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Early to Middle Holocene transition in the Pastos Chicos record, dry Puna of Argentina

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a multi-proxy record and its paleoenvironmental interpretation from Pastos Chicos (23° 40′ 29″ S; 66° 25′ 32″ W; 3781 m asl), Susques, Jujuy province, Argentina. The analysis includes a study of fluvial sediments and geomorphology, and the contained diatoms and pollen record at centenary resolution. Two main environmental phases characterize the ~9000–4200 BP interval. The first phase was a humid period between ~9000 and 7300 BP (*circa* 10,000–8100 cal. BP) which showed organic soils formation in a floodplain broadly vegetated by grasses with a high and stable water table level. The second phase developed between 7300 and 6000 BP (~8100–6800 cal. BP) and showed a moderately drier environment interrupted by punctuated humid events such as those around 7000 and 6300 BP. This environment could be interpreted as a permanently existing meandering river with a floodplain with shallow oxbow lakes, bordered by a diverse shrub steppe. After 6000 BP, the fluvial system turned into a braided river situated in a sandy floodplain with dunes and ephemeral ponds. At the end of the sequence (i.e. post ~4200 BP), salt crusts developed and the river lowered its base level by 8 m. These results seem to show that the Pastos Chicos river basin evolved from low energy and more humid conditions established during the Early and the first part of the Middle Holocene, to drier ones in a system with more energy during some events of the second part of the latter period. The start of this aridization process at ~6000 BP in the basin, seems to be substantially later than other observations in local records of the Andean area. This could be due to physiographic control of the moisture by the catchment area (~1000 km^2) that generates a catchment-averaged regional scale signal of smaller amplitude, which is delayed for individual tributaries. These studies, with other ongoing analysis, will improve the accuracy of the models of resource structure in the area in several space–time scales and, consequently, advance knowledge concerning the organizational pattern of human societies in the past.

1. Introduction

Over the last 15 years, the volume of environmental information available for the Tropical Andean region has increased, allowing tracing general environmental trends and its variability in broad scales. However, discrepancies between records and particular environmental situations or responses to large climatic shifts have been detected in several localities in both Andean slopes, particularly regarding Middle Holocene conditions (*e.g.* Grosjean, 2001; Latorre et al., 2002, 2003, 2006; Rech et al., 2002, 2003; Servant and Servant-Vildary, 2003; Quade et al., 2008).

The available data in the Puna of Argentina (*e.g.* Valero-Garcés et al., 1996, 1999a, 1999b; Lupo, 1998; Morales, 2004, 2011; Olivera et al., 2004; Grana and Morales, 2005; Yacobaccio and Morales, 2005; Lupo et al., 2006; Tchilinguirian, 2009; Oxman, 2010) seem to share these regional tendencies (*i.e.* Thompson et al., 1995, 1998, 2000, 2003; Bradbury et al., 2000; Ramírez et al., 2003) but research in the area is considerably scattered in comparison with that in Northern Chile, Bolivia and Peru (see general reviews in Tchilinguirian, 2009, and Morales, 2011). In order to gain knowledge about past environmental conditions during the Holocene in this particular area and their impact in

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human societies in the past, new paleoenvironmental studies are required, particularly taking into account the regional discrepancies and the environmental diversity recorded between localities.

For this reason, the research project funded by ANPCyT ("Agencia Nacional de Promoción Científica y Tecnológica") and called "Social Change, Resources Management and Paleoenvironments in the Puna of Atacama during Holocene" has fostered several studies on the impact of broad-scale environmental changes (hemispheric to regional) at particular moments and places, and consequences for the resource structures exploited by human populations that inhabited the area in the past. Within this project, mainly wetland records from several sites at different latitudes and altitudinal ranges have been studied to cover the diverse environmental settings of the Puna (Morales, 2004, 2011; Olivera et al., 2004; Yacobaccio and Morales, 2005; Grana and Morales, 2005; Morales and Schittek, 2008; Morales et al., 2008, 2009; Tchilinguirian, 2009; Oxman, 2010). This paper describes one of these research cases, a multi-proxy study which includes diatoms, pollen, sediment, and paleosol analysis of the alluvial deposits of the middle Pastos Chicos basin, located in the vicinity of Huancar (Jujuy Province, Argentina) and comprising the first half of the Holocene.

2. Geographical setting

The studied area is situated in the Puna region, which comprises the arid highlands of Northwestern Argentina located between 22° and 27° S and 3000–4500 m asl. This area is characterized by high solar radiation due to its high altitude, high daily thermal amplitude, marked seasonality in rainfall, and low atmospheric pressure. The precipitation in this area is *ca*. 200 mm/y and is largely governed by the South American Monsoon System (Garreaud et al., 2003, 2009). This system produces about 80% of the annual precipitation occurring in the Andes highlands between December and February (Salati et al., 1979; Bianchi and Yañez, 1992; Marengo and Rogers, 2001; Vuille and Keimig, 2004).

The desert biome of the Puna bears considerable altitudinal variation in vegetation communities ranging from "*Tolar*" (shrub steppe) mainly composed of the *Asteraceae* family (*Fabiana* spp., *Bacharis boliviensis, Adesmia* spp., etc.) located at <4000 m asl to "*Pajonal*" (highland grasslands) situated at >4000 m asl and mostly composed of the *Poaceae* family (*i.e.* mainly *Festuca* spp. *and Stipa* spp.). Between the *Pajonal* and the *Tolar* there is a narrow ecotonal belt, currently located at 3900–4100 m asl, composed of a mixture of both shrub and herbaceous steppe. Both the *Tolar* and *Pajonal* also include a particular kind of vegetation community with a patched distribution: the *vegas* (wetlands) (Morales, 2004, 2011; Tchilinguirian, 2009). This community is constituted of soft grasses dominated in most cases by the *Cyperaceae* family (*Scirpus atacamensis, Juncus depauperatus, Hypsella* spp., *Plantago* spp., etc.) (Braun Wilke et al., 1999). Primary productivity is relatively high in these wetland environments which are usually concentrated in perennial and stable hydrological systems such as primary basins and high valleys (Olivera, 1997). Yacobaccio (1994) defined these patches as 'nutrient concentration zones' or ZCN (*Zonas de Concentración de Nutrientes*) because they contain the majority of the available regional biomass of this desert.

The few rivers and high Andean springs associated with wetlands are the main sources of freshwater, which is a critical resource for human populations. A main river in the Puna of Jujuy is the Pastos Chicos-Coranzulí-Las Burras drainage system. The Pastos Chicos river is 95 km long and extends from a southernmost limit between the provinces of Jujuy and Salta, to the confluence with the Coranzuli River (Fig. 1). The two rivers are the main tributaries of Las Burras River, which drains the Laguna de Guayatayoc-Salinas Grandes complex. Numerous ephemeral water courses flow into the Pastos Chicos main course. However, the Pastos Chicos River has a perennial base flow due to groundwater recharge in the Taire mountain range. This water regime generates marked discharge

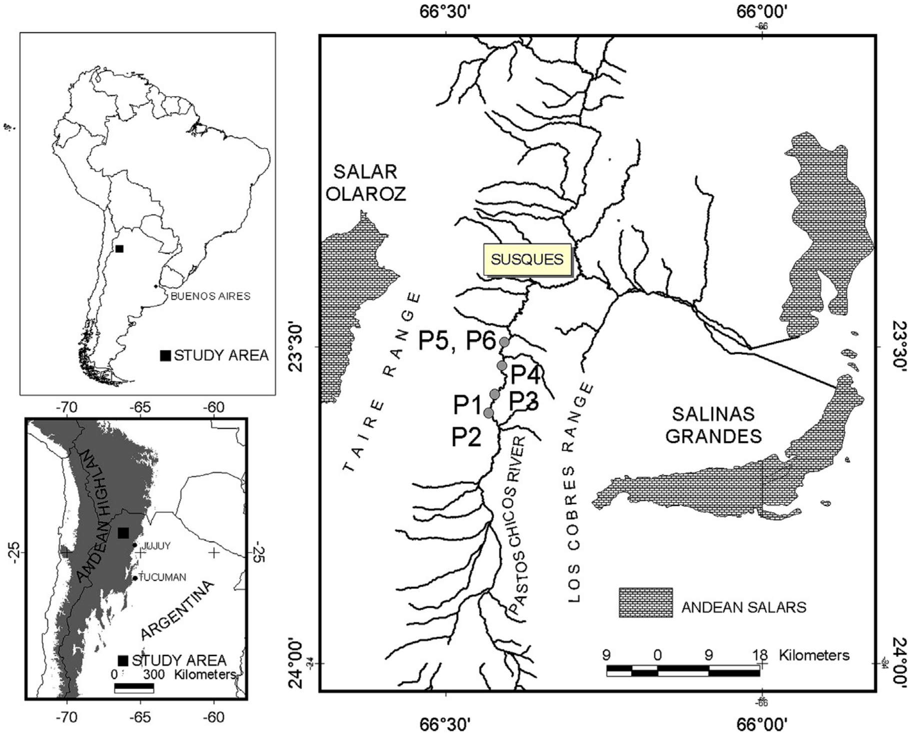

Fig. 1. Study area.

variability along the year, particularly due to strong increases during the rainy season (i.e. austral summer, December–March).

The Pastos Chicos catchment has two types of wetlands. Organic wetlands (locally known as "*vegas*") appear in the upper basin, due to the presence of perennial springs (Moore, 1987) that generate topogenous peats. The *vegas* support abundant riparian vegetation from their spring headwaters (mostly between 4100 and 4500 m asl) through the low elevation shrub desert where water quickly evaporates and infiltrates the unconsolidated streambeds. Deep soils with high organic values, hydromorphic and frost features can be found here (Histosols, Criols and Crioacuents). The channel occupied few spaces in the wetland-backswamp area where the phreatic level is near the surface. Surrounding the *vegas*, tussock grasses of *Stipa*, *Nasella* and *Festuca* dominate. These river wetlands have fresh waters and are only supported by small groundwater reservoirs, which respond to high mountain precipitation and the moisture carried by Easterlies intercepted by the Taire Range.

The second type of wetlands appears in the lower and middle basin. They are composed of salty soils and shrubs of the Puna belt vegetation (locally known as Tolar-Campo usually located between 3000 and 3800 m asl). Here, the Patos Chicos River has perennial flow and a high sinuosity migrating channel with a well developed sand alluvial plain. No organic soils appear and only Typic Torripsament and Typic Torrifluvents are found. Water flows are supported by middle basin springs and by summer rainfalls. The sedimentary profiles studied in this paper are located near this salty wetland.

2.1. Geomorphological setting

The Pastos Chicos River catchment covers 988 km^2 and occupies a north–south oriented Neogene tectonic depression bounded on the west by the Taire mountain range (5120–4200 m asl) and Los Cobres Mountains (4200–4500 m asl) in the east. No glacial landforms have been detected in its watershed. Moraine ridges are located 50–75 km away, in the peaks of Neogene volcanoes that rise to over 5200 m asl There, the frontal moraines are located at 4400 m asl suggesting that the Late Pleistocene wet and cold weather conditions affected the high altitude area as in other areas of the Argentinean Altiplano (Sayago et al., 1991; Zipprich et al., 2000; Ammann et al., 2001; Smith et al., 2006; Zech et al., 2006). Evidence of local permafrost above 4200 m asl appeared in some southwestern slopes (solifluction lobes) and in wet soils. An active cryogenic rock glacier has been detected over till deposits above 4700 m asl, suggesting that there is permanent active permafrost above this altitude.

The Pastos Chicos valley has two different geomorphic sections along its north–south length. The northern section is occupied by a playa-lake system (~ 14 km^2) surrounded by alluvial fans. The playa lake is composed by reddish, very fine sands and mud with parallel lamination (facies 1a). The alluvial fans contain structureless or crudely bedded, light and reddish medium and very coarse sands (facies 1b).

In the middle section, Pastos Chicos valley is excavated in Paleogene sedimentary and pyroclastic rocks. These rocks are covered by Pliocene deposits of conglomerates, 5–10 m thick, that form a regional pediment level of Pleistocene age. Into the Pastos Chicos valley, three levels of fluvial terraces of Holocene age are developed at 5, 3 and 2 m above the floodplain level, respectively. These levels are affected by gullying and piping. Other evidence of recent erosion is preserved in the river banks, which have risen up to 6 m high, are vertical and have recent slope failures. The current active channel is a single stream with low sinuosity, dominated by deposition of mid-channel and bank-attached sand bars. Parallel laminate and cross-stratified pale yellow sands are the dominant lithofacies (facies 2). Floodplain areas are characterized by sandy scroll bar deposition and some sand chute channels overlain by thin red mud layers. The floodplains also contain poor preserved relicts of recently abandoned sandy straight channels. Small alluvial fans (<5 km^2) wash down the Taire and Los Cobres ranges into the Pastos Chicos valley and occupy the edges of the floodplain.

Near the borders of the Pastos Chicos alluvial plain, Early–Middle Holocene deposits are preserved as fluvial terraces that extend over 30 km. These are paired and depositional terraces and have an average height of 5 m and are the most persistent surfaces in the river valley.

3. Materials and methods

Six sedimentary outcrops were studied along the mid-section of the Pastos Chicos basin (Figs. 1and 2). The profiles are aligned along the river over 8 km. Profile P1 is located upstream and P6 downstream. Both aerial photos and satellite imagery were analyzed to identify geomorphologic features with the aim of reconstructing paleogeography from the late Quaternary at local and regional scale. The mapping of the moraines and fluvial terraces has allowed the reconstruction of the geographical and altitudinal extent of the late Quaternary glaciers and floodplains. Modern river stratigraphy and geomorphology were studied. The current extent and altitude of modern wetlands were determined, to compare them to the geography of paleowetlands during the Early Holocene. This provided a better understanding of both modern and Holocene alluvial sedimentation.

Detailed field studies of the Holocene deposits were performed on outcrops exposed over more than 20 km through the longitudinal Pastos Chicos river profile, in order to identify lithofacies, lithofacies associations (FA) and geometry of sediment bodies. A number of gullies have dissected the terrace and exposed the 3-D geometry of the stratigraphy in ways that permitted alluvial element (cf. Miall) reconstruction and lithostratigraphical correlation. Distinctive lithofacies types were defined in terms of relative scales of strata thickness and internal structures, yielding information on depositional features and formative processes at relatively small scale (Bridge, 1993). Lithofacies were classified on the basis of grain size, sedimentary structures, biological components and geometry following the procedures of Friend (1983) and Miall (1982, 1996).

The lateral and vertical distribution and distinctive spatial relation of lithofacies (three-dimensional geometry strata shape data) formed the basis for the FA definitions. Descriptions of the FAs and their characteristic lithofacies, as well as interpretations of the depositional environments, are presented below and illustrated in Fig. 2. These data yielded more information about larger-scale aspects of the Pastos Chicos depositional environment. The six profiles were divided into main allostratigraphic units (A1-A2, A3, B1, B2, B3 and C units), separated by discontinuities (Miall, 1996).

Twenty-eight samples were recovered from Pastos Chicos Profile 1, the main record (i.e. P1, 23° 40′ 29″ S; 66° 25′ 32″ W; 3781 m asl). The bulk organic matter of two of these samples -PCH2-M2 and PCH1-M3- using conventional ^{14}C dating were dated to 7900 ± 100 BP (LP 1836, peat, Table 1) and 8900 ± 130 BP (LP 1841, peat, Table 1), respectively. The dated peat was composed of complete and broken plant epidermis fragments. Such terrestrial plant material will not suffer from a ^{14}C reservoir effect and is therefore highly desirable for dating. Another age was obtained from a bird bone included in the P1 (PCH2-M15) sample, dated to 6935 ± 69 BP (AA 94570, bone, Table 1). With these three dates, a linear interpolation age-depth model (Bennett, 1994) was applied in P1, in order to estimate a numerical age for each of the analyzed samples. This model has been applied, assuming a constant

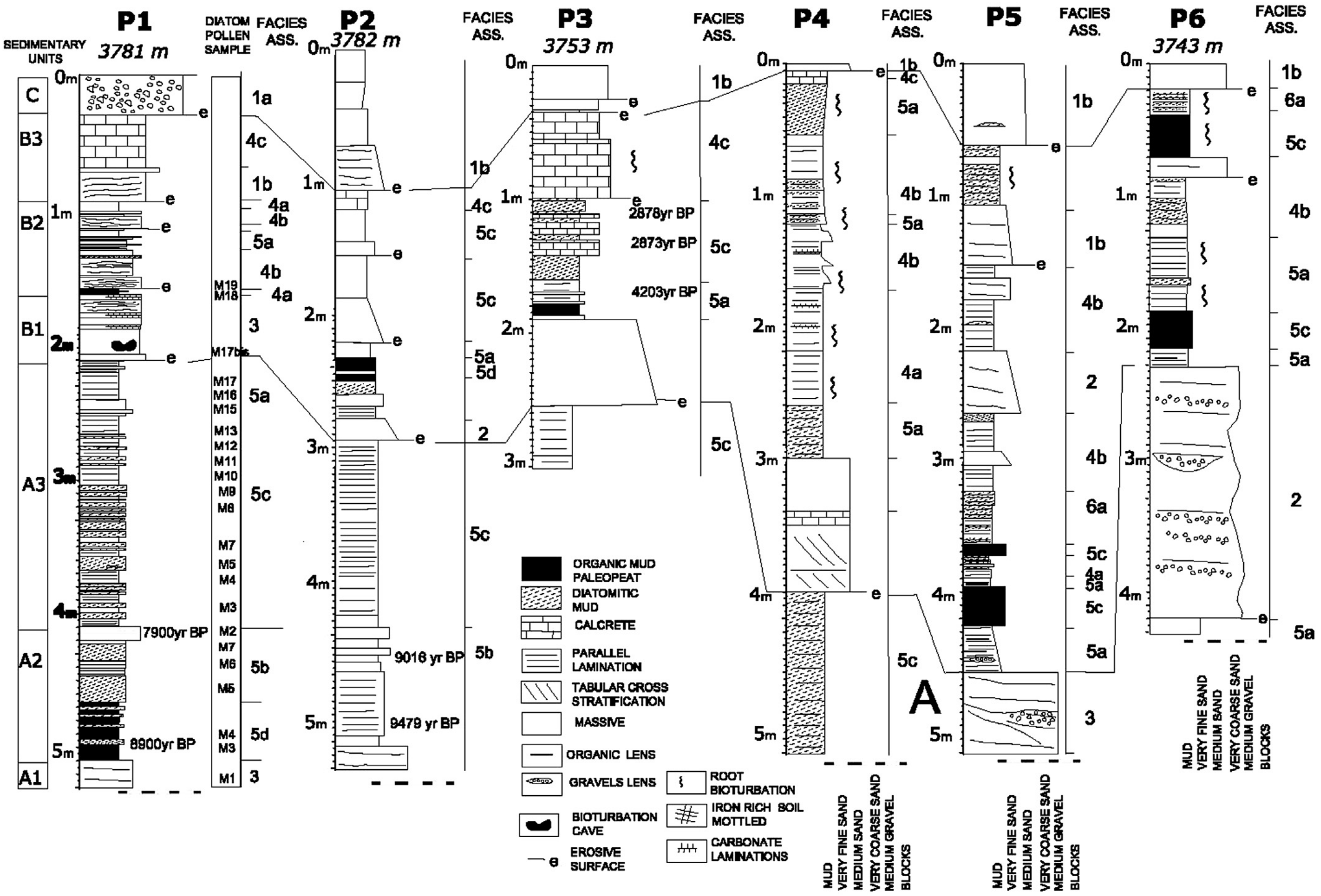

Fig. 2. Stratigraphic correlation of the geological logs of sections P1–P6 in Pastos Chicos Valley.

sedimentation rate between dates, due to the sedimentary accumulation and pollen counts in the chronological packages (11.49 y/cm between the peat dates; 6.34 y/cm between the 7900 ± 100 peat sample and the 6935 ± 69 dated bone sample) of this sequence (unit A). The absence of channel erosion surfaces within the overbank unit and the relative homogeneity suggest a single aggradational fluvial cycle during this period. Two other radiocarbon ages (9016 ± 49 and 9479 ± 50 BP, Table 1) obtained from unit A and located in a stratigraphically correlated profile (P2: 23°40′31.18″S, 66°25′34.55″O, 3781 m asl) provide further support for the inferred ages for this unit.

Three samples (PCH2-M17 through M20) come from the uppermost part of Unit B in section P1. This unit has several peat lens dated to 4203 ± 58, 3065 ± 50, 2873 ± 36 and 2877 ± 36 BP (Table 1) in profile P3 (23°36′55.99″S, 66°25′35.88″O, 3753 m asl).

Two paleoenvironmental proxies were analyzed in the P1 record: diatoms, and pollen. The diatom content of the sediments was studied in the full set of samples ($N = 28$); whereas the pollen analysis was performed in half ($N = 14$). The techniques involved in these studies are described below.

3.1. Diatoms

The diatoms analysis followed the standard procedures suggested by Battarbee (1986): oxidation of the organic matter with 30% H_2O_2 and elimination of carbonates with HCl; and elimination of the oxidant with three washes with distilled water. The treated material was mounted in slides with Naphrax®. Between 300 and 400 valves were counted and taxonomically assigned in each slide. The observation was carried out using a Reichert-Jung (Polyvar)

Table 1
Radiocarbon and calibrated ages (IntCal04, Reimer et al., 2004) from the Pastos Chicos record, Argentina.

Lab code	Profile	Sample	Material	Measured ^{14}Cage (BP)	∂C13	Larger probability range 2σ calibrated age (cal. BP)	Unit
LP1337	P1	PCH1-M3	Peat	8900 ± 130	−27	9886–10,197	A
LP1836	P1	PCH2-M2	Peat	7900 ± 100	−27	8596–8790	A
AA94570	P1	PCH2-M15	Bird bone	6935 ± 69	−20.4	7658–7933	A
AA79818	P2	M2	Peat	9016 ± 49	−25	10,176–10,234	A
AA79825	P2	M1	Peat	9479 ± 50	−23.5	10,653–10,786	A
AA79835	P3	PCH4-M2	Peat	4203 ± 58	−26.2	4691–4762	B
AA79820	P3	PCH3-M2-C8	Epidermis fragments	2877 ± 36	−21.7	2955–3067	B
AA79827	P3	PCH3-M1-C6	Epidermis fragments	2873 ± 36	−23.2	2952–3066	B
AA79833	P3	PCH4	Epidermis fragments	3065 ± 50	−23.9	3241–3355	B

binocular microscope (OM) under 1000× magnification. To confirm the taxonomic assignment of some of the smallest diatoms, a Phillips XL30 TMP Scanning Electronic Microscope was used, ranging between 5000 and 30,000×.

The taxonomical identifications were based on the monographic works of Germain (1981), Round et al. (1990), Krammer and Lange Bertalot (1991–96), Lange-Bertalot (2000), Rumrich et al. (2000) and several other papers. The ecological interpretation rested on the ratio between frequencies of species with different life form affinities (littoral/benthic and aerophilic), and the ratio between frequencies of salty and fresh water diatoms according to their salinity affinities, following the works of Lowe (1974), De Wolf (1982); Vos and De Wolf (1993) and Van Dam et al. (1994), among others.

3.2. Pollen

This analysis followed the standard procedures for Quaternary pollen (Faegri and Iversen, 1989): incorporation of *Lycopodium* sp. marker spores to the material; elimination of carbonates with HCl, of humus with KOH 10% and of silica with HF 70%; acetolysis to eliminate organic remains, and ultrasound to separate the material from fine particles. The treated material was mounted in slides with glycerin and paraffin. At least 200 pollen grains were counted and taxonomically assigned using a Zeiss-Axiolab microscope (OM) under 400×. Several regional palynological standard works (Heusser, 1971; Markgraf and D'Antoni, 1978) and the pollen herbarium from the Pollen Research Group at the National University of Jujuy were used as reference material for taxonomic issues.

The interpretation of the pollen analysis is based on descriptions of the modern regional vegetation (Cabrera, 1976; Braun Wilke et al., 1999). The total abundance of pollen types and the relative frequencies between them in each sample are the basic variables. Particularly, the ratio between the relative frequencies of herbaceous steppe and shrub pollen was used as an environmental moisture index.

4. Results

4.1. Lithostratigraphy

Analysis of the outcrop sections reveals that the Holocene alluvial fill comprises 16 basic lithofacies (Table 2). The lithofacies are grouped into two main associations (Table 3): channel-fill sediments (facies 1, 2 and 3) and fine-grained overbank deposits (facies 4 and 5). The proportion of channel deposits to floodplain deposits varies, but the latter are usually of greater cumulative thickness than the former.

Facies Association 1 consists of crudely bedded alluvial sediments dissected by a paleostream transverse to the Pastos Chicos river course. This facies ranges between 0.5 and 2 m in thickness and was developed as a result of the lateral accumulation of the alluvial fan. Facies 2 and 3 consist of bedded sand sediments that fill several paleochannels. These deposits are up to 1–2 m thick. The lower bounding surface of these depositional units is a sharp channel base overlying fine-grained overbank material. A paleostream parallel to the current Pastos Chicos River suggests that this represents the ancient Pastos Chicos channel.

Facies Association 4 presents features associated with ephemeral and oxidant conditions, with small amounts of organic matter. Facies Association 5, in contrast, is dominated by interbedded thin laminae of diatomites and bioturbated grey muds, organic paleosols and well-preserved plant epidermis and vascular plant bundles. Facies Association 6 consists of mounds of structureless medium sands accumulated by eolian processes.

In the Pastos Chicos valley, deposits of the Holocene terrace have accumulated over a major erosion surface (Fig. 3), which cut Upper Pleistocene and Tertiary sediments (limestone and fine sandstone). The three basic stratigraphic units A, B, and C are separated by channel erosion features (Miall, 1996).

4.1.1. Unit A: Early Holocene and beginning of Middle Holocene

At the base of the Holocene deposits there is an extended, thick outcrop of alluvial, fine organic sediments (Unit A, Fig. 3) that borders the valley. This unit is a prominent lithostratigraphic unit in the valley and represents a low energy fluvial system with organic paleowetlands, oxbow lakes and back swamp muds (Facies Association 5) of Early to Middle Holocene age. In section P1 (Fig. 2), Unit A buries limestone. At the top, Unit B truncates Unit A with a channel-scoured contact. At section P1, Unit A is a 1–3 m thick outcrop that continues over 100 m, composed of greyish-green overbank Facies Association 5b, 5d, and 5a, with minor development of Facies 5c and at the very base channel

Table 2
Summary of lithofacies used in this study.

Facies code (Miall, 1996)	Description	Sedimentary structures	Interpretation
Gmc	Gravel, clast-supported	Structureless	Debris flow
Gmm	Gravel, matrix-supported	Structureless	Debris and Mud Flow
Gh	Gravel, clast supported	Horizontal bedding common clast imbrication	Channel fill; bar
Gt	Gravel, clast-supported	Trough cross-bedding	Channel fill; bar
St	Sand medium to very coarse	Trough cross-bedding	Channel fill; bar
Sh	Sand, very fine to very coarse	Horizontal bedding	Channel fill; bar
Shv	Sand, very fine to very coarse	Horizontal bedding, hydromorphic features	Channel fill; bar
Shc	Sand, very fine to very coarse	Horizontal bedding, carbonate features	Channel fill; bar
Shvc	Sand, very fine to very coarse	Horizontal bedding, hydromorphic and carbonate features	Channel fill; bar
Sl	Sand, very fine to fine	Horizontal lamination	Crevasse
Slx	Sand, very fine to fine	Planar lamination, oxidation features	Crevasse
Slv	Sand, very fine to fine	Planar lamination, hydromorphic	Crevasse
Sb	Sand, very fine to very coarse	Structureless, bioturbated	Soil in Levee
Sol	Sand, black organic, very fine to coarse	Planar laminations	Overbank and backswamp
Sm	Sand, very fine to very coarse	Structureless	Sand sheet
Smx	Sand, very fine to very coarse	Structureless, oxidation mottled	Ponds in distal alluvial fan
Fol	Mud, clay, organic	Planar laminations	Overbank and backswamp
Fdl	Silt, diatomitic	Planar laminations	Overbank and backswamp
Fdb	Silt, diatomitic	Structureless, bioturbated	Overbank and backswamp
Fdm	Silt, diatomitic	Structureless	Overbank and backswamp
Flv	Mud, clay, green	Planar laminations, hydromorphic features	Ox-bow fill in floodplain
Fl	Mud, clay	Planar laminations	Ephemeral backswamp
Lm	Gypsic and calcic duricrust in sand	Structureless	Spoil in overbank

Table 3
Description, dominant lithofacies, and depositional environment of the facies associations (FAs) preserved in terrace exposures of the Rio Pastos Chicos.

Depositional environment	Facies association	Lithofacies characteristics	Description	2D shape and paleocurrents
Gravelly braided fan from the side of the valley.	1a	Gmc, Sm, Gmm	Crudely bedded, clast supported and coarsening-upward sequences of crossbedded and laminated gravels with minor sand and mud. Reddish to gray.	Wedge, paleocurrent transversal to Pastos Chicos north-south direction.
Sand sheet fan from the side of the valley.	1b	Sm, (Gh, Gmm)	Structureless to crudely bedded, coarse sand. Structureless to crudely supported clast gravel. Reddish gray.	
Sandy braided channels	2	Sh, St, (Gh, Gt)	Horizontally stratified, planar-crossbedded, thought bedded coarse sands and stratified gravels lens.	Channel, paleocurrent parallel to Pastos Chicos direction.
Coarse braided Channels	3	Gh, Gt, Ghx, Sh, Smx, (Fdl, Fol)	Horizontally stratified, planar crossbedded, though bedded medium to fine gravels and coarse to medium sands, gray. Bright yellowish brown concretion and mottled fine gravel lenses. Thin, wedge, laminated diatomitic mud and organic matter.	Channel, paleocurrent parallel to Pastos Chicos direction.
Playa lake system, ephemeral lagoons	4a	Fl, Sl (Fdl)	Laminated bedded fine to very fine sand and thin laminated mud. Reddish gray. Wedge layer of laminated diatomitic mud.	Sheet and wedge
Distal fan (sand lobes with shallow playa lake system in floodplain	4b	Sm, Fl (Fdl)	Structureless, medium to very fine gray sand, interbedded thin laminated, reddish mud	Wedge to sheet
Salty-phreatogenic soils or salt-dominant playas in floodplain	4c	Shc, Lm	Calcic and gypsic duricrust in planar bedding sands and laminar diatomitic mud	Wedge
Lagoon in floodplain, hydromorphic conditions	5a	Flv, Slv (Fol, Fdl)	Laminated mud and fine sand, poor to moderate bioturbated. Olive gray. Wedge layer of thin laminated organic matter or diatomitic mud.	Wedge
Crevasse mineral soils in backswamp area	5b	Sol, Fdlv, Fdb, Fdm	Planar laminated organic fine dark sand interbedded with fine diatomitic, hydromorphic, structureless, fine laminated or bioturbated mud.	Wedge
Oxbow fill, hydromorphic conditions.	5c	Flv, Fdl, (Sh, Shv)	Planar laminated to bioturbated hydromorphic mud and clay interbedded with fine white diatomitic layers.	Channel, ribbon
Backswamp with peat in low energy floodplain	5d	Fol, Ddl, Fdb (Sd)	Planar laminated organic black sediments interbedded light gray laminated diatomitic muds and silts. Thin wedge layer of gray fine sands.	Sheet
Eloic sheet, nebkhas	6	Sm	Structureless fine to medium sand, light gray.	Sheet

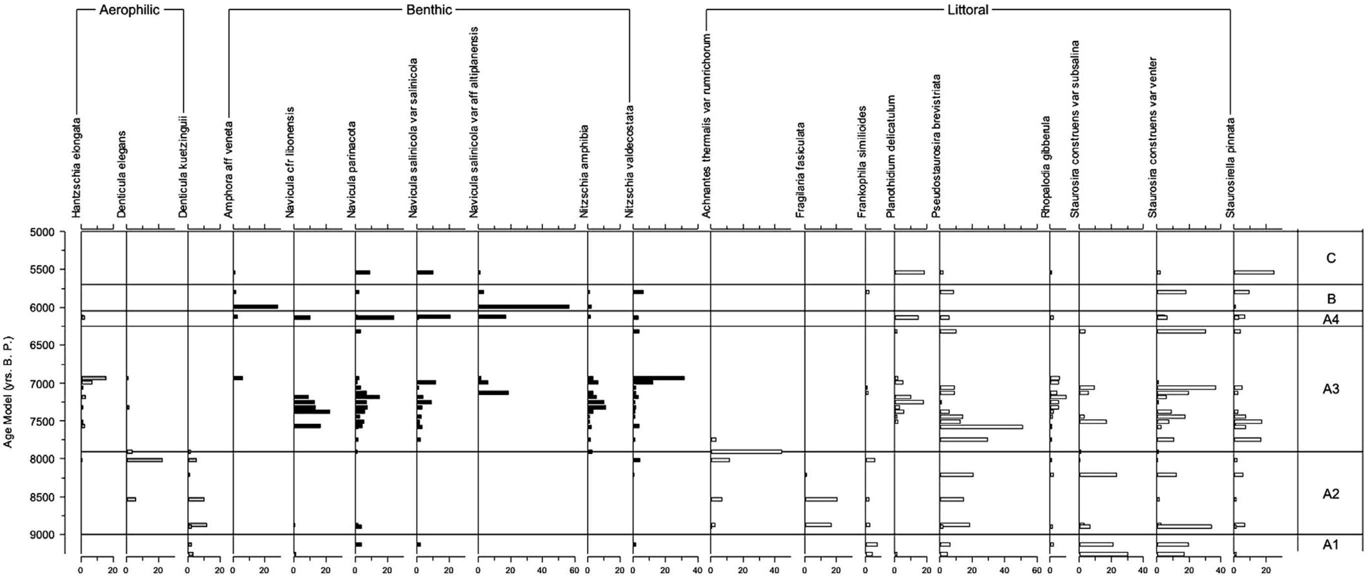

Fig. 3. Frequencies of the most indicative diatom taxa identified in PCH record. The left axis shows ages corresponding to the age/depth model. Dates after 6000 BP were assigned to post 4200 BP by stratigraphic association. At the right margin the graphic shows the diatom zonation and stratigraphic units.

Facies 3. The latter (subunit A1) is expressed as pale green, medium coarse horizontal bedded and structureless sand. Unit A2 consists of thinly laminated, hard, black, organic layers (5–20 cm) interbedded with thin, light gray laminated diatomaceous silt (Facies Association 5d). The organic material contains uncarbonized, well-preserved plant epidermis and vascular plant bundles of 1–2 mm length. These organic layers represent back swamps with development of organic soils. Samples taken near the lower and top contacts in section P1 have 8900 ± 130 BP and 7900 ± 100 BP, respectively (Table 1). In section P2, a peatbed within Unit A returned dates of 9476 ± 50 BP and 9016 ± 49 BP, confirming both, the stratigraphic correlation and the Early Holocene age.

Unit A2 is composed of structureless, light grey, very fine sand and diatomaceous silt interbedded with laminated dark grey medium organic sand (Facies Association 5b). Subunit A3 (2 m) is characterized by thinly laminated, green (2.5 Y 7/3) mud and clays interbedded with thin (2 cm) layers of massive and white diatomite. No organic matter has been found, and thus the unit remains undated. Subunit A2 is located in P1 and the uppermost A3 subunits in P1, P2, P3 and P4 profiles.

4.1.2. *Unit B: Middle Holocene*

Unit B is composed by channel Facies Association 2 and 3 in the lower section (subunit B1), overbank Facies 4a, 4b, 5d in the middle section (subunit B2) and carbonate pond deposits of Facies 4c which were located in the uppermost section of the sequence (subunit B3). These subunits appear in several profiles (P1, P2, P4 and P6). In P1, Facies Association 2 comprises mainly stratified, medium to coarse sand in channel bodies with sharp bases. The facies has light colors and absence of organic matter. The facies Association 3 is stratified medium to coarse gray sand. The stratified sand bedding planes are commonly accentuated by laminae of scare plant fragments and coal fragments.

Overbank deposits of Facies Association 5d overlie channel deposits of Facies Association 2 (*e.g.* in section P3) and is composed by thinly laminated green muds and peats. In P1 profile Facies Association 4a is dominated by laminated, fine to very fine sand and mud with a wedge lens of thinly laminated diatomitic mud. The facies occurs as sheet bodies, with great lateral extension. The palaeoenvironmental setting has been interpreted as comparable to a playa lake system or floodplain ephemeral lagoons. The sediments of Facies Association 4b wedge into sheet-type deposits with flat scoured bases and flat tops. The outcrops are up to 0.5–1 m thick and over 100 m long. Dominant facies are structureless medium to very fine sand, interbedded with horizontally laminated mud. A terminal fan model was proposed to explain the ephemeral sand.

The uppermost sediment is Facies Association 4c. This subunit is an indurated salty and carbonate-rich layer. The parent material is a diatomite mud or very fine sand matrix sediments. This floodplain unit is sheet-like or a laterally extensive lens (traceable for up to 1 km) that is intercalated within the dry mud-flat (Facies Association 5a) and wetland Facies (4b). Maximum thickness of the layer reaches 1 m. This duricrust is a significant element of fluvial architecture and allows correlation between vertical sections over tens of kilometers in the middle section of the Pastos Chicos basin. It shows predominance of nodules, tubules or laminae of carbonate and dispersed gypsum crystals. The various types correspond to different degrees of carbonate or gypsum accumulation. The base of duricrust graded into wetland deposits (facies 5a) or dry mud-flat sediments (facies 4b). In contrast, the contact between the carbonates and the overlying clastic fan deposits (unit C, facies 1a or 1b) at the toe of the sequence is commonly sharp.

The different types of carbonate-gypsum accumulations are related to paleosol (nodules, tubules) and natural bodies of standing, short lived water ponds developed in a semi-arid climate and in periods of reduced clastic sediment input (laminated and structureless). It is suggested that recharge into the pond areas was mainly from groundwater.

The radiocarbon dates of Profile 3 (i.e. 4200 ± 58 BP, in the lower peat of unit B1 and 2878 ± 38 BP and 2873 ± 36 BP, in middle section of subunit B2) suggest that the formation of both, unit B and fluvial terraces was developed in the late Holocene.

In the upper section, unit C is composed of grey coarse horizontal bedding agglomerates and conglomerates, deposited in small alluvial fans dominated by debris flows coming from lateral supply (facies 1a).

4.2. *Diatom record*

In the twenty-eight analyzed samples from Pastos Chicos P1 profile, 150 taxa were identified at the species and sub-species levels. The frequencies of the species in each sample are detailed in Morales (2011) and the most relevant illustrated in Fig. 3.

In P1 profile, the Fragilareaceae group (mainly composed by genus *Staurosira, Staurosirella, Pseudoestauroira, Fragilaria, Tabularia y Ulnaria)* was the most important in the flora composition. *Nitzschia* sp., accompanied by several *Navicula* sp., *Achnanthes* sp., *Denticula* sp., *Encyonema* sp. and *Rhopalodia* sp. were also frequent.

In the lower 8 samples of unit A (A1 and A2), the genus *Staurosira* dominates four of the eight samples (*S. construens* var. *subsalina* in three cases and *S. construens* var. *venter* in the remaining case). The rest of the samples were dominated by *Pseudostaurosira brevistriata*, *Tabularia fasiculata*, *Navicula lauca* and *Achnanthidium thermalis* var. *rumrichorum*. Other species that show important frequencies in the record are *Staurosirella pinnata*, *Nitzschia valdecostata*, *Frankophila similoides*, *Encyonema neogracile* and *Denticula kuetzingii*.

The Fragilariaceae dominated nine of the twenty samples analyzed in the upper section of the P1 record (A3) (*S. construens* var. *venter* in five cases and *S. pinnata* and *P. brevistriata* in the remaining two, respectively).

Genus *Navicula* dominates in seven samples (*N. parinacota* in two cases, *N. libonensis* in two samples. and *N. lauca*, *N. salinicola* var. *salinicola* and *N. salinicola* var. *atacamensis* in one each) and *Nitzschia* two (in both cases the species was *N. valdecostata*). Two other species, *Planothidium delicatulum* and *Achnanthes thermalis* var. *rumrichorum,* dominate the samples of this part of the record. Other frequent taxa in this environmental archive are *Staurosira construens* var. *subsalina*, *Rhopalodia gibberula*, several species of the genus *Nitzschia* (such as *N. palea*, *N. vitrea*, *N. liebertrutii*, *N. hungarica*, *N. commutata* and *N. amphibia*), *Hantzschia elongata*, *Fragilaria capucina* var. *vaucheria*, *Brachysira neoexilis* and *Amphora veneta* (Fig. 3).

4.2.1. *Unit A: Early Holocene and beginning of Middle Holocene*

The conditions inferred from diatoms are coincident with those suggested by the geomorphological analysis which suggests a floodplain wetland environment, moist during the most part of the year and with development of paleosols (peat). The analysis of the ecological affinities of the diatoms recovered from Pastos Chicos, and the moisture and salinity indexes calculated from them, distinguish two phases of contrasting environmental conditions in the record (Fig. 6). The break between the two phases occurs in P1 within Unit A3, in facies 5c (Figs. 2–4).

The first phase, between ~9000 and 7300 BP, can be interpreted as a generally moist and relatively stable environment (Fig. 6). Alternatively, it can be interpreted to represent a wetland edge,

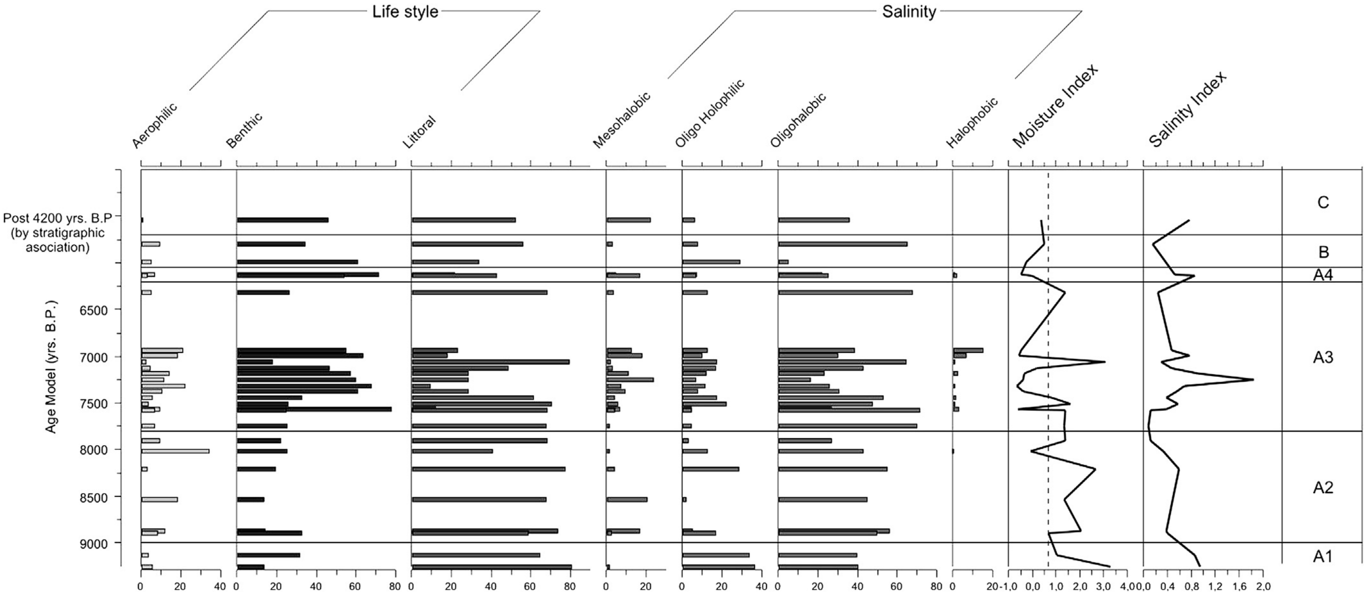

Fig. 4. Ecological affinities of the diatom samples from PCH record in terms of lifestyle and salinity. The two graphs on the right illustrate the Humidity Index (Littoral/[Benthic + Aerophilic] diatoms) and Salinity ([Salt + Brackish]/Freshwater diatoms) obtained from the ecological affinities frequency values. The dotted line in the moisture index graph shows the mean value of the series (for more details see Morales, 2011). The left axis shows ages corresponding to the age/depth model. Dates after 6000 BP were assigned to post 4200 BP by stratigraphic association. At the right margin the graph shows stratigraphic units.

supporting broadly vegetated littoral areas. Negative anomalies in the moisture index suggest the phase to be interrupted by at least one drier pulse around 8000 BP, recorded in Unit A2 in facies 5b (Figs. 2–4). In samples from zone A1, high frequencies of littoral forms of Fragilariaceae group are present. These species have a broad tolerance to salinity fluctuations, and suggest the presence of a wetland environment with a broad littoral area and variations in its salinity between ~9300 and 8900 BP.

The second phase also represents a wetland environment, but the diatom assemblages indicate it to be a much drier and salty one. The diatom indexes point to more arid and brackish conditions (Fig. 4). Anomalies in the indexes suggest episodic more moist pulses to have interrupted the arid conditions, around 7000 and 6300 BP.

The prolonged aridity of the second phase after 7300 BP, can be compared to the brief arid pulse recorded at 8000 BP. The brief pulse at 8000 BP appears to have been slightly more arid (based on the rise in the frequency of aerophil species) than was typical after ~7300 BP.

It is possible to identify two different environmental periods in unit A3 (Fig. 4). The first one is characterized by similar conditions to the units A1 and A2, and extends from ~7800 BP to a noticeable dry pulse around 7300 BP. Starting at 7300 BP and up to the end of unit A3, around 6000 BP, drier conditions prevailed, characterizing

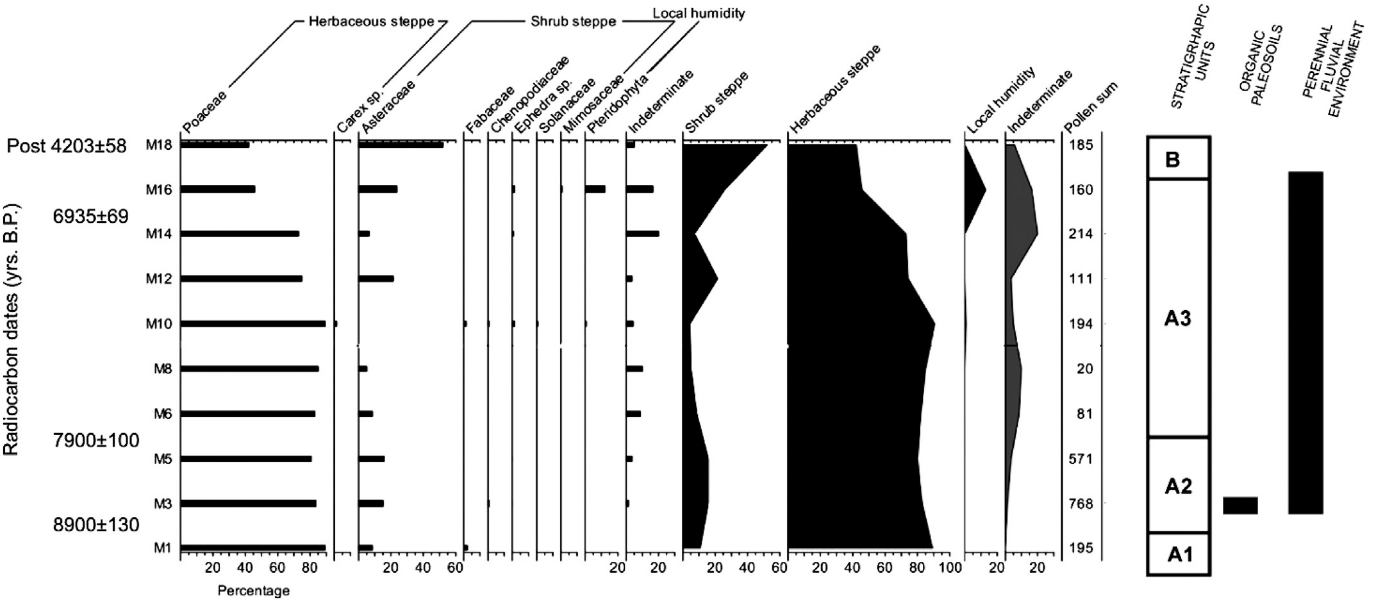

Fig. 5. Pastos Chicos pollen spectra and stratigraphic units.

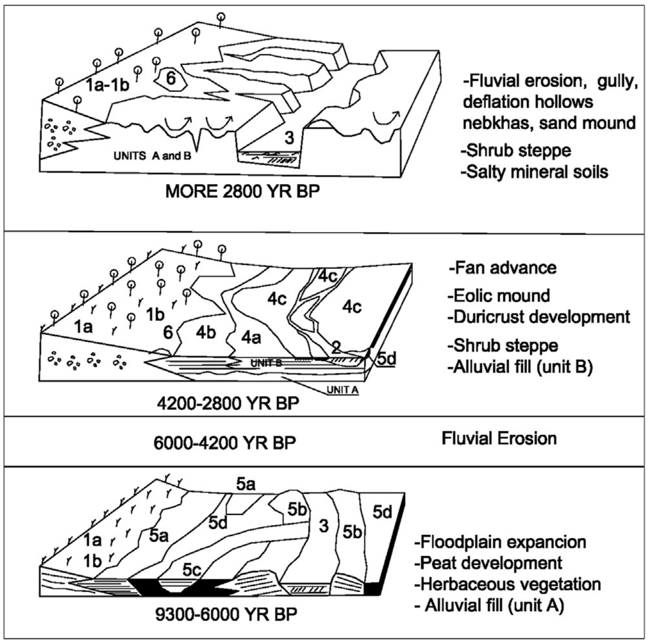

Fig. 6. Pastos Chicos valley geologic evolution and facies distribution.

the second environmental moment. Framed in these dry conditions, at least two moister events were detected, the first around ~7000 BP and the second one at 6300 BP (Fig. 4). Particularly dry conditions, probably the driest moment in the studied sequence, between 7500 and 7000 BP are also suggested in this allofacies, judging by the rise in aerophilic diatoms and the values of the salinity index obtained from the diatom ecological affinities.

4.2.2. *Unit B: Middle Holocene*

Any paleoenvironmental inferences from samples in section P1 from Units B and C must be taken with caution due to the low quantity of samples associated to each of them. However, the arid and slightly vegetated environment suggested by the diatoms analysis is clearly compatible with the transitional moment between the previous environment and an arid floodplain, as inferred by the geological studies.

4.3. *Pollen record*

Only ten of the fourteen samples collected in section P1 had enough material to be included in the pollen analysis. One division (Pteridophyta), six families (Poaceae, Asteraceae, Fabaceae, Chenopodiaceae, Solanaceae and Mimosaceae) and two genus (*Carex* sp. and *Ephedra* sp.) have been identified during this study.

In general terms, the Poaceae family dominated most of the pollen samples, with relative frequencies ranging between 80 and 40%, followed by Asteraceae (50–5%). Most of the other taxa are much less frequent (represented by less than 5%), with the only exception being sample M16 where Pteridophyta reached 15%.

4.3.1. *Unit A: Early Holocene and beginning of Middle Holocene*

Based on the changes in the frequency of pollen types, two major environmental phases were identified in section P1. The lower part, dating to between ~9300 BP and ~7000 BP, shows clear evidence of a humid environment, likely a paleowetland, with a clear dominance of herbaceous species (Poaceae) that represents the typical vegetation in higher settings today (>4000 m asl). At sample M10 (~7200 BP, Figs. 2and 5) an important change in the pollen spectra composition was detected, consisting of an increase in the diversity of pollen types, although the Poaceae family is still dominant. Towards ~7000 BP, the sequence showed a gradual and steady increase in the frequency and diversity of the regional vegetation, represented by shrub steppe species of Asteraceae, Chenopodiaceae, Fabeaceae, Solanaceae and Verbenaceae, over the local vegetation, represented by fern spores and grasses (Poaceae) that are indicative of moist conditions. Higher up, at sample M16 (~6300 BP) the pollen spectra reveal a noticeable change in the dominant species with a marked presence of the herbaceous steppe mainly composed of Asteraceae, Ephedra, and Mymosaceae, accompanied by Poaceae and Pteridophyta, a composition that had not been previously recorded, and indicating an increase in local humidity within a shrub steppe context. Sample M18, located above an erosive contact, and excluded in the age-depth model, probably corresponds to the Late Holocene and shows a trend similar to that of M16, with a strong presence of shrub steppe elements.

In short, pollen analysis suggests two different environmental phases in the Pastos Chicos record: a) the first, between 9300 and ~7000 BP, shows the dominance of an herbaceous steppe, indicating colder and moister conditions that might have produced a downslope advance (up to 500 m of variation) of herbaceous steppe vegetation, towards lower altitudes where nowadays a shrub steppe landscape dominates; b) the second phase, between ~7000 and 6300 BP, shows a clear increase in abundance and diversity of elements related to the shrub steppe, suggesting the gradual installation of a dry landscape, similar to the present day.

5. Discussion

The new information obtained from sediments, diatoms and pollen analysis, combined with the chronological controls, provide a base line for the reconstruction of successive paleoenvironmental change in the Pastos Chicos valley, illustrated in Fig. 6. Geologic data indicates that the Pastos Chicos River had a stable and perennial fluvial environment associated with extensive, densely vegetated areas during the Early to Mid-Holocene (*ca.* 9300 to 7300 BP; *ca.* 10,000–8700 cal. BP). During this period, the river seems to have been a low energy fluvial system with large back swamp areas associated with channels. The back swamps were replaced by wetlands that have produced hydromorphic green soils observed in the sedimentary sequence and crevasse splay fine sand sediments with high frequencies of littoral forms of diatoms, such as Fragilariaceae.

The source of fluvial peat sediments in geological records of the Atacama Desert has been highly controversial, with regard to the arid paleoenvironmental conditions traditionally accepted for the Mid-Holocene. Various authors provide explanations for the phenomenon. Grosjean et al., 2001, for example, explain peatbeds as local phenomena, resulting from geomorphic processes associated with locally higher groundwater table levels, only forming in some valleys. In contrast, Rech et al. (2002, 2003) interpreted them to be regional features, driven by a more humid climate. Servant and Servant-Vildary (2003) suggested that fluvial wetland environments would have developed under conditions of non-stormy type precipitations that would favored infiltration of meteoric waters and consequently improved the groundwater recharge. Another possible explanation is to relate peat formation to the dynamics of organic sedimentation currently observed above 4100 m asl in high Andean wetlands (*vegas*), such as those located in the Taire mountain range. There, moisture abundance is due to springs that permanently feed wetland systems. The main water sources are the combination of orographic rainfall (mostly restricted to austral summer) and the retention of moisture by almost permanently frozen soils (due to the cold conditions produced by altitude) that allow for relatively stable humid soils throughout the year. This hydrologic setting determines a low energy discharge and low seasonal variation in wetland streams, also reducing the erosion and inorganic deposition processes. The absence of the latter is mentioned as a necessary primary condition to allow organic soil development and paludization processes (*e.g.* Hall, 1990), whatever further controls on peat may function.

Therefore, facies 5d at P1 represents a fluvial system that was mainly sustained by a seasonal, but evenly distributed, low intensity precipitation regime during the Early Holocene. This interpretation is consistent with pollen information that shows grasses as almost the unique pollen type during this period, indicating the proliferation of highland vegetation that is located today above 4000 m asl, where temperature is lower and humidity is higher and more evenly distributed throughout the year. The organic fluvial paleosols and the paludal sediments (facies 5d, Table 3) of the Pastos Chicos record have formed in a river that had: 1) a perennial discharge with low volume and variability, 2) a low sedimentation and low energy fluvial process in an alluvial floodplain, 3) shallow and stable groundwater levels (located <0.1 m depth), 4) high primary productivity and biomass (indicated by the presence of peat sediments, grasses pollen, ferns spores and epiphytic diatoms), and 5) a flow similar to the river's equilibrium profile (not incising its channel too much, and creating a broad, relatively thin spread of overbank deposits). Presently, these conditions are frequently found in many valleys of the high drainage basin located above 4000 m asl.

The suggested role of equilibrium profile conditions in the origin of wetlands such as those of this locality was discussed by the 'base-level model' established in North America decades ago (Bryan, 1941; Antevs, 1954; Haynes, 1968; Waters and Vance Haynes, 2001; Quade et al., 2003). In this model, the causes of aggradation and/or erosion of wetlands are controlled by the depth of water tables and the resistance of alluvial inorganic or organic sediments. Wetland environments controlled by high water-table densely vegetated and with cohesiveness of wet and fine-grained sediments generates deposits that are relatively resistant to erosion when water tables are high. In contrast, when water tables are low hydromorphic vegetation dies, organic soils dry and the deposits become much more susceptible to water and eolian erosion. In this case, the alluvial organic sediments are easily incised by water, which form channels in sediments and, consequently, increase the erosive power of the stream (Rech et al., 2003).

Several paleoenvironmental records in central Andes have evidence of grassland and peat development during the Early Holocene (Geyh et al., 1999; Rech et al., 2002; Grosjean et al., 2005; Maldonado et al., 2005; Nester et al., 2007). These dates clearly overlap with the ages of units A of the present study (~8700–10.000 cal. BP) and indicate that an important climate change occurred at regional scale in the tropical Andes.

Between 7300 and 6000 BP (~8100–6800 cal. BP), the Pastos Chicos River had a broad backswamp area with several oxbow lakes that silted up with green clays and white structureless diatomite mud (facies 5c, Unit A3). During this period, the river showed a perennial flow regime and high sinuosity in the formation of channels. The pollen data show an increase in species abundance around 7300 BP (M10) and a gradual but steady trend towards drier conditions, illustrated by the rise in shrub steppe elements, probably interrupted by short term events (i.e. centennial or decadal) of increased moisture, as inferred from the diatom record (for example those occurred around 7000 and 6300 BP). The existence of hydromorphic and bioturbated oxbow deposits in geological records in desert areas usually indicates higher levels of groundwater tables in valleys due to climatic conditions, perennial discharge, meandering streams and fine (mud and clay) sedimentation. Local closures of fresh or brackish waters are required to form the diatom wetland deposits observed, but local water depths need not be more than 1 m (Quade et al., 2008). Similar meandering river sediments have been documented in Rio Desaguadero valley (Baucom and Rigsby, 1999; Rigsby et al., 2005), and were interpreted as reflecting periods of increased effective moisture on the Altiplano.

Around 6000 BP the oxbow lake had mostly filled and shallowed and began to dry out, in coincidence with the increase in shrub steppe pollen taxa and the rise in the salinity index of diatoms. The punctual increase in *Pteridophyta* pollen around 6300 BP (M16) is interpreted as related to channel migration. Between 6000 and 4200 BP (~6800 and 4700 cal. BP), the perennial Pastos Chicos River was incised and large wetlands of unit A were degraded. The gradual increase in pollen of shrub steppe (M14–M18) and the absence of peat sediments until downcutting suggests a decrease in vegetation cover and sediment supply. This implies that the downcutting of Pastos Chicos was associated with a more arid phase. The existence of such a phase is also evident in other areas of Andean highlands such as Desaguadero River (Rigsby et al., 2005) and in other deserts (Bull, 1997).

After this erosive phase, the paleoenvironmental conditions seem to have changed radically. A first episode of high energy channels deposits accumulation (unit B1) occurred, followed by another one of green mud and peat dated ~4200 BP. The pollen and soil data obtained from profile P1 indicates brief wetland formation and biomass recuperation in the beginning of the Late Holocene. Afterwards, a dry-mud, flat environment (unit B2) with small peat patches developed between 3060 and 2800 BP (~3300–2900 cal. BP). The sedimentology of unit B2 is similar to that located in the northern section of the Pastos Chicos basin, where a playa lake system was surrounded by alluvial cones. During Late Holocene, the dry mud-flat system seems to have occupied the entire northern and southern Pastos Chicos sections. Fining-upward sequences such as the ones preserved in facies 4a and 4b generally result from sedimentation in distal alluvial fans. The thin laminae mud and very fine sand of this facies may record individual fan sheet-flood and inundation cycles and are probably related to regional dryness with a low precipitation frequency and an increase in storm precipitations (Servant and Servant-Vildary, 2003). These conditions were related to rapid fluctuations in alluvial fan discharge, high rates of fine lateral supply sediment and the poor erosional capacity of the Pastos Chicos River.

The final overbank infilling was represented by nodular calcretes and carbonate-gypsum laminated deposits that were accumulated in ephemeral shallow ponds or in small salt lakes. In some places (profile P6), shallow ponds have deposited laminated diatom layers or green mud, and during dry phases they have also developed poor organic soils. Finally, after ~2800 BP, characteristics similar to the present have been observed in the geological record, showing valley incision accompanied by the formation of fluvial terraces composed by light, coarse sands and fine gravels, evidently different to those previously analyzed for the Early and Mid-Holocene (i.e. 9300–6000 BP).

In sum, the fluvial evolution proposed for Pastos Chicos system seems to have been associated with an important geo-ecological change in the Puna, due to modifications of the boundaries of altitudinal vegetation zones within the Holocene. Several other paleoenvironmental archives show grassland and peat developments during the Early Holocene and beginnings of Mid-Holocene. The Quebrada Lapao record, located 40 km further north, showed peat soil and paleowetland developments between 9380 ± 110 and 7550 ± 90 BP (Yacobaccio and Morales, 2005; Morales, 2011). The Aguilar record, located almost 300 km away in the eastern Dry Puna border, has grassland pollen taxa from Late Pleistocene to *ca.* 7500 yr BP, followed by shrub taxa (Markgraf, 1985). These changes seem to have been linked to major modifications in climate that affected the abundance and distribution of rainfall along the year, which in turn affected erosion, sediment supply and water discharge, especially in sources of fluvial drainage systems located in high locations.

6. Conclusion

The sedimentary history of the Pastos Chicos river floodplain provides a record of local to subregional landscape evolution in the dry Puna of Argentina during the Early to Late Holocene. The sedimentary, pollen and diatom records indicate a paleohydrological change along the Holocene and its impact on vegetational assemblages and their evolution. This paleoenvironment was a meandering stream with extensive wetlands and oxbows in the floodplain associated with a grassland steppe during the Early Holocene and the beginning of the Mid-Holocene (9300–6000 BP), followed by fluvial erosion in a shrub steppe context (during the second half of the Mid-Holocene), changing to a playa lake and alluvial fan system associated with shrubland between 4200 and 2800 BP at the onset of even drier conditions.

Summing up, the observed changes indicate that the landscape during the first half of the Holocene may have been very different from today. These paleoenvironmental changes have probably generated a drastic modification in human organizational patterns due to restructuring of resources. In this way, water, pastures and, consequently, potential hunting preys seem to have been much greater during this span (9300–6000 BP) than in recent times, including the most arid phase (7500–6000 BP). In archaeological terms, the occurrences of peat and perennial water environments located in the Pastos Chicos valley suggest potentially rich habitats that probably attracted fauna, particularly camelids, allowing the occupation and/or exploitation by hunter–gatherers. These kind of linkages have been already detected in some localities in the North Chilean slope of the Andes, where initial human occupations seem to have been chronologically related to regional favorable environmental conditions recorded by paleolake sediments, fossil groundwater bodies, multi-proxy cores, and paleosol studies (Messerli et al., 1993; Nuñez and Grosjean, 1994; Geyh et al., 1999; Núñez et al., 1999, 2002; Rech et al., 2002; Ramirez et al., 2003; Grosjean et al., 2005; Maldonado et al., 2005; Nester et al., 2007). This initial stage in human occupation of the area during the final Pleistocene and the beginning of the Early Holocene only took place when the Puna area became an attractive landscape in terms of critical resources for human populations.

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