbesina enceliodes* and *Solanum eleagnifolium*.

Psammophytic steppe occupies the coastal areas, continental dunes and areas with sandy soils. This community

Table 1
Late Cenozoic localities of fossil vertebrate fauna from southwestern Buenos Aires Province, Argentina

Site	Site name	Latitude (S)	Longitude (W)	Age (radiocarbon dates when available)	Sequence type	References
I	Grünbein	38.44	62.12	Late Miocene (Huayquerian Age)	Aeolian sequence	Deschamps et al. (1998) and Deschamps (2005)
II	Barrancas de Sarmiento	38.42	62.15	Late Miocene (Huayquerian Age)	Aeolian sequence	Verzi and Deschamps (1996) and Deschamps (2005)
III	Las Obscuras	38.43	61.45	Early Pliocene (Montehermosan Age)	Aeolian sequence	Deschamps (2005)
IV	Farola Monte Hermoso	38.55	61.45	Early Pliocene (Montehermosan Age)	Fluvial sequence	Zavala (1993) and Deschamps (2005)
V	Dique Paso Piedras	38.25	61.46	Late Pliocene	Fluvial sequence	Deschamps (2005)
VI	Bajo San José (Río Sauce Grande, Terraza I)	38.29	61.47	Middle Pleistocene (ca. 0.4 Ma) (Bonaerian Age)	Fluvial sequence	Deschamps and Borromei (1992); Verzi et al. (2004a) and Deschamps (2005)
VII	Playa del Barco	38.56	61.40	12,000 ± 100 (Lujanian Age)	Paleoichnological	Aramayo and Manera de Bianco (1996) and Quattrocchio and Borromei (1998)
VIII	Arroyo Napostá Grande (Chacra Santo Domingo)	38.32	62.03	Late Pleistocene–Holocene (Lujanian–Platan Ages)	Alluvial sequence	Grill (1997) and Quattrocchio et al. (1998)
IX	Paso Otero	38.34	58.42	Late Pleistocene (Lujanian Age)	Zoo-archaeological	Prado et al. (1987)
X	Fortín Necochea	37.23	61.08	6.010 ± 400	Zoo-archaeological	Crivelli-Montero et al. (1987) and Tonni (1990)
XI	La Toma	38.17	61.45	995 ± 64	Zoo-archaeological	Rabassa et al. (1989)
XII	Lobería I	37.40	58.45	440 ± 60	Zoo-archaeological	Tonni (1985)

is represented by *Poa lanuginosa*, *Digitaria californica*, *Hyalis argentea* and *Alyssum alyssoides* (Verettoni, 1965).

Halophytic steppe is present in coastal areas and saline soils. It is characterized by *Atriplex undulata*, *Salicornia ambigua* and *Suaeda patagonica* (Verettoni, 1961).

Shrubby woodland generally occurs on soils with calcareous crusts and consists of shrub and thorn scrub communities with scarce trees. Characteristic taxa include *Geoffroea decorticans*, *Prosopidastrum globosum*, *Discaria longispina*, *Condalia microphylla* and *Ephedra triandra*.

To the west, the dry Pampa borders the xerophytic woodland vegetation, the "Espinal", forming a broad ecotone (Cabrera, 1976). The "Espinal" is characterized by the dominant trees *Prosopis flexuosa* and *P. caldenia*, which are accompanied mainly by thorn shrub communities of the shrubby woodland. This vegetation coexists with a psammophytic steppe and shrub halophytic steppe taxa near the Atlantic coast. The annual precipitation is <500 mm with water deficit >300 mm with annual temperature between 20 and 7 °C. The xerophytic woodland–grassland ecotone can be classified as semiarid (D) according to the Thornwhaite climatic classification (Burgos and Vidal, 1951).

Zoogeographically, the studied area is included within the Central or Subandino Dominion of the Andino-Patagónica Region, according to Ringuelet (1961). This dominion is interposed between the Pampásico and Patagónico dominions and its fauna has influence of both. Characteristic of the Pampásico Dominion are the marsupials *Monodelphis*, *Lutreolina* and *Didelphis*, the dasypodid *Cahetophractus*, the caviomorph rodents *Lagostomus*, *Cavia* and *Myocastor*, the sigmodontine rodents *Reithrodon*, *Akodon*, *Oxymycterus* and *Calomys*, and the canid *Pseudalopex* among others. The influence of the Patagonian Dominion is seen in the presence of the rodent *Microcavia*, the dasypodid *Zaedyus*, the mustelid *Lyncodon*, among others.

4. Geological setting

The withdrawal of a wide transgression called "Mar Paranense" that covered from Patagonia to the Amazonian Basin (Ramos, 1999), toward 10.8 Ma (Pascual, 1984), left extensive plains in which a new sedimentary and biotic cycle began. The expansion during the Late Miocene of the Antarctic continental ice sheet farther than the modern limits, caused a global cooling event which triggered the

Table 2
Late Cenozoic pollen records from southwestern Buenos Aires Province, Argentina

Site	Site name	Latitude (S)	Longitude (W)	Radiocarbon dates	Sequence type	References
1	Arroyo Tapalqué (Empalme Querandíes)	37.00	60.07	1950±100		Prieto (1996)
				7560±160	Alluvial sequence	
				9070±140		
				9100±150		
				9330±190		
				9490±150		
				10,750±200		
2	Río Quequén Salado (Paso Otero 5)	38.12	59.06	3950±35	Archaeological	Holliday et al. (2003) and
				4210±65		Grill et al. (in press)
				6629±129		
				7794±71		
				8793±89		
				9399±116		
				9560±50		
				10,190±120		
				10,440±100		
3	Río Quequén Salado (Estancia Thomas)	38.53	60.32	7720±100	Alluvial sequence	Grill (2003)
4	Arroyo Chasicó	38.24	62.51	9930±140	Alluvial sequence	Borel et al. (2001)
5	Río Sauce Chico	38.05	62.16	4400±300	Alluvial sequence	Prieto (1996)
				6170±170		
6	Arroyo Napostá Grande (García del Río)	38.21	62.20	Late Pleistocene and Holocene (2610±60)	Alluvial sequence	Grill (1995) and Quattrocchio et al. (1998)
7	Arroyo Napostá Grande (Chacra Santo Domingo)	38.32	62.03	Late Pleistocene and Holocene (1960±100)	Alluvial sequence	Grill (1997) and Quattrocchio et al. (1998)
8	Arroyo Napostá Grande (Grünbein)	38.46	62.15	3560±100	Alluvial sequence	Grill and Quattrocchio (1996) and
				3850±100		Quattrocchio et al. (1998)
				5580±100		
9	Río Sauce Grande (Balneario Saldungaray)	38.10	61.45	2820±50	Alluvial sequence	Borromei (1998)
				7100±80		
10	Río Sauce Grande (Terraza II)	38.29	61.47	Late Pleistocene and Holocene (2830±90 5010±120)	Alluvial sequence	Borromei (1995) and Quattrocchio and Borromei (1998)
11	Monte Hermoso 1	38.57	61.22	7030±100	Archaeological	Quattrocchio et al. (1998)
				7125±75		
12	La Olla 1	38.60	61.21	7580±60	Archaeological	Fontana (2004)
				7920±90		

loess sedimentation cycle. This sedimentation, including both loess (sediments with a high content of volcanic-derived particles) and loessoid sediments (reworked loess) (Zárate, 2003), was related to a phase of Late Miocene (ca 10 Ma) orogeny in the Andes, which acted as a barrier to moisture-laden Pacific winds. This initiated "the desertification of Patagonia caused by the rain shadow while precocious Pampa environment probably came into prominence at about this time" (Patterson and Pascual, 1972 in Marshall et al., 1983, p. 68).

In the southern Pampa (Argentina), at least the last 9–3 Ma record is described as sequences composed of alternating loess and palaeosol units. These sequences indicate climatic fluctuations, alternating between arid and cold (loess deposition) and warm and humid (palaeosol development) intervals. The largest loess deposits in South America extend from 23°S to 41°S in the southern plains of the continent (Teruggi, 1957; Bargo and Deschamps, 1996). Sea level changes produced different geomorphic features including erosion, differences in the equilibrium river profiles, regressive and transgressive events and built of shell terraces during the regressive phases.

The present drainage system flows across Tertiary loessoid stratigraphic units known as the Saldungaray and La Toma (Furque, 1967), and Monte Hermoso (Zavala, 1993) formations. The Sauce Grande is the main river in the southwest Pampa (Fig. 1). Remains of three levels of ancient terraces document different episodes of incision and valley fill. These deposits were assigned to La Delta, San José and Agua Blanca sequences (dated as Late Pliocene, Middle Pleistocene and Late Pleistocene–Holocene respectively; Zavala and Quattrocchio, 2001; Deschamps, 2005). The alluvial deposits are known as the Chacra La Blanqueada Formation (Holocene; Rabassa, 1989) (Fig. 2).

The complex terraces in the Río Sauce Grande were interpreted within a model of the evolution of valleys in arid–semiarid regions (Zavala and Quattrocchio, 2001). In this model, valleys were active only sporadically and behave most of the time as geomorphologically depressed zones, hosting locally sourced gravitational and eolian deposits. Late Pleistocene–Holocene and Historical Times were locally characterized by eolian deposits known as the Saavedra and Matadero Saldungaray formations, respectively (Rabassa, 1989; De Francesco, 1992).

From both surface and geophysical data, neotectonic evidence is registered in Río Sauce Chico (Quattrocchio et al., 1994). An E–W megafracture, resolved in a surface secondary fracture system, was inferred from geophysical data. The modern activity of the system may be responsible for the Late Pleistocene strata deformation and other stratigraphical and geomorphological anomalies. The last deformation was subsequent to the deposition of sediments of Late Pleistocene age.

5. Paleoenvironmental reconstructions

5.1. Late Miocene

The oldest exposures of Cenozoic sediments in the area are those of Grünbein (Figs. 1 and 2; Table 1, site I) and Barrancas de Sarmiento (Figs. 1 and 2; Table 1, site II), near Bahía Blanca city. They are composed of loessoid sediments that were devoid of pollen, but yielded vertebrate remains. The fauna, especially the octodontoid rodents of the genera *Xenodontomys* and *Phtoramys*, suggested a Late Miocene age for these deposits, and allowed their correlation with other loessoid sediments of central Argentina (Verzi and Deschamps, 1996; Deschamps et al., 1998; Verzi et al., 2004b; Montalvo et al., 2005). The trend toward increasing hypsodonty observed in the anagenetic lineage of the genus *Xenodontomys* and in other caviomorph rodents is related to adaptations to open environments within the climatic deterioration of the Late Miocene (Verzi, 2001).

5.2. Early Pliocene

Other loessoid sediments cropping out at Las Obscuras (Fig. 1; Table 1, site III), in the middle basin of Río Sauce Grande, were also sterile in pollen, but the mammal remains, especially the octodontoid rodent *Actenomys priscus*, suggest an Early Pliocene age for these deposits, which can be correlated with the base of the Monte Hermoso Formation, of the Montehermosan Stage/Age, cropping out at Farola Monte Hermoso (Fig. 1; Table 1, site IV) on the Atlantic coast.

In the Early Pliocene, grasslands were dominant at high latitudes, developed during a global cooling event and marine transgression (Janis, 1993), probably locally responsible for the cliffs of Grünbein and Barrancas de Sarmiento (Zavala and Quattrocchio, 2001). Between 5 and 3 Ma, Lambeck et al. (2002) proposed global warm conditions in view of low values of $\delta^{18}O$ in foraminifera of marine sediments, and low range sea level oscillations. At this time, the environments could have been similar to the modern Chaqueña Phitogeographic Province with open xerophytic woodlands, but more humid, with seasonal differences in rainfall (Pascual and Ortiz Jaureguizar, 1990).

5.3. Late Pliocene–Middle Pleistocene

During this interval, the sedimentological record is poor, because this area would have been affected by erosion processes (and no deposition; see Fig. 2). Isolated deposits are found within river valleys.

Semidesertic environments that began their development during the global climatic deterioration of the Late Miocene were dominant during the Pliocene in the west of Argentina. The final rise of the Sierras Pampeanas acted as a wind shadow, increasing the desertification of the western areas (Pascual, 1984). A sharp sea level fall around 3 Ma (Haq et al., 1987) enabled the "Great American Biotic Interchange" (Stehli and Webb, 1985). In the southeastern coast of Buenos Aires Province, the caviomorph rodent fauna suggests a strong arid pulse for the end of the Late Pliocene that could be coeval with the global climatic deterioration at the Gauss–Matuyama boundary (Verzi, 2001).

In the study area, a single Late Pliocene event has been identified in the conglomerates of the La Delta Sequence within the valley of Río Sauce Grande at Dique Paso Piedras (Table 1, site V; Figs. 1 and 2). Geologic and sedimentological data suggest that this deposit could represent the second stage of initial filling within a transport zone, or zone 2 of the evolution of fluvial valleys in arid and semiarid zones. This process is related to the beginning of a transgressive cycle of an interglacial period (Zavala and Quattrocchio, 2001).

The Middle Pleistocene is recorded at Bajo San José, in the Bajo San José Sequence of the Río Sauce Grande (Figs. 1, 2 and 3A; Table 1, site VI). This unit was deposited by a braided river, typical of arid to semiarid environments. The characteristic longitudinal bars and channels fills would have provided varied niches for the rich fauna found in these deposits (Deschamps and Borromei, 1992; Deschamps, 2003, 2005). No pollen has

Fig. 3. Photographs of several localities mentioned in the text. (a) Bajo San José showing the lower and upper sections of the San José Sequence. (b) Playa del Barco. (c) Sauce Grande River showing the Pleistocene–Holocene boundary. (d) Arroyo Napostá Grande showing the Pleistocene–Holocene boundary. (e) Pehuén-Có ichnological site showing a trackway on Pleistocene sediments, assigned to *Megatherium americanum*. (f) A human footprint on Holocene sediments of the Monte Hermoso I archeological site.

been found, but mammals, especially the caviomorph rodent *Ctenomys kraglievichi*, as well as murid rodents and Tayassuidae, suggested the strongest warm pulse so far recognized for the Pleistocene of southern South America. Verzi et al. (2004a) correlated this pulse with MIS 11 because it is the longest and warmest, but not necessarily humid, interglacial documented for the past 0.5 Ma. This warm pulse is in agreement with the relative high sea level proposed for the deposition of the San José Sequence through the analysis of sequence stratigraphy (Zavala and Quattrocchio, 2001). These authors correlate the exposures of Playa del Barco (Figs. 1 and 3B; Table 1, site VII), near Pehuén-Có beach in the Atlantic coast, with this sequence.

High temperatures were also recorded globally during the Middle Pleistocene. Vrba (1985) suggested a rise of global temperature documented through the faunal record around 450–500 ka. Lambeck et al. (2002) pointed out an interglacial episode around 600 ka, although they could not determine its beginning and end or relate it to the Milankovitch cycles.

5.4. Late Pleistocene

The Late Pleistocene–Holocene sediments are mostly recorded in the modern riverbanks and highlands. They were studied in the Río Sauce Grande (Figs. 1 and 3C) and Arroyo Napostá Grande (Figs. 1 and 3D) valleys. The lithostratigraphic units of the Late Pleistocene are the Lower and Middle sections of the Agua Blanca Sequence, whose lithofacies suggest an eolian environment with ephemeral water, reflecting arid to semiarid conditions, and the eolian Saavedra Formation (Figs. 1 and 2).

The late Late Pleistocene is characterized by the predominance of Brassicaceae in most of the palynological assemblages (Table 2, sites 2, 7 and 10; Palynofacies 1 and 2, Pollen Zones NG-sd4 and SG-4, respectively; Figs. 5 and 6) (Quattrocchio et al., 1995, 1998). The development of these herbaceous taxa may imply an environmental disturbance, caused by aridity and strong aeolian activity, which may have caused also a decrease of grasslands (León and Anderson, 1973).

In studied pollen profiles from southwestern part of Buenos Aires Province (dry Pampa, Table 2, sites 3, 6 and 10) (Grill, 1993, 2003; Quattrocchio et al., 1995; Quattrocchio and Borromei, 1998), the presence of barren samples is noteworthy in the Late Pleistocene sediments suggesting extremely arid conditions. However, the Middle Section of the Agua Blanca Sequence (see Fig. 2) of some localities in the Arroyo Napostá Grande (Table 2, sites 6 and 7) (Quattrocchio et al., 1998) yielded pollen communities (Pollen Zones NG-gr4 and NG-sd4, Figs. 4 and 5)

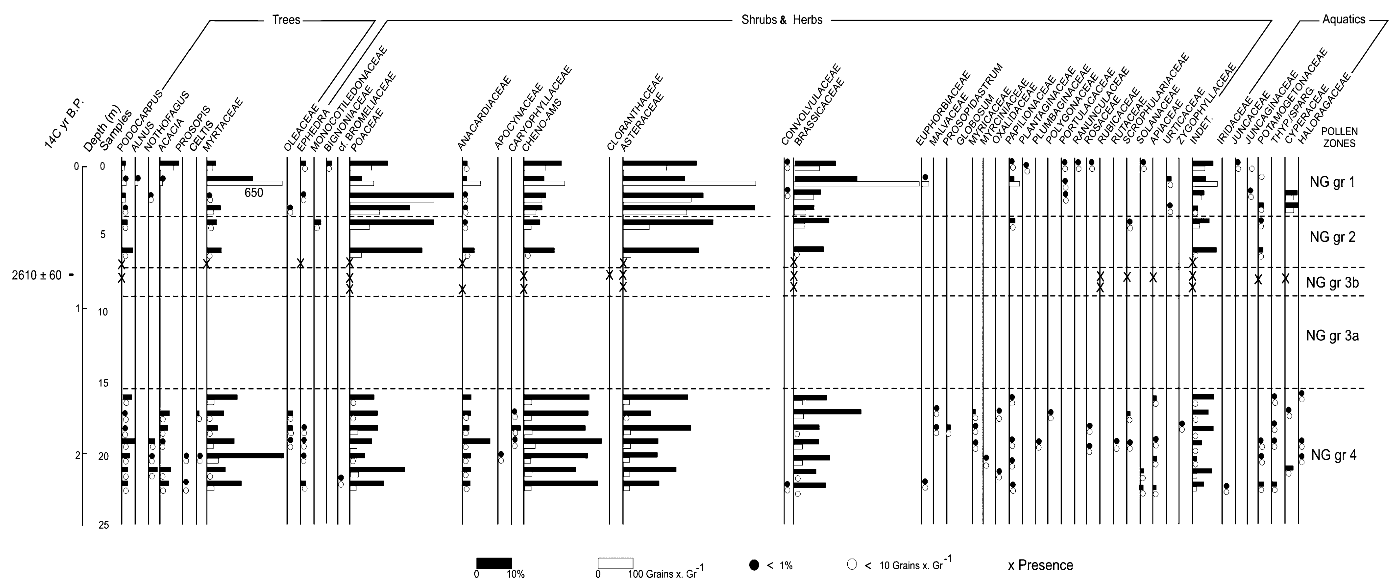

Fig. 4. Fossil pollen diagram at García del Río, Arroyo Napostá Grande. From Grill (1995).

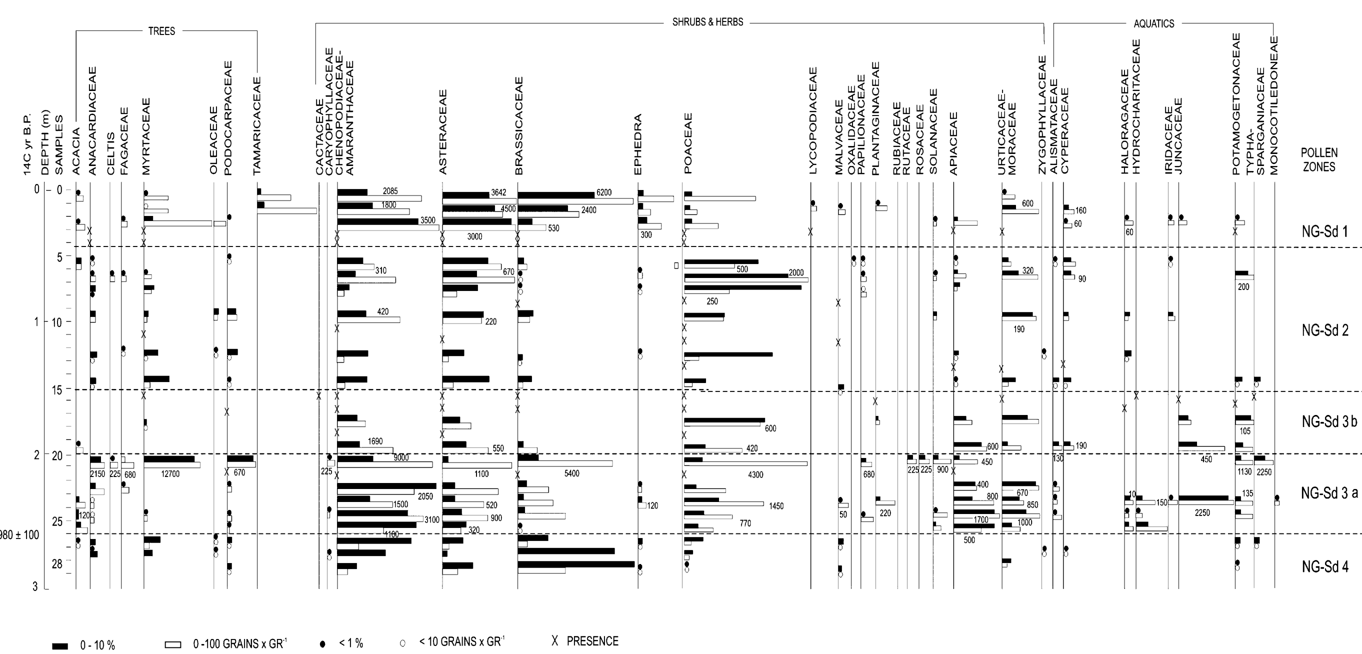

Fig. 5. Fossil pollen diagram at Chacra Santo Domingo, Arroyo Napostá Grande. From Grill (1997).

characteristic of halophytic and psammophytic steppes, with representatives of the xerophytic woodland vegetation. The pollen association characteristic of the halophytic steppe (Chenopodiaceae–Amaranthaceae and Asteraceae) and scarce aquatic pollen (Potamogetonaceae, Thyphacea–Sparganiaceae, Haloragaceae and Cyperaceae) indicates arid to semiarid paleoclimatic conditions with local humid conditions. In addition, the low pollen diversity and concentration suggest a reduced vegetation cover that reflects severe continental environment conditions (Grill, 1993; Quattrocchio et al., 1995). Pollen analysis of alluvial sediments in the middle basin of the Río Sauce Grande (Table 2, site 10; Pollen Zone SG-4, Fig. 6) (Borromei, 1995) and at Empalme Querandíes (Table 2, site 1; humid Pampa) (Prieto, 1989) showed similar results.

At the Paso Otero 5 archaeological site (Fig. 1), middle basin of the Río Quequén Grande (Table 2, site 2; Palynofacies 1 and 2: pre-10,400 years BP) (Grill et al., in press) the presence of ruderal vegetation within the palynomorph group is noteworthy: clumps of Brassicaceae and Asteraceae pollen. The main factor responsible for the destruction of pollen grains is pH (above 8.15) associated with biochemical and chemical oxidation (Grill et al., in press).

The vertebrates found in Arroyo Napostá Grande, Chacra Santo Domingo (Table 1, site VIII), in the Middle Agua Blanca Sequence (*Lama guanicoe*, *Equus* (*A.*) *neogaeus*, *Chaetophractus villosus*, *Macrauchenia patachonica*) suggest arid to semiarid open environments of grasslands (Deschamps and Tonni, 1992), in agreement with Prado et al. (1987) who studied Paso Otero site (Table 1, site IX) some 300 km eastward, and suggested mean winter temperatures below 10 °C, not biologically usable.

The ostracod association of these levels (Table 1, site VIII and Table 2, site 7) shows low specific diversity (*Sarscypridopsis aculeata* and *Darwinula* sp. n. form A, Bertels and Martínez, 1990). The record of *S. aculeata* and the carbonate on the shells suggest arid climatic conditions with sporadic precipitation, high evaporation and carbonate supersaturation. Occasional precipitation originated low energy and ephemeral shallow water bodies favorable for *Darwinula* sp. n. form A. Evaporation processes raised the salt concentration (oligo- to mixohaline) favorable for *S. aculeata*. Sterile levels suggest continuity of evaporation processes that ended in the disappearance of ostracods. Abundant shells of the gastropod *Littoridina parchapii* are associated (Quattrocchio et al., 1998; Martínez, 2002).

A remarkable sea level fall with respect to the present one was recognized at Pehuen-Có paleoichnological site in the Buenos Aires Province coast (Figs. 1 and 3E), where the floodplain sediments are in the modern marine abrasion platform. These sediments bear ichnites of extinct mammals that were dated 12,000 ± 100 years BP (Aramayo and Manera de Bianco, 1996; Quattrocchio and Borromei,

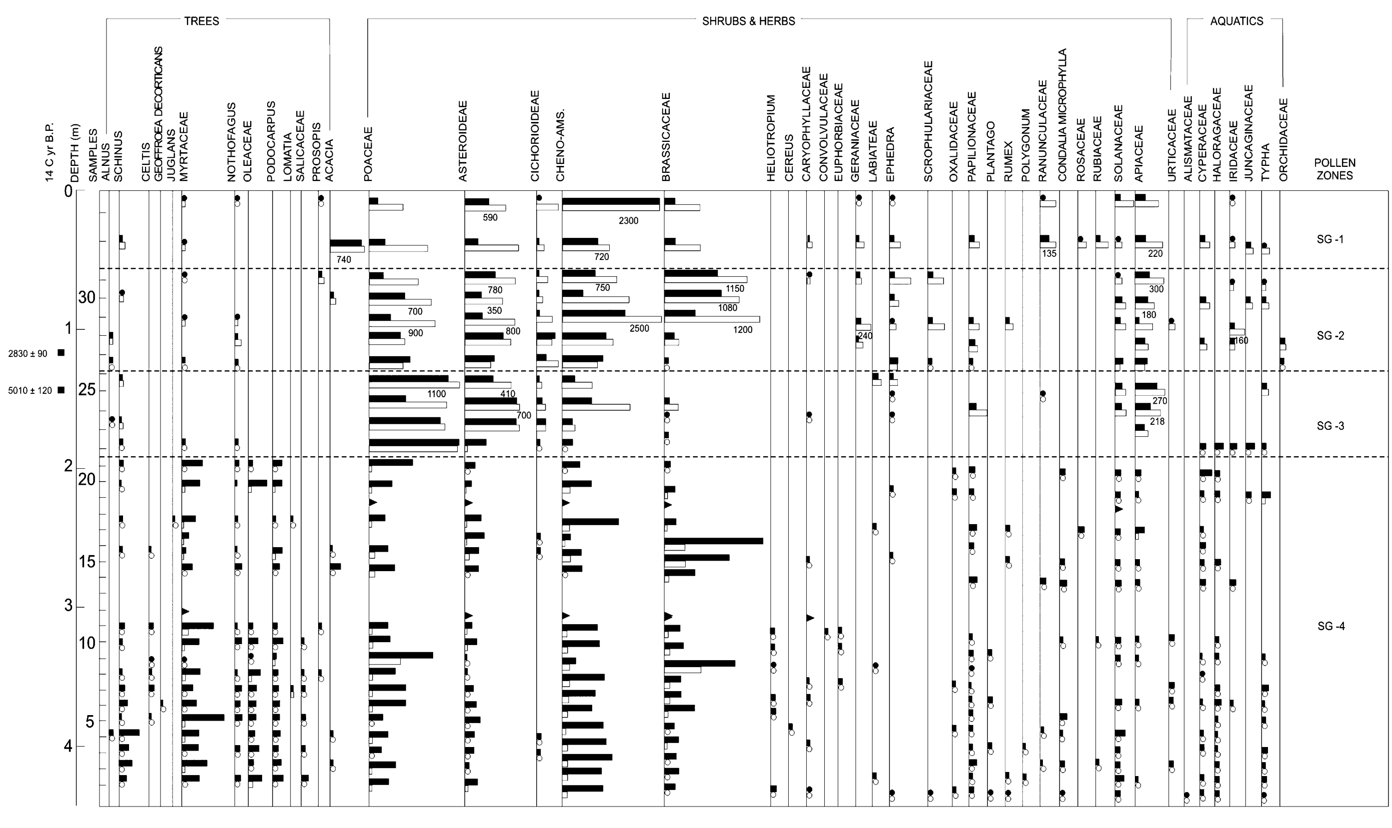

Fig. 6. Fossil pollen diagram at Terraza II, Río Sauce Grande. From Borromei (1995).

1998), and consequently, the sea level fall may correspond to the Younger Dryas event. Another interpretation suggests that these deposits are older and may correspond to the lowstand between 120,000 and 18,000 years BP (Zavala, personal communication, 2006). As a result, a depositional eolian cycle of loessic sands and sandy loess occurred, during which many valleys were completely obliterated (Zárate, 1991).

The Late Pleistocene–Holocene transition in south Buenos Aires Province is characterized by stability and pedogenesis suggesting relative humidity and warmer climatic conditions (Rabassa, 1987).

5.5. Early–Middle Holocene

The pollen record of the Arroyo Chasicó suggests stable conditions that favored soil formation at the beginning of the Holocene, dated 9930 ± 140 years BP (the "Espinal"; Table 2, site 4) (Borel et al., 2001). In the Paso Otero 5 archaeological site (Table 2, site 2) (Grill et al., in press) between ca. 10,400 and ca. 9400 years BP loamy facies are associated with a palaeosol. The associated palynofacies (Palynofacies 3 and 4) show the dominance of amorphous organic matter land plant-derived (non-fluorescent). These two events can be probably correlated with Puesto Callejón Viejo Palaeosol (Fidalgo et al., 1973; Fidalgo 1992; Tonni et al., 2001).

At Monte Hermoso I locality (Table 2, site 11; Figs. 1 and 3F), in the south coast of Buenos Aires Province, the palynological assemblage (Pollen Zone MH-1; Fig. 7) dated at 7125 ± 75 and 7030 ± 100 years BP reflects the development of a vegetation community characteristic of coastal dunes (psammophytic herbaceous) and interdune ponds with a slight marine influence suggesting locally humid conditions. Sea level was still lower than present (Zavala et al., 1992; Quattrocchio et al., 1998). Similar conclusions are given by Pardiñas (2001) based on the micromammal record of this site.

La Olla 1 site (Table 2, site 12; Fig. 1), located in the coastal inter-tidal zone on the Atlantic Ocean, is spatially and temporally associated with Monte Hermoso I locality (site 11) distant 200 to 1000 m eastward. The pollen record reveals the development of a halophytic plant community in a coastal environment from ca. 7920 to 7580 years BP (Fontana, 2004).

A shift to subhumid-dry climate after 7000 years BP was proposed by Prieto et al. (2004) in the northeastern humid Pampa region (Río Luján) as suggested by marl formation and disappearance of shallow lake gastropod species. Between 6000 and 5580 years BP, the high diversity and abundance of marine dinocysts and acritarchs found in pollen analyses in the lower basin of Arroyo Napostá Grande (Table 2, site 8; Pollen Zones NG-g1 and NG-g2, Figs. 8 and 9) indicate a transgression (Grill, 1993; Grill and Quattrocchio, 1996). In the mouth of the Río Quequén Salado (Table 2, site 3), the relative sea level rise (presence of dinocysts and acritarchs) caused the destruction of the littoral environment, which is reflected by Pollen Zone QS-3 (7720 + 100 years BP; Fig. 10) (Grill, 2003). This sea level rise flooded the riverbeds producing deposition of gray muddy facies toward 6000–5000 years BP (Isla, 1989; Zárate, 1991).

This event is associated with the spread of grasslands inland, reflecting more temperate conditions. The pollen

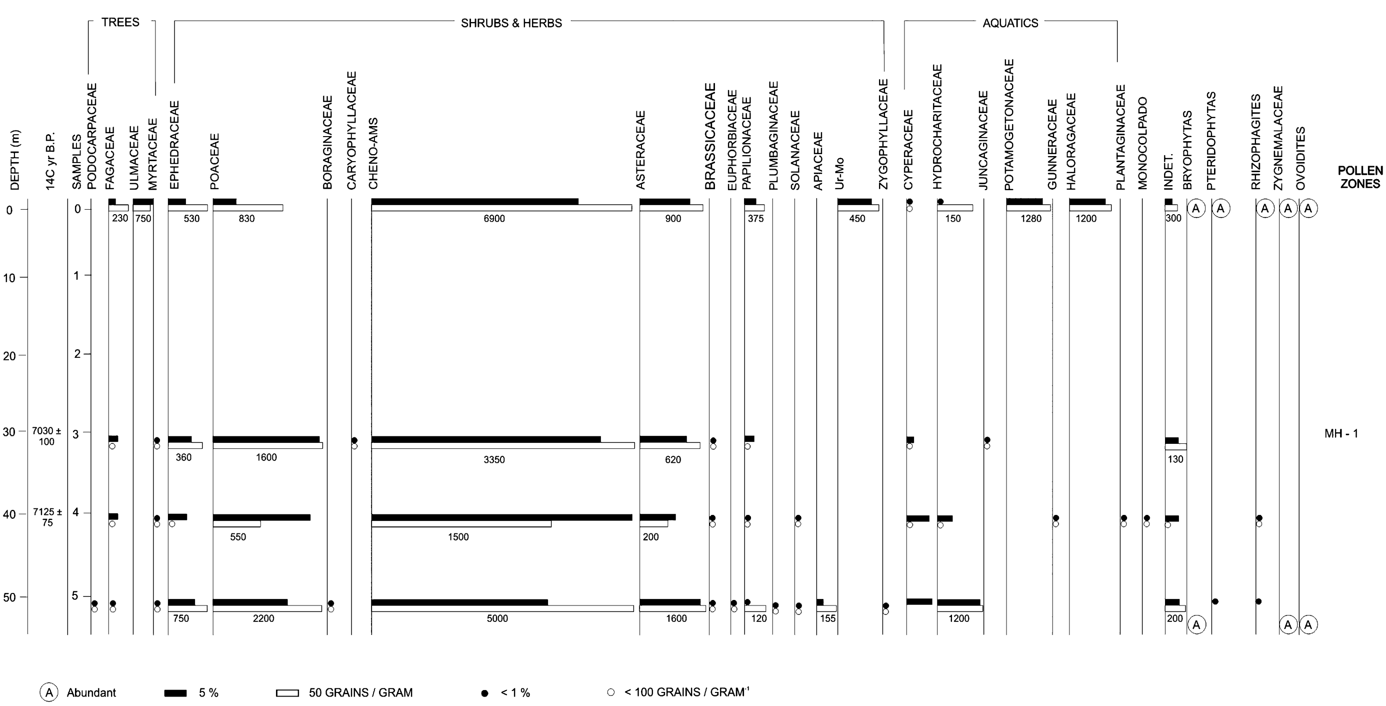

Fig. 7. Fossil pollen diagram at Monte Hermoso I. From Quattrocchio et al. (1998).

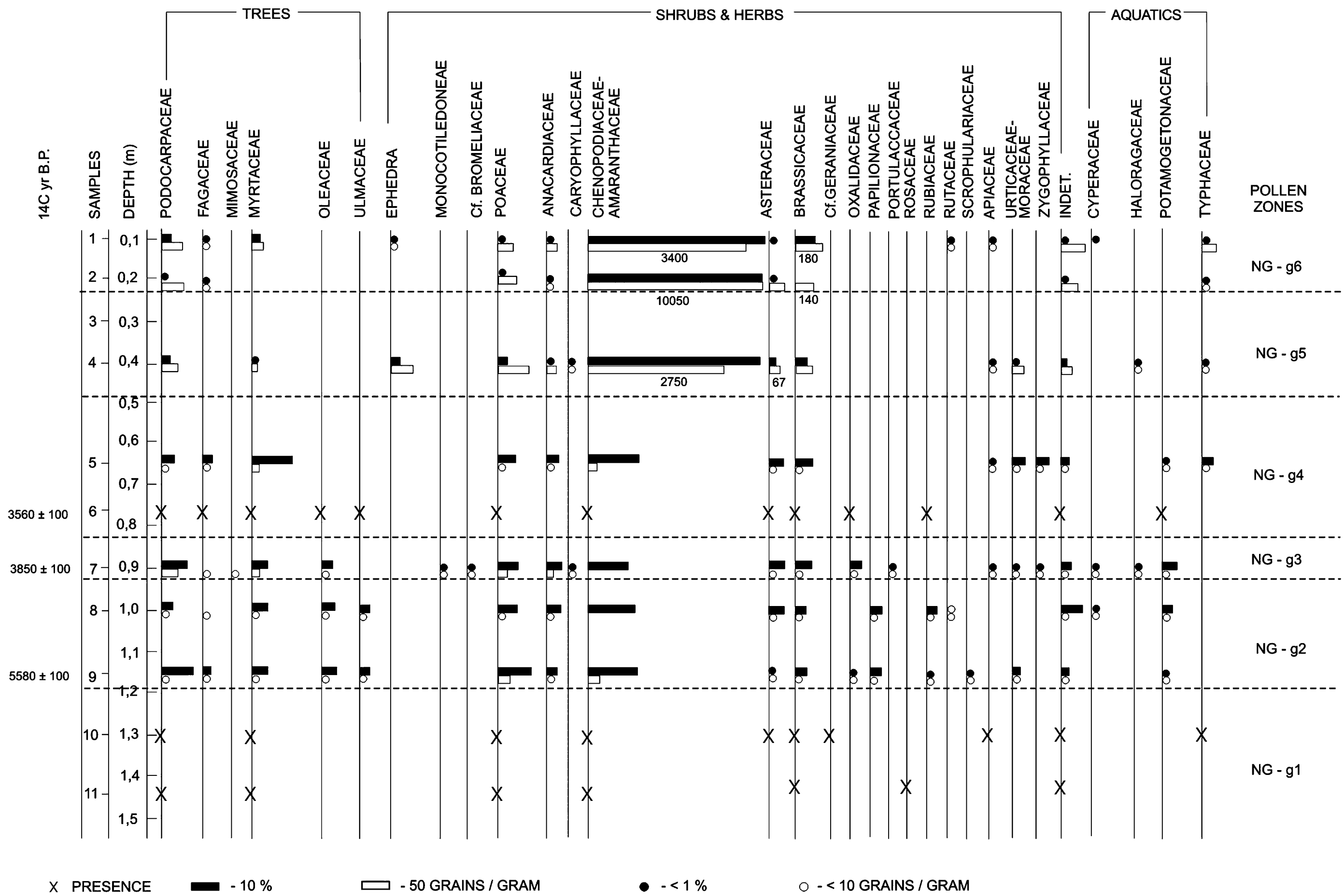

Fig. 8. Fossil pollen diagram at Grünbein, Arroyo Napostá Grande. From Quattrocchio et al. (1998).

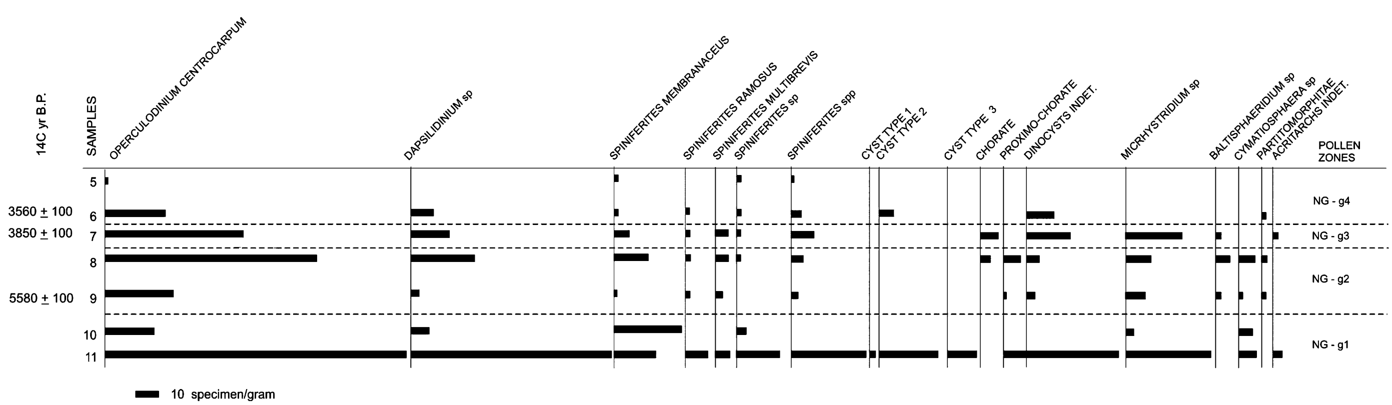

Fig. 9. Fossil aquatic palynomorphs diagram at Grünbein, Arroyo Napostá Grande. From Grill and Quattrocchio (1996).

record from the middle valley of the Río Sauce Grande (Table 2, site10) shows a regional vegetation of gramineous steppe associated with typical lithofacies from environments of valleys which are subject to frequent flooding indicative of more humid conditions (Pollen Zone SG-3 dated 5010 ± 120 years BP, Fig. 6) (Borromei, 1992, 1995; Quattrocchio and Borromei, 1998). This lithofacies are ''spring'' deposits produced by waterlogging within the river valley caused by the rise of the phreatic bed over the base (Zavala and Quattrocchio, 2001). This phenomenon plus the vegetal communities suggest humid climate. Similar conditions are also registered in alluvial sediments (Table 2, site 9) from the upper valley of the Río Sauce Grande, 35 km north of site 12 (Borromei, 1998).

In Paso Otero 5 (Table 2, site 2) (ca. since 6600 years BP), Palynofacies 5–9 indicate local humid conditions probably related to a flood margin of stream or river settings (Grill et al., in press).

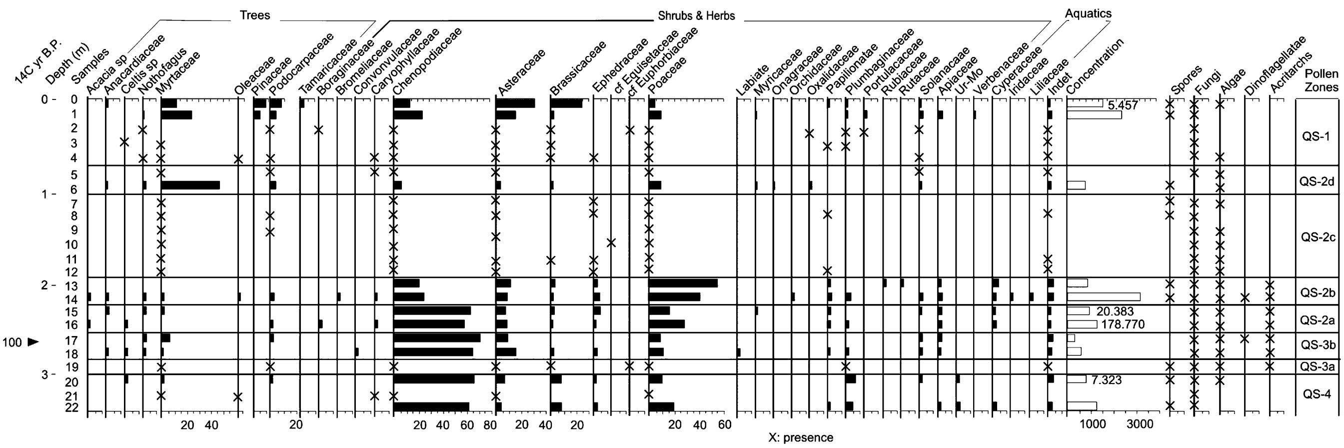

Fig. 10. Pollen diagram at Estancia Thomas, Río Quequén Salado. From Grill (2003).

At Fortín Necochea (Table 1, site X) (dry Pampa, Fig. 1) the record of mammals of Brazilian lineage (*Monodelphis dimidiata* and *Holochilus* sp.) dated 6010 ± 400 years BP also suggests warm and humid conditions (Crivelli-Montero et al., 1987; Tonni, 1990). Temperate and moister environmental conditions are also inferred from records of Austral-Brazilian fern flora (pollen data) recorded along streams in south-central Buenos Aires Province between 10,000 and 5000 years BP (Prieto and Quattrocchio, 1993).

5.6. Late Holocene

During the Late Holocene, there is evidence of greater climatic variability, from short episodes of semiarid to humid and warm conditions. In southwestern Buenos Aires Province, the climatic change toward drier conditions took place when marine regression began (Zárate, 1991). In the lower basin of the Arroyo Napostá Grande (Table 2, site 8) the marine influence ended approximately 3000 years BP (Pollen Zone NG-g3; Fig. 8) (Grill and Quattrocchio, 1996; Quattrocchio et al., 1998).

The pollen assemblage from Río Sauce Grande section dated 2830 ± 90 years BP (Table 2, site 10; Pollen Zone SG-2, Fig. 6) indicates vegetation of psammophytic herbaceous steppe with scarce shrubby woodland elements related to eolian activity, with fluvial episodes indicating arid to semiarid conditions (Borromei, 1995). Similar conditions are shown in pollen data (Pollen Zone NG-gr2; Fig. 4) and sedimentary facies analyses (after 2610 ± 60 years BP) from Arroyo Napostá Grande section (Table 2, site 6) (Grill, 1993, 1995).

In the middle valley of Arroyo Napostá Grande, Chacra Santo Domingo (Table 2, site 7), the pollen assemblage (1960 ± 100 years BP) suggests a vegetation of gramineous steppe and hydrophytic communities (Pollen Zone NG-sd3, Fig. 5) (Grill, 1993, 1997) associated with a "Brazilian" and/or aquatic vertebrate fauna (fish, anurans, the Anatidae birds *Anas platalea* and *Dendrocygna*, and the rodents *Holochilus brasiliensis* and *Cavia aperea*; Deschamps and Tonni, 1992; Table 1, site VIII). The southern expansion of Brazilian fauna, and the persistence of central and Patagonian elements suggest the amelioration of previous arid and semiarid conditions. Water bodies could have locally modified the arid conditions favoring the ingression of the Brazilian fauna (Quattrocchio et al., 1988; Deschamps and Tonni, 1992). Besides, the presence of eremic forms (the dasypodids *Chaetophractus villosus* and *Zaedyus pichiy*, the camelid *Lama guanicoe*, the rodent *Reithrodon auritus*, the fox *Pseudalopex gymnocercus*, among others) could have been favored by the influence of the nearby ranges. Ostracods identified in these levels suggest isolated, shallow water bodies, with low energy and salinity, and dense aquatic vegetation. The species *Chlamidoteca incisa*, *Cypridopsis vidua* and *Candonopsis brasiliensis* live currently in south Brazil. The abundance of *Cyprideis salebrosa* indicates fresh to brackish waters (Quattrocchio et al., 1988).

5.7. Historical Times

The vertebrate fauna from La Toma archaeological site (995 ± 65 years BP) (Table 1, site XI) in the upper valley of Río Sauce Grande (Fig. 1) also contains "Brazilian" elements (*Dasypus* and *Cavia aperea*) indicating warmer conditions (Rabassa et al., 1989) probably coeval with the Medieval Climatic Optimum of XII and XIII centuries.

A mammal association found at Lobería I archaeological site (Table 1, site XII; humid Pampa; Fig. 1) suggests arid to semiarid environment before 440 ± 60 years BP probably related to the Little Ice Age between XVI and XIX centuries (Rabassa et al., 1989).

During the Late Holocene and Historical Times, vegetation of halophytic steppe and psammophytic herbaceous steppe associated with eolian environments indicating semiarid conditions is recorded in the uppermost portion of the Río Sauce Grande, Terraza II section (Table 2, site 10; Pollen Zone SG-1; Fig. 6) and Arroyo Napostá Grande section (Table 2, sites 6 and 7; Pollen Zones NG-gr1 and

NG-sd1, respectively; Figs. 8 and 5). Pollen associations of this unit bear Chenopodiaceae–Amaranthaceae, Asteraceae and Poaceae (Quattrocchio and Borromei, 1998; Quattrocchio et al., 1998). The human influence is indicated by the presence of *Pinus*, Myrtaceae (*Eucalyptus* type) associated with some ruderal taxa like Brassicaceae (*Diplotaxis tenuifolia*) and Tamaricaceae (*Tamarix* sp.) (Grill, 1997).

Pollen records as well as geological and paleontological evidence yielded by exposures from north, southwestern and northeastern Buenos Aires Province also suggest a regional aridization (Rabassa et al., 1989; Grill, 1993, 1995, 1997; Prieto, 1996) during this period. This interval is represented in the area by the eolian Matadero Saldungaray Formation and the upper levels of the overflow deposits of the Chacra La Blanqueada Formation (see Fig. 2), which have both remains of European fauna (*Bos taurus* and *Ovis aries*). The neospecies found (*Ctenomys talarum*, *Lepus europaeus*, *Ovis aries* and *Bos taurus*) inhabit the area today. *Lama guanicoe* has undergone a retraction caused by climate changes (Tonni and Politis, 1980).

6. Conclusions

The most relevant features of the Quaternary studies from southwestern part of the Buenos Aires Province (southern Pampas) exposed above lead to the following conclusions:

- The oldest exposures of Cenozoic sediments are composed of loessoid sediments that resulted sterile in pollen samples, but yielded vertebrate remains, especially octodontoid rodents (*Xenodontomys* and *Phtoramys*), which suggest a Late Miocene age for these deposits, and allowed their correlation with other loessoid sediments of central Argentina. Other loessoid sediments were also sterile in pollen, but mammal remains (i.e. the rodent *Actenomys priscus*) suggest an Early Pliocene age for these deposits (Deschamps, 2005).
- In the Middle Pleistocene no pollen has been found, but mammals, especially the octodontid rodent *Ctenomys kraglievichi* as well as murid rodents and Tayassuidae, suggest the strongest warm pulse so far recognized for the Middle Pleistocene of southern South America.
- Late Pleistocene environments were extremely arid to arid associated with more continental environments and related to lower sea level. For the Pampas, Tonello and Prieto (in press) inferred that the arid conditions during the Late Pleistocene were associated with more "continental condition" due to the expansion of the landmass with a lower sea level in the Buenos Aires Province Atlantic coast.
- Those palynological levels with no pollen content recorded in most of the Late Pleistocene alluvial sequences could be related to glacial stages dated at 15,000–14,500 and/or 11,500–10,500 years BP (Heusser, 1987, 1989; Rabassa et al., 1992).
- Based on sedimentological, palynological and faunal evidence, the climate for the Late Pleistocene in the southern Pampa region is characterized by precipitation ca. 100 mm lower than at present. This would be related to the influence of maritime polar air masses triggered by the northward displacement of the polar front (about 5–7° of latitude), and the intensification of the westerlies due to the ice cover in Antarctica together with the extent of sea ice, as suggested by Heusser (1989) for high latitudes (Quattrocchio and Borromei, 1998).
- The Late Pleistocene–Holocene transition in southern Pampa region is characterized by stability and pedogenesis suggesting relative humidity and warmer climatic conditions.
- During the Early and Middle Holocene, the climatic amelioration of humidity and temperature could be related to the displacement of maritime tropical air masses to higher latitudes than at present, as suggested by Heusser (1989) for other latitudes (Quattrocchio and Borromei, 1998).
- The relative rise of sea level flooding the riverbeds toward 6000–5000 years BP is related to the spread of grasslands inland reflecting more temperate and humid conditions. The presence of a regional vegetation of gramineous steppe is associated with "spring" deposits produced by waterlogging within the river valley, caused in turn by the rise of the phreatic bed over the bottom surface.
- During the Late Holocene, the pollen records, as well as geological and paleontological evidence, reflect a greater climatic variability, from short episodes of semiarid to humid and warm conditions. Markgraf (1991) indicates that the climate of southern South America during the last 3000 years had an oscillatory behavior perhaps related to the Southern Oscillation.
- The paleoclimatic trends documented in this paper are also reflected in the Río Sauce Chico (Table 2, site 5) for the Late Pleistocene–Holocene, by means of qualitative analysis using modern pollen–vegetation–climate relationship as an analogue (Tonello and Prieto, in press).
- The southwestern Buenos Aires province is an ecotonal area from a biogeographic point of view, and consequently, very sensitive to paleoclimatic changes. Exposures of several localities yielded a relatively continuous fossil record of the last six million years, especially of the Late Pleistocene–Holocene, that allowed a detailed multidisciplinary study. The proposed paleoclimatic trends will be useful for comparison with other areas of the Pampean region.

Acknowledgments

This research was supported by CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas) SECyT (Secretaría General de Ciencia y Tecnología) and Universidad Nacional del Sur, Bahía Blanca, Argentina.

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