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The mid to late Holocene transition in Barrancas, Jujuy, Argentina: Regional climate change, local environments and archaeological implications

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ABSTRACT

This paper presents the preliminary results of a multiproxy analysis of the Cruces 2 record (PCC2), located in the area of Barrancas, Dpt. of Cochinoca, Province of Jujuy, Argentina. Our studies included geomorphology, organic matter and carbonate content, magnetic properties of sediments, diatoms and pollen analysis, with the purpose of exploring the environmental characteristics of the locality from the mid- to late Holocene transition (ca. 4500 BP) to 1000 BP. This research contributes to an ongoing effort to model resource structure during the Holocene in the South-central Andes highlands of Argentina, thus allowing a more informed debate regarding the availability, distribution and characteristics of human habitats in this region, contributing to predict and explain patterns in the archaeological record both at regional and local scales.

The PCC2 record indicates that the mid- to late Holocene transition in the locality implied a change from more regionally dry and mostly stable conditions to more humid but unstable conditions. During the regionally wetter late Holocene the energy of the Barrancas hydrological system increased, including frequent torrential events, but these conditions were punctuated by discrete, recurrent and/or intense regionally dry episodes. Locally, these dry events manifested as episodes of paludization/paleosoil formation in Barrancas and other localities of the dry Puna, which took place at 3260, 3000, 2500, 2100, 1490/1460, and 1050 cal BP.

The consolidation of a group of cultural traits locally known as “the Formative Period” in the South-central Andes – village settlements, pottery, agriculture and/or pastoralism - may have been part of a sociocultural strategy to cope with resource uncertainty and economic risk brought on by late Holocene environmental instability from ca. 3500 BP on.

1. Introduction

Previous works have shown the utility of paleoenvironmental studies in setting high-resolution environmental scenarios for the past in order to model hunter-gatherers strategies and decision-making during the Holocene (e.g. Morales et al., 2008; Morales, 2011; Tchilinguirian and Morales, 2013; Yacobaccio and Vilá, 2013; Oxman and Yacobaccio, 2014; Tchilinguirian et al., 2014a, b; Hoguin and Oxman, 2015; Oxman et al., 2016). From this perspective, paleoenvironmental studies are not a mere complement of the archaeological evidence, but a useful methodological tool to model human social organization and expected archaeological patterns.

The Barrancas Archaeological Project has recently begun exploring the paleoenvironmental evolution of the area of Barrancas (Dpt. of Cochinoca, Province of Jujuy, Argentina; S 23°18′08,7; W 66°05′15,2; 3666 m a.s.l.) throughout the Holocene (Bustos et al., 2016; Oxman, 2016). These studies aim to contribute to the modeling of past human habitats in the Dry Puna of Argentina, their availability and characteristics, drawing on pre-existing regional environmental archives and the analysis of local sedimentary sequences.

In this paper, we present preliminary results of the study of the Cruces 2 record (PCC2), including an estimation of organic matter and

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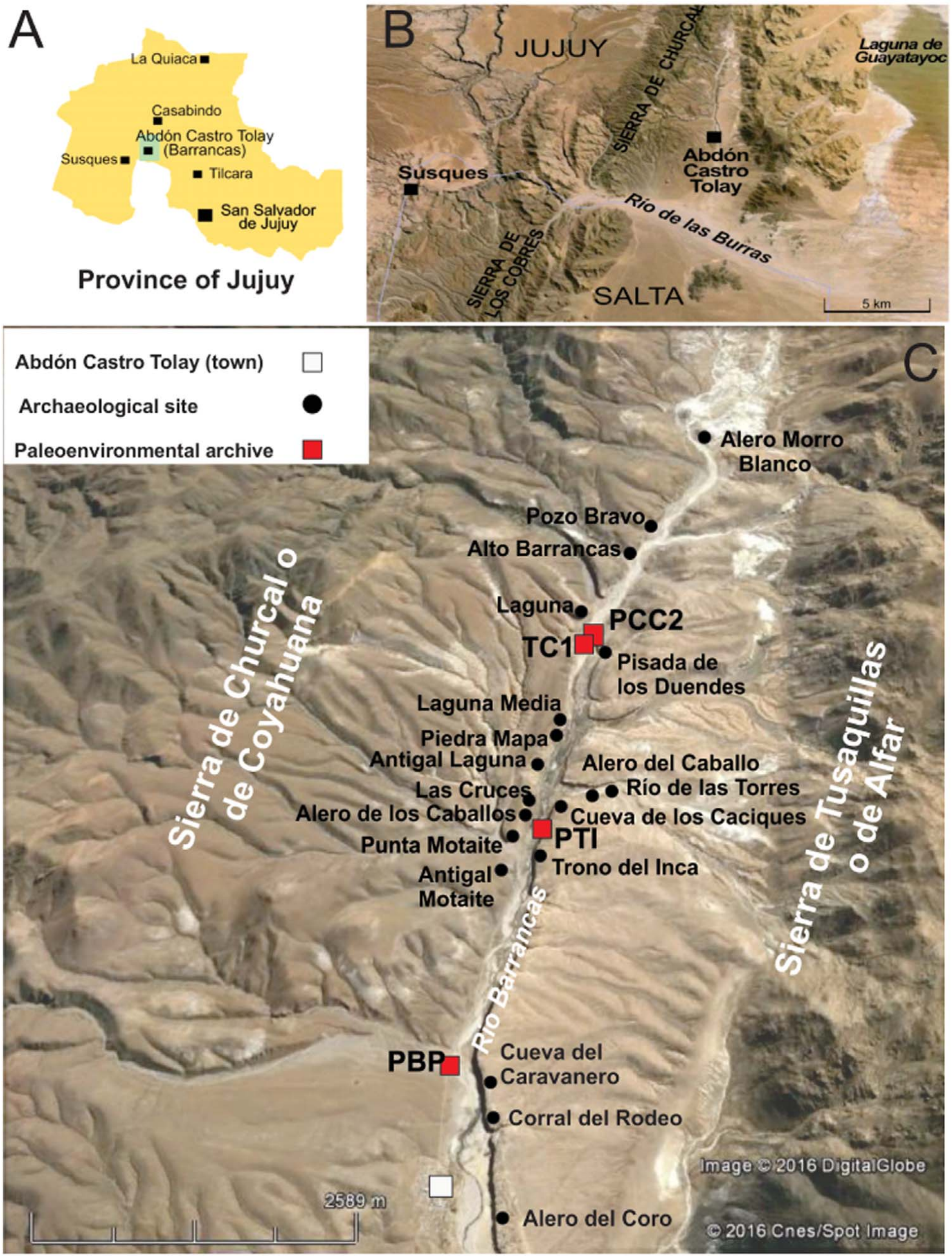

Fig. 1. A) Location of the study area within the province of Jujuy, Argentina. B) Location of the Barrancas river basin and Barrancas-Abdon Castro Tolay. C) Map of archaeological sites and paleoenvironmental archives in the Barrancas river basin. TC1: Testigo Cruces 1. PCC2: Cruces 2 profile. PTI: Trono del Inca profile. PBP: Barrancas Pueblo profile. Image source: Google Earth. 23°18′42.09″S; 66°03′24.81″W. October 16, 2014 (accessed April 11, 2017).

carbonate content, description of magnetic properties, diatoms and pollen analysis. Due to the chronology represented in this record the results presented here allow for the preliminary discussion of the characteristics of the mid/late Holocene transition in the locality, in the context of the available regional paleoenvironmental models (Rodbell et al., 1999; Bradley, 2000; Riedinger et al., 2002; Thompson et al., 2006; Reese et al., 2013). We expect this further refinement of paleoenvironmental models to increase our knowledge of resource structure during the mid- to late Holocene transition and later, thus allowing a more informed debate regarding the availability, distribution and characteristics of human habitats in the Argentine Dry Puna along the Holocene, and consequently, contributing to predict and explain patterns in the archaeological record of the region and the locality of Barrancas.

1.1. The Puna ecosystem

The Puna of Argentina constitutes the eastern sector of the Puna of Atacama, located between 19° and 27° S and between 3000 and 4500 m a.s.l. It is a high Andean plateau crossed by NE-SW mountain ranges (Fig. 1) and defined as a highland desert biome, characterized by high solar radiation, low atmospheric pressure and low mean annual precipitation, which varies from > 300 mm/year in the northwestern sector of the region ("Dry Puna") to < 100 mm/year in the southeast ("Salt Puna"); approximately 80% of the total annual rainfall occurs between December and March, governed by the South American Monsoon System (Zhou and Lau, 1998; Vuille and Keimig, 2004). Precipitation also varies along an altitudinal gradient; for similar latitudes, rainfall increases with altitude. Because of its aridity, fresh water is the critical resource for past and present human populations in the Puna. A few permanent freshwater basins, salt lakes, pans and playas constitute the general hydrological landscape. Primary productivity is mainly concentrated on stable systems like primary basins, high valleys and wetlands (Dollfus, 1991).

The environmental conditions of this biome result in a patchy distribution of vegetal and animal resources in both the Dry and Salt Puna.

Three general plant communities can be identified (Cabrera, 1976; Arzamendia et al., 2006; Borgnia et al., 2006): the shrub steppe (*Tolar*), located between 3500 and 3900 m a.s.l.; the herbaceous steppe (*Pajonal*), located between 4100 and 4700 m a.s.l.; and wetlands (*vegas*). Ecotonal belts between the shrub and the herbaceous steppe are located between 3900 and 4100 m a.s.l.

Wetlands, or *vegas*, are dense and discrete grasslands with high vegetation coverage and high primary productivity, frequently associated to palustrine water systems; their springs and headwaters are mostly located between 4100 and 4500 m a.s.l. and are usually fed by small groundwater reservoirs. *Vegas* play an essential role in water supply and storage in the Puna because of the soil development processes that occur within their limits and the stability of their vegetation (Schittek et al., 2012). Therefore, they represent a critical feature in the Puna landscape as the foci of ecosystem services for both animal and human populations, particularly since they occur along the whole altitudinal range of the Puna. From an Environmental Archeology point of view, the ability to model human mobility patterns and resource exploitation in the Puna landscape in the past depends on achieving better understanding of the variations in wetland availability and their characteristics along the Holocene.

1.2. The Puna landscape during the Holocene

Past environmental conditions during the Holocene in the South-central Andes have been extensively studied in the past two decades. In broad terms, there is a general consensus that during the early Holocene (10000–8000 BP) the Puna was probably moister, colder, and more homogeneous than today (Thompson et al., 1995; Grosjean et al., 1997; Thompson et al., 1998; Geyh et al., 1999; Thompson et al., 2000; Bradbury et al., 2001; Abbott et al., 2003; Ramírez et al., 2003; Thompson et al., 2006); with a weaker seasonality in rainfall and a low to moderate frequency in short-term climate variability (Morales, 2011).

The general environmental conditions of the mid-Holocene in the area have been a subject of debate (Grosjean, 2001; Grosjean et al., 2003; Latorre et al., 2003, 2006). However, we consider that there is enough evidence to support a general trend towards aridization during the mid-Holocene (8000–3500 BP) that caused hydrologic stress in the south-Central Andes and Northwestern Argentina (Tchilinguirian and Morales, 2013). This general trend notwithstanding, the mid-Holocene may be divided into two periods. The 8000–6000 BP span may be characterized as a "transitional" phase, where several localities with high groundwater levels - reached during the early Holocene - allowed the permanence of wetlands until at least ca. 7000 BP (Grosjean, 2001; Servant and Servant-Vildary, 2003; Yacobaccio and Morales, 2005; Tchilinguirian, 2009; Tchilinguirian et al., 2014a). In contrast, the second half of the mid-Holocene - between 6000 and 3500 years BP - seems to have been extremely arid and somewhat more variable in the short term in a regional scale. Paleoenvironmental records information on this period are scarce in the Argentine Puna; most of the information on past Puna environments must be derived from regional models developed from Peruvian and Bolivian ice core records and high Andean lake cores.

The late Holocene (3500 years BP - present day) was probably colder and more humid than the mid-Holocene (Grosjean, 2001) and coincides with the onset of the current characteristics and periodicity of ENSO (El Niño Southern Oscillation) events. The Huascarán and Sajama Ice Cores show clear evidence of wetter and colder conditions beginning at ca. 4000 years BP (Thompson et al., 1998, 2000; 1995). Titicaca lake levels, which are a good proxy of moisture balance in the region, show a strong increase ca. 3000 BP from the previous low stand conditions (Abbott et al., 1997). High-resolution records such as Quelccaya Ice Cores have allowed the identification of the Medieval Climate Anomaly (MCA) from 1100 to 1300 CE, characterized by more variable and slightly higher $\delta^{18}O$ values (Thompson et al., 2013), which is indicative of warmer and drier conditions for the area, compared to the following period – Little Ice Age - or even to modern times (Diaz et al., 2011).

1.3. Archaeological background

The earliest human occupation of the Argentine Dry Puna is recorded at ca. 11000 BP (Aguerre et al., 1973; Hernández Llosas, 2000). These groups were probably small and highly mobile, although they used particular rockshelters and caves recurrently within their annual mobility cycle (Yacobaccio and Vilá, 2013). The archaeological record shows an increase in intensity and recurrence of occupations of the region during the early Holocene, followed by a sharp reduction in the number and continuity of archaeological sites during the mid-Holocene, probably linked to the process of aridization documented in Section 1.2 (Yacobaccio et al., 2016b). Particularly from 6000 BP on, environmental stress may have triggered a series of organizational responses among human groups in the Puna, namely a reduction in residential mobility coupled with an increase of logistic mobility components (Yacobaccio and Morales, 2005) and progressive specialization and intensification of camelid exploitation (Aschero and Martínez, 2001; Yacobaccio et al., 2001) which would eventually lead to the development of a camelid domestication process between 6200 and 3500 BP (Yacobaccio et al., 2001; Yacobaccio and Vilá, 2013). These processes prompted increasing social complexity among hunter-gatherers (Morales, 2011), the introduction of ceramic technology (ca. 2900 BP) and the development of village-settled communities in the Puna (ca. 2100 BP) (Morales et al., 2009).

The area of Barrancas, were the Cruces 2 Profile is located, must be understood as part of this overall sequence of social change in the Puna of Jujuy. Although our research in this area is still at an early stage, and therefore results are preliminary, radiocarbon dates indicate that Barrancas and its surroundings has been at least intermittently occupied throughout the Holocene. Three dates – ca. 2250, 2800 and 3200 BP - were obtained for occupations of the Morro Blanco rockshelter, located near the headwaters of the Barrancas river. Morro Blanco presents rock art, pottery sherds – most of them very similar to the Chilean Los Morros type ceramics (Agüero and URIBE, 2011) - and lithic artifacts. Punta Motaite is a large open-air site where 37 structures were identified, most of them circular. Pottery sherds, ceramic pipe fragments and triangular pedunculated lithic projectile points were recovered from surface collection and excavation. We have obtained a date for this occupation at ca. 1800 BP. Other sites in the Barrancas area have been chronologically situated based on characteristics of the lithic technology and correlation with other well-dated sites in the region. For example, the occupations at Laguna Media 7 have been assigned to the mid-Holocene, probably between 6000 and 4000 BP (Yacobaccio et al., 2016a).

Thus, the research of archaeological and paleoenvironmental records in this area is of utmost importance to contribute to the small corpus of evidence available for the mid- to late Holocene transition in the Puna of Jujuy.

2. Materials and methods

2.1. Geological setting

The locality of Barrancas (also known as Abdón Castro Tolay), Jujuy Province, is located in the Dry Puna and its summer precipitation reaches 180 mm/yr. The town of Barrancas-Abdón Castro Tolay is located in the right margin of Barrancas River, a tributary of Las Burras River, which drains into Salinas Grandes basin. Several archaeological sites and paleoenvironmental archives are under study by the research team (Fig. 1). The Barrancas river catchment has 190 km^2 (Fig. 2) and its flow depends heavily on the seasonal precipitation regime. This river presents sharp flow increases during summer, but it remains dry for the

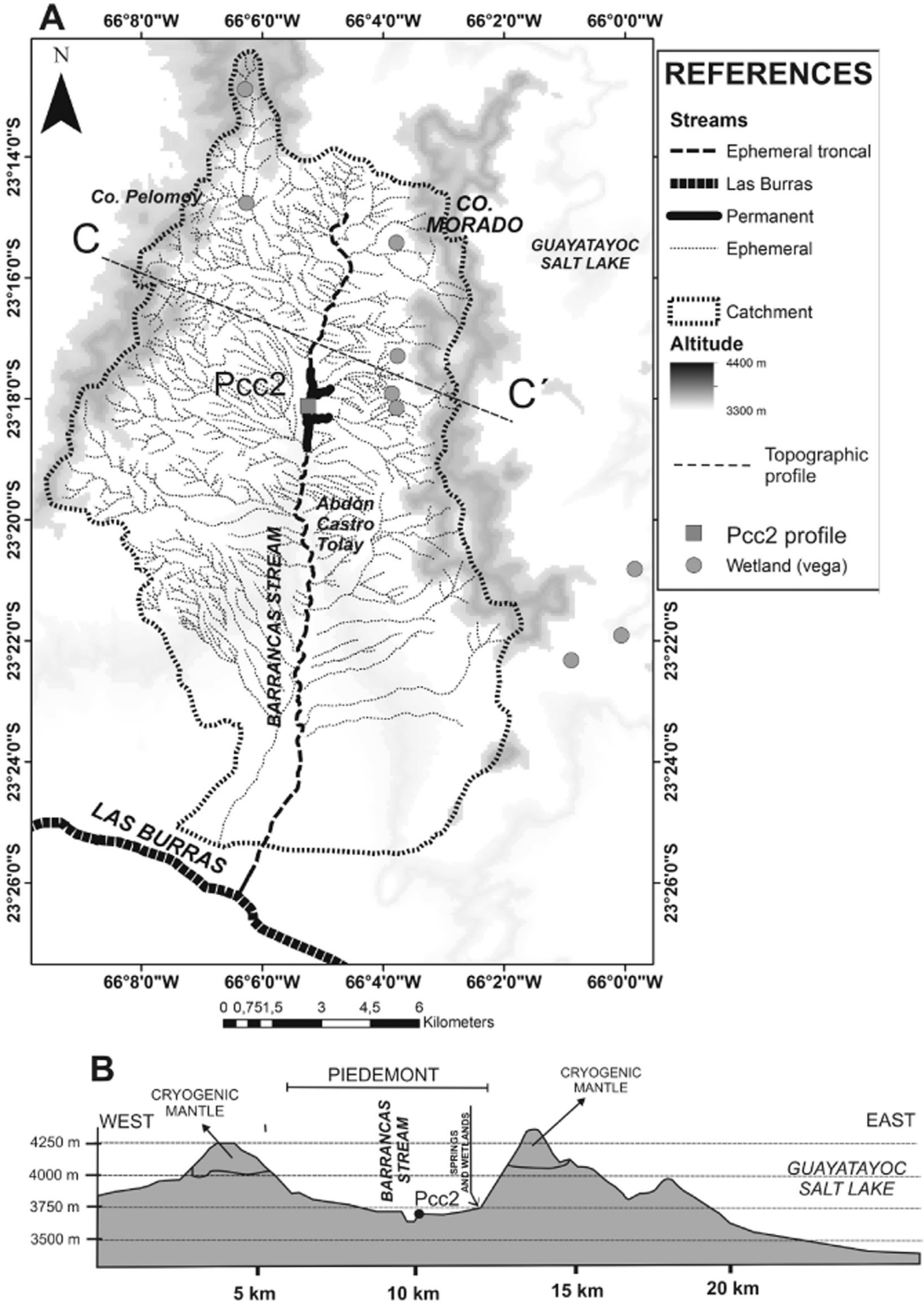

Fig. 2. A. The Barrancas river basin. B. West to east profile (C – C′ in panel A) of the Barrancas area.

most part of the year, with the exception of the mid-course, which presents a limited but permanent flow in the narrowest portion of the canyon, where two other affluents with groundwater charge come together and the alluvium is thinner. There are a total of four springs in the western flank of the Tusaquillas range where groundwater surfaces along fractures in the igneous rocks, creating small wetlands spanning an approximate 0.8 km^2 each (Fig. 2). Four fluvial terrace levels were detected. The highest terrace (+ 9 m above riverbed, Allounit A, Fig. 3) is the most extended. The other terraces, intermediate (+ 6 m, Allounit B, Fig. 3) and low (+ 3 and + 2 m, Allounits C and D, respectively, Fig. 3) are odd erosion terraces associated to fast excavation by the fluvial system.

2.2. The Cruces 2 profile

The sedimentary profile Cruces 2 (PCC2) is located in the mid-course of the Barrancas River, with an upstream catchment area of approximately 54 km^2. At this site, the river flows along a valley 450 m-

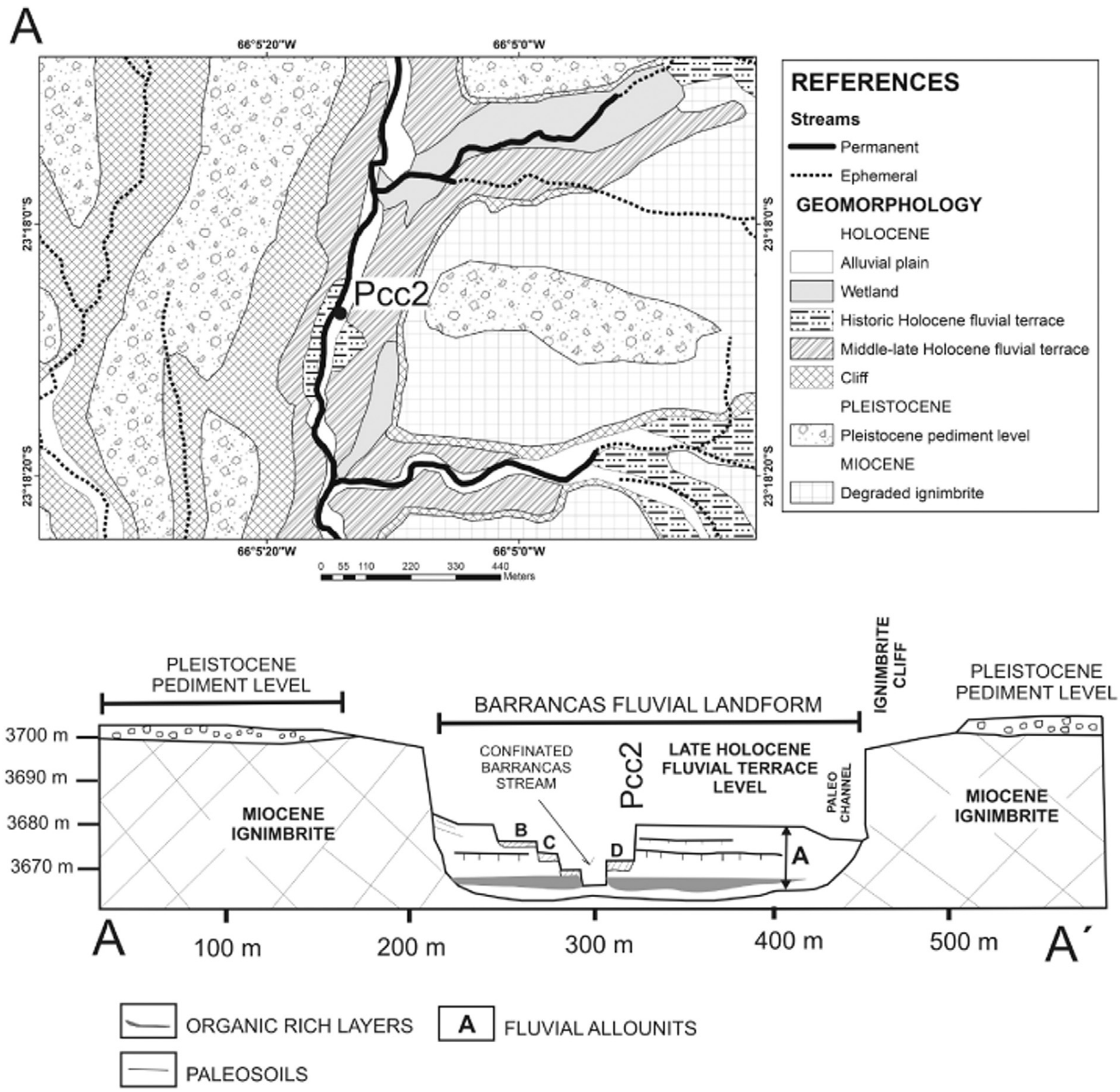

Fig. 3. Geomorphology and fluvial Allounits in PCC2.

wide and 20-m deep, cut into Miocene ignimbrites covered by thick Pleistocene piedmont deposits (Fig. 3). PCC2 is a 765-cm high exposed profile of an alluvial terrace that rises to 12 m above the river bed. A total of 74 samples was extracted from PCC2 (1 every 10 cm). Up to now we have obtained two radiocarbon dates from peaty sediments in PCC2: 4510 ± 80 BP (LP2799; 2σ 4887–5347 cal BP; midpoint 5117 cal BP) and 2080 ± 80 BP (LP2925; 2σ 1881–2291 cal BP; midpoint 2086 cal BP). The former was obtained from the bottom section of the sequence and the latter at a depth of 450 cm, which indicates that PCC2 is representative of the mid- to late Holocene transition and at least the first half of the late Holocene. Due to insufficient organic content materials and the presence of several erosion unconformities we have not been able to obtain other dates for this sequence; however, specific geomorphological events recorded in this sequence have been dated by stratigraphic correlation to other sedimentary deposits dated in nearby sites of the same basin (Fig. 1). The earliest date in PCC2 falls within the latest chronology of the Cruces 1 core, which was extracted from the Barrancas river bed (Morales et al., this volume), suggesting that the lowest section of PCC2 corresponds to the top section of the Cruces 1 core.

2.3. Methods

The geomorphology of the Barrancas River basin was studied through satellite imagery interpretation (Landsat and higher resolution Google Earth TM images) and terrain survey. The stratigraphy of PCC2 was studied following Miall (1982, 1996) and Friend (1983), describing the lithofacies grain size, sedimentary and soil structures and color. Those lithofacies were associated to local sedimentary facies in order to interpret the general sedimentary environment.

Determination of organic matter (OM) and carbonate content (Ct) was conducted on the full sample set (n = 74) by loss on ignition (LOI), using a muffle furnace at 390 °C for 16 h (OM) and 950 °C for 2 h (Ct) (Pirola, 2014). Samples were previously pulverized in a ceramic mortar and dried overnight at 95 °C.

Magnetic properties were also measured on the 74 samples, which were previously air-dried and pulverized in a ceramic mortar. Initial mass magnetic susceptibility (χ) was measured with a Bartington MS2 instrument while magnetic hysteresis cycles were obtained using a Molspin Ltd. vibrating sample magnetometer. Hysteresis curves provide bulk magnetic parameters, such as saturation magnetization (Ms) and saturation remanence (Mrs), and grain-size related parameters, such as coercive force (Hc) and coercivity of remanence (Hcr). Frequency dependence at room temperature and variation of magnetic susceptibility at high temperatures were determines using a Kappa Bridge susceptometer.

Pollen content was analyzed in 28 samples from the bottom and the top of the sequence. We followed the standard procedures for Quaternary pollen analysis (Faegri et al., 1989). Between 190 and 200 grains of pollen were counted for each sample because pollen concentrations in these samples were extremely low. Between 4 and 8 slides were prepared and observed per sample to reach this pollen count. Pollen count and taxonomical classification was conducted using a Zeiss-Axiolab optical microscope under 400 and 1000 ×. 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). Pollen zones were determined by CONISS stratigraphically constrained Cluster Analysis (Grimm, 2004).

The diatom analysis was performed only on the bottom 330 cm of the sequence (samples M0 – M33) following the standard procedures described by Battarbee (1986). Samples were observed using OM (1000 ×) and SEM (30,000 ×) and taxonomic classification was carried out on 300–400 valves in each slide based on the monographic works of Levkov et al. (2013), Krammer & Lange-Bertalot (1991-6), Round et al. (1990), Rumrich et al. (2000) and literature specific to the Argentine Puna (Maidana et al., 1998; Seeligmann and Maidana, 2003; Maidana and Seeligmann, 2006; Seeligmann et al., 2008; Maidana et al., 2009, 2011; Grana et al., 2016). Ecological affinities were assigned following the works of Lowe (1974), de Wolf (1982), Vas and De Wolf (1993) and Van Dam et al. (1994), as well as literature specific to certain taxa (e.g. Levkov et al., 2013). An index constructed with the ratios of diatom taxa with different life-forms [(Benthic + Epiphytes + Planthonic)/ Aerophiles], and specific ecological information of relevant species were used for the environmental reconstruction.

Due to time and methodological constraints, biological proxies – diatoms and pollen - have only been analyzed in a subset of PCC2 samples. For this reason, sedimentology/geomorphology, magnetic properties and OM/carbonate content results constitute the focus of our paleoenvironmental discussion, complemented by diatoms and pollen results when available.

3. Results

3.1. Stratigraphy

Holocene deposits consist of 4 allounits separated by erosive cut and fill surfaces (type 4 discontinuity sensu Miall, 1996, Fig. 3). Allounit A comprises paleosoils and fluvial sediments of the + 9 m fluvial terrace. Allounits B, C and D consist of coarse, well-stratified sediments that form the intermediate and lower fluvial terraces. These deposits are 1 to 2.5 m thick and are separated from Allounit A by an erosive unconformity. Their age is post-1000 BP. The PCC2 sequence presented here corresponds to the 9 + terrace (Allounit A, Fig. 4). PCC2 sediments present 16 lithofacies (Table 1, Fig. 5), grouped into 7 facies (Table 2) representing channel fill deposits (Facies 1a and 1b), floodplain deposits (Facies 2, 3, 4 and 5) and aeolian sheets (Facies 6).

Allounit A (+ 9 m terrace) consists of six sedimentary subunits (allounits A1, A2, A3, A4, A5 and A6), each corresponding to fluvial events separated by erosive discontinuities (Fig. 4). These surfaces extend hundreds of meters up and downriver from the PCC2 site. Erosion surfaces are generally flat, except for the base of the last fluvial event (Allounit A6) which presents a cut and fill shape, cutting at least 2 m into Allounit A5 (Fig. 5).

Allounits A1 and A2 are 2 m-thick, composed by dark-greenish bioturbated sands, organic paleosoils and laminated clays with organic matter (Facies 1a), including vascular plant fragments (1–2 mm). A1 and A2 outcrops could be identified 800 m down and 400 m upriver from the PCC2 site. These organic-rich layers correspond to a permanent fluvial system that had multiple, thin channels, and small water bodies with riparian vegetation. Permanently high and stagnant groundwater prompted the development of organic or peaty material layers (fens) and created a reducing environment, resulting in olive-green sediment colors due to formation of Fe^{2+} and Fe^{3+} hydroxyl salts. Paleoenvironmental proxies studied for Allounits A1 and A2.1 are not presented here, because they are not exposed in the PCC2 profile site. Instead, they appear as buried levels recovered from the Cruces 1 core (Morales et al., this volume). However, for greater simplicity and in order to provide the full geological context for PCC2, we present a detailed stratigraphy of the complete sequence as a provisional composite of TC1 and PCC2 in Fig. 5.

Allounit A3 is a 1.6 m-thick upward fining sequence of very coarse basal sands (facies Sp, Sh) and greenish bioturbated clays (facie Fb) culminating in a sandy, fine-grained paleosoil (FOb), with a dark color and a well-developed medium block structure with abundant roots (SOb). This paleosoil is 0.2 m-thick, of the mineral-humic type, dated to approximately 2100 BP. This unit was also identified up to 400 m upriver and downriver from PCC2. Allounit A3 corresponds to a sinuous fluvial environment that evolved into a floodplain. The floodplain sustained the formation of backswamp hydromorphic fine soils associated to shallow water tables. An alluvial, humic soil formed towards the end of this cycle, associated to slightly lower water tables, compared to the previous phase. This soil includes a higher proportion of sand, which is indicative of a proximal overbank environment (near an active channel).

Allounit A4 consists of a 1.5 m-thick fine gravel facies with a high proportion of sand (lithofacies Gh, Gp, Sh) of well stratified, light yellow to light brown channel fill deposits (bars). Yellowish mottles and concretions (typical of goethite) and root traces (0.3–0.5 mm diameter and 2–10 cm long) are common in this facies. These deposits are overlain by dark gray, fine clay and very fine sand layers that evidence intense bioturbation and a great number of root traces. Organic matter lenses up to 2 m–long also occur in this Allounit. 1300 m downriver and 400 m up, these facies appear as mineral paleosoils. These facies were deposited by a permanent, moderate energy fluvial system with braided channels and shallow water tables, which caused the formation of goethite in the capillary fringe. Later in the same phase the system lowered its energy giving rise to wetlands and paleosoils that supported abundant vegetation.

Allounit A5 is 1.6 m–thick, composed by light colored, coarse, massive sediments with no signs of bioturbation. It presents carbonate concretions and calcic horizons. These features are indicative of an ephemeral fluvial system with prevailing aerobic conditions.

Allounit A6 (2 to 0.5 m-thick) is discontinuous and can only be observed in a few sectors. It consists of channel fill sediments 1.7 m-deep and 7 m–wide constituted by dark-colored sand and organic matter. Floodplain sediments – 0.5 m of sand and organic matter deposits - can also be observed to both sides of the channel. The deposition environment was probably a perennial, sinuous channel with a vegetated floodplain and small water pools.

A thin aeolian sheet (0.3–0.4 m) covers the alluvial terrace (facies 6, Table 2). Towards the ignimbrite slopes that limit the valley there are usually massive, colluvial-type deposits intercalated with the fluvial sediments.

Allounits B, C and D post-date the formation of Terrace I. They are 1 to 2 m-thick, coarse alluvial deposits composed of light-colored medium gravel and very coarse sand, which may contain intraclasts of the organic pelites found in Allounit A. There are no paleosoils, organic

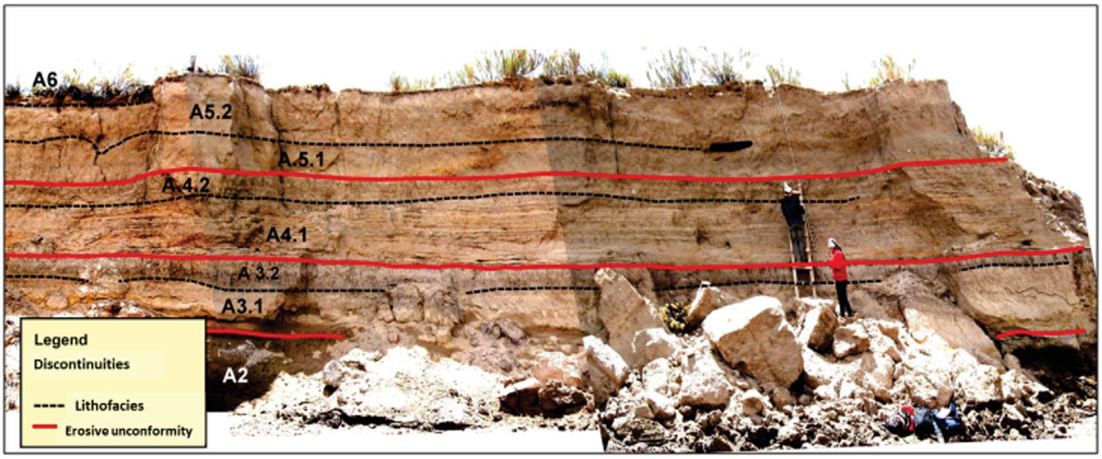

Fig. 4. PCC2 profile: Allounit A2 – A6 and erosion unconformities.

matter and fine sediments in these Allounits.

3.2. Organic matter (OM) and carbonate content

Both OM and carbonate content are low and stable throughout the sequence (mean = 2.11%; SD = 1.91% and mean = 2.85%; SD 3.02%, respectively). Three samples present extreme OM values: M2 (10.04%); M14 (10.47%) and M15 (8.11%). Isolated but extremely high carbonate values coincide with sectors of the sequence that presented carbonate concretions in samples M30 - M27 and M73 (Fig. 7).

From sample M56 up, both OM and carbonate contents were below the mean of the series, as was the case for the M33 – M42 and M03 – M12 segments. Samples between M20 and M32, in turn, presented generally high carbonate contents but low OM values.

3.3. Magnetic properties

Hc and Hcr values (Fig. 8), the shape of hysteresis loops (Fig. 9), frequency-dependent magnetic susceptibility and variation of susceptibility at high temperatures indicate that the prevailing magnetic fraction in the PCC2 sequence is either magnetite or titanomagnetite. The determined detritic magnetic mineralogy is consistent with those of the nearby source areas. Only one sample (M35), located above a sedimentary unit presenting iron oxide mottles, yielded high Hcr values. This is indicative of the presence of goethite in the M35 sample, which may have been formed during a relatively wet period by chemical weathering.

The Day plot of Mrs/Ms vs Hcr/Hc (Fig. 10) indicates that the dominant magnetic particle size is single domain with superparamagnetic particles (SD + SP). The source of SP particles may be linked to a) volcanic glass inputs or b) neoformation of SP magnetite associated to pedogenetic processes in subhumid to dry environments (mean annual precipitation < 700 mm; Orgeira et al., 2011). Both processes may be operating in different sections of the PCC2 sequence. A few samples (Fig. 10, red dots) fall within the boundaries of a mixed assemblage of single domain and multiple domain particles (SD + MD). As discussed in the article by Morales et al. (this volume), this type of mixed assemblage, with titanomagnetite with high Ti content, might be related to aeolian input of sediments eroded from the Coranzulí volcano basalt flows, located to the NW of the PCC2 site.

There are 3 sections of PCC2 characterized by higher values of extensive parameters (χ, Ms and Mrs, Fig. 8): M21-M31, M36-M41, and M56-M61. Since there is no associated increase of Hc and Hcr values, the increase of extensive parameter values may be interpreted as an increase in magnetic mineral content within these sections. Both the M21-M31 and M36-M41 sections underlie edaphized sedimentary levels. Thus, the increase of χ, Ms and Mrs values detected in these two sections could be associated to the lixiviation of superparamagnetic magnetite particles neoformed by edaphization processes. In contrast, the increase of extensive parameter values in the M56-M61 segment is more likely associated with an increased detritic input. These magnetic data are consistent with a grain increase in sedimentology (coarse sand

Table 1
Summary of litho-facies in the PCC2 sequence.

Facies code (modificated, Miall, 1996)	Description	Sedimentary structures	Interpretation
Gh	Gravel, clast supported (Fig. 6.a)	Horizontal bedding common clast imbrications	Channel fill, bar
Gmc	Gravel, matrix supported	Massive	Debris flows
Gt	Gravel, fine to medium	Trough crossbeds	Channel fills
Gp	Gravel, fine to medium (Fig. 6.a)	Planar crossbeds	Channel fill, bars
Sd	Fine gravel to coarse sand (Fig. 6.b)	Normal graded	Channel fill, bar
Sh	Sand, very fine to very coarse	Horizontal bedding	Channel fill, bar
Sb	Sand, very fine to very coarse	Massive, bioturbated	Mineral palosoils in overbank
Sm	Sand, very fine to very coarse with minor gravel	Massive	Sand flows
SO b	Sand, very fine to medium, black humic	Blocky aggregates	Mineral paleosoil in overbank
FO b	Mud and very fine sand, black humic	Blocky aggregates, bioturbated	Mineral humic paleosoil in overbank
SOh	Sand, black and green (Fig. 6.c)	Horizontally bedded, roots	Bar with organic and humic deposition
SOp	Sand, black and green	Planar crossbedding, roots	Bar with organic and humic deposition
F b	Mud and very fine sand (Fig. 6.d)	Massive, bioturbated	Mineral gley paleosoil in overbank
Fm	Mud, clay	Massive	Overbank, mudropes over bar
FO l	Mud and clay with organic lenticular layers (Fig. 6.e and f)	Laminar	Overbank with organic deposition
P	Carbonate matrix in gravel sand, white chromas	Massive	Paleosoil

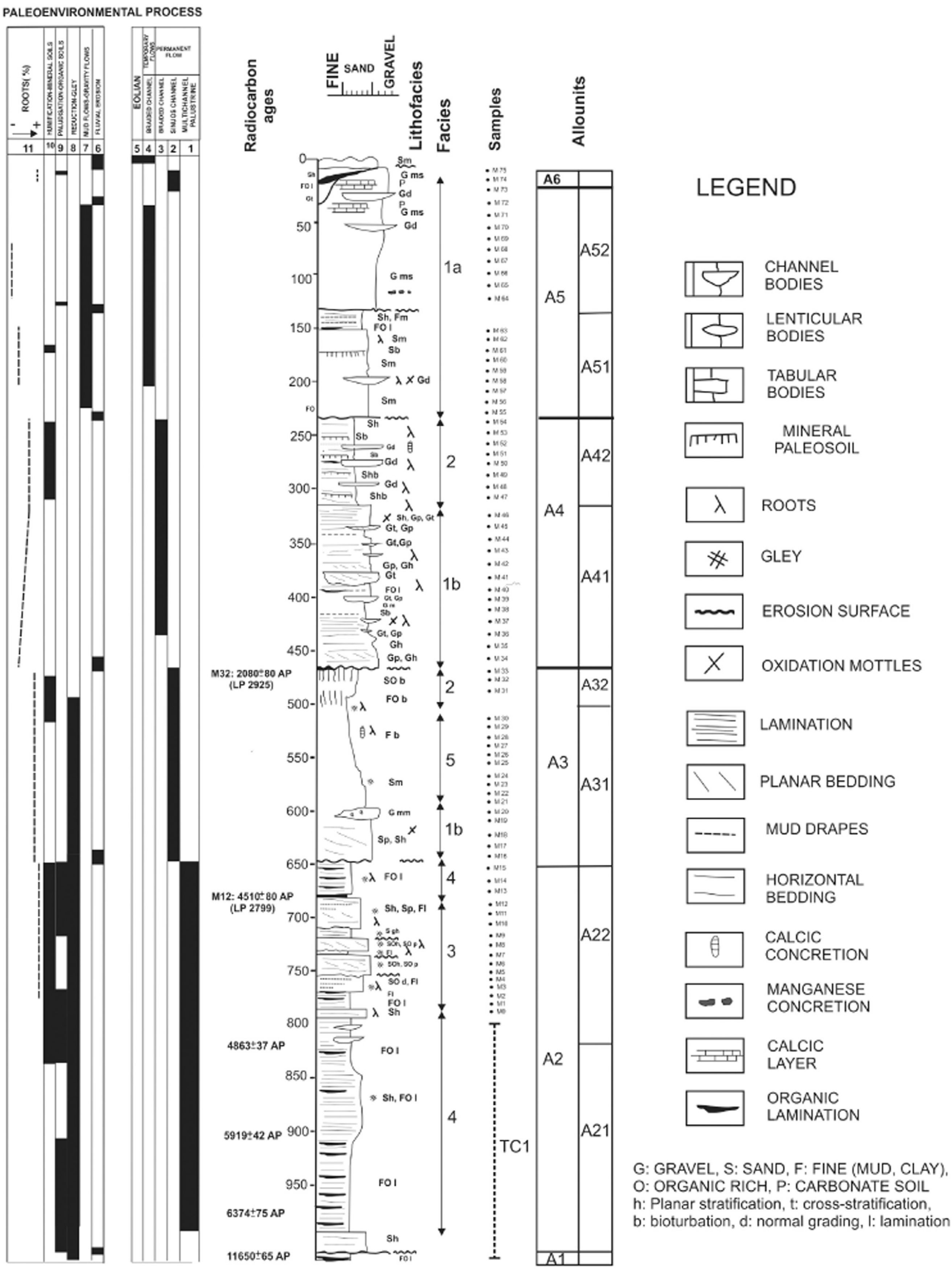

Fig. 5. PCC2 lithofacies and overall stratigraphy. Allounits A1 and A1.2. correspond to the Cruces 1 core (TC1, Morales et al., this volume).

Table 2
Description of dominant litho-facies and depositional environment of the facies preserved in the exposed terraces of the Barrancas fluvial system.

Facies (FAs)	Dominant or characteristic lithofacies	Description and two-dimensional strata shape (Friend et al. 1979, Friend, 1983)	Depositional environment
1a	Gms, Sm Gm, Sh, Fl	Fine to medium gravel and very coarse sand. Massive matrix-supported, crudely bedded gravel (Gms and Sm). Fine gravel crudely bedded in small channel bodies (Gm). Tabular 20–30 cm horizontally bedding sand with thin mud drapes (Fm).	Channel, gravity flows and ephemeral flood events
1b	Gh, Gp, Gd	Very Coarse to medium sand to fine gravel, horizontally bedding in tabular bodies. Gravel planar crossbed and graded in small channel bodies. Roots.Mottles.	Sandy braided channels Perennial flow
2	Sb, Shb, Sh, Gd, FOl	Fine and very fine sand with massive and blocky aggregates, bioturbated and roots, gray chromas. Medium and coarse light sands with horizontally bedding and bioturbated sand in small channel bodies.	Humic paleosoil in overbank and in multichannel alluvial plain
3	SOh, SOp, FOl, Fl	Tabular to wedge layer of gray fine to medium sands with laminated olive gray diatomitic mud and organic sediments	Backswamp close to channel (crevasse lobes and chute channels)
4	Fl, FOl, Sgh, Sd	Planar laminated organic black fine sediments. Interbedded light olive gray laminated diatomitic muds and silts. Wedge layer of olive and gray fine to medium sands.	Backswamp with peat in low energy floodplain
5	Fb, Fm, Sh	Massive and bioturbated fine sediments	Overbank with gley soils
6	Sm	Massive medium sand	Aeolian sheet and nebkhas

and gravel) observed in the field.

Finally, samples with high OM content usually present lower magnetic mineral content. This may be due to postdepositional processes (i.e. dilution of magnetic minerals in reducing conditions) or due to environmental causes (e.g. formation of shallow ponds with lower aeolian input) (Orgeira et al., 2011).

3.4. Diatoms analysis

Overall, the 33 samples included in the diatom analysis presented a very low valve frequency (~100,000 v/g); only 17 samples reached the minimum valve content to be considered fertile for analysis (M0 to M18, with the exception of M6 and M15). Altogether, 124 diatom taxa were identified in the analyzed section of PCC2; only 16 presented a frequence of over 5% in at least one sample. The most frequent species

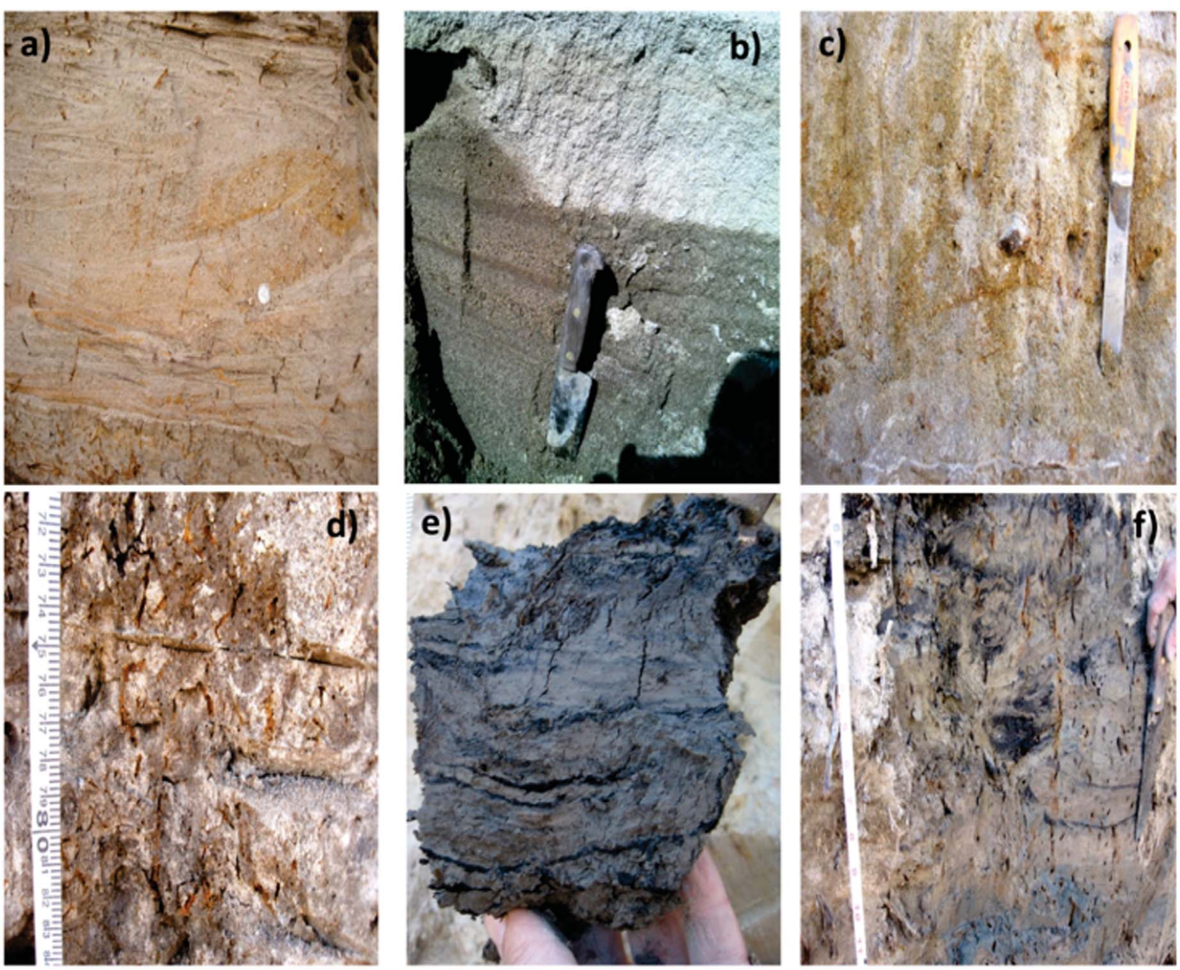

Fig. 6. Examples of lithofacies described in Table 1. a) Lithofacies Gh and GP. 3.5 m deep; b) very coarse, upward-fining, laminated sands (lithofacies Sd, Sh with Fl). Light colors, no bioturbation; c) massive sands with disperse gravel (lithofacies Gmc), 5 m deep; d) massive, bioturbated clays, with root traces and gleyzation (lithofacies Fb), 4.5 m deep; e) lithofacies FOl, greenish to grayish clays laminated with OM, 6,8 m deep; f) Brown and greenish clays with lenticular OM laminae and vegetal macroremains (lithofacies FOlb) at 5.6 m deep. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

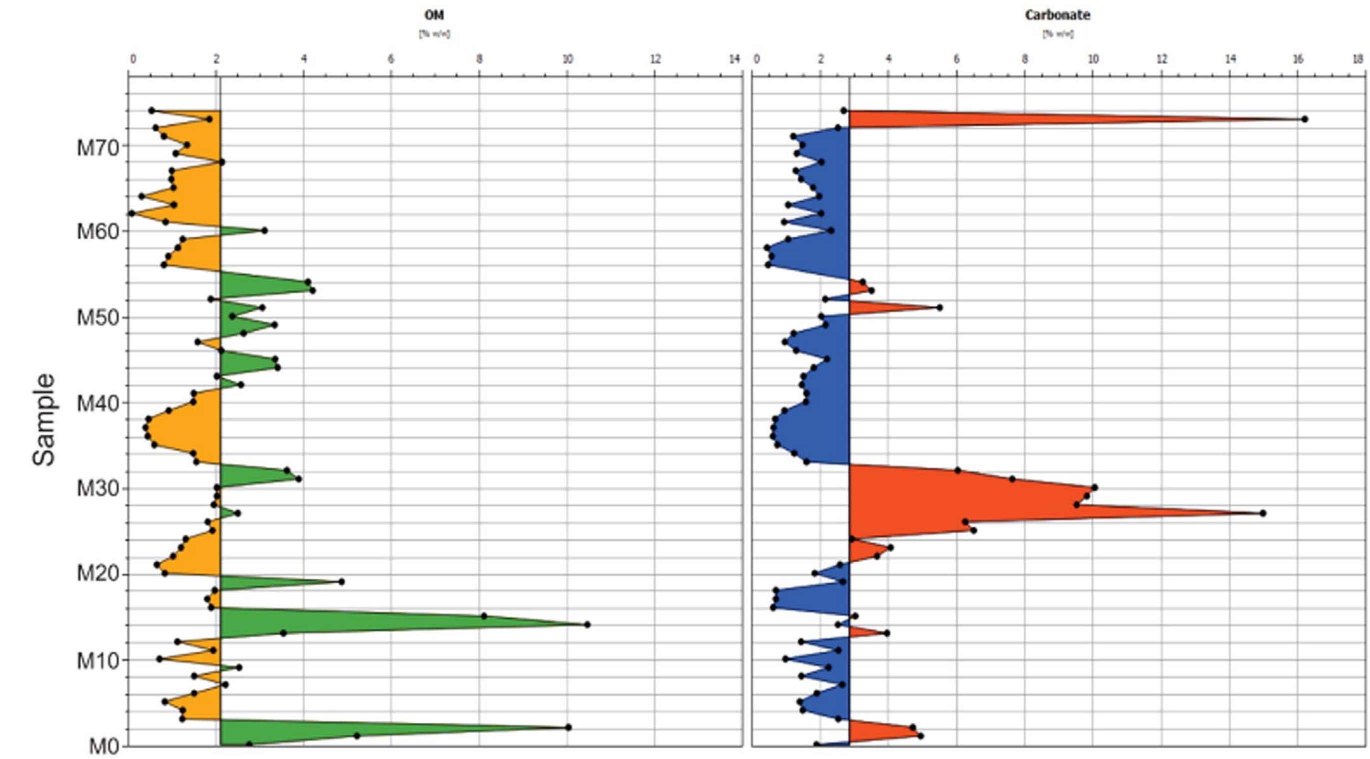

Fig. 7. OM and carbonate content (% dry w/w) obtained by LOI. Values above the mean of the series is represented in green or red; values below the mean is represented in yellow or blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

were *Luticola andina; Luticola subaequalis; Luticola sp6*; *Navicula lauca; Nitzschia liebertrutti; Nitzschia palea; Nitzschia valdecostata; Nitzschia vitrea*, *Planothidium lanceolatum*, *Pinnularia borealis* and *Hantzschia amphyoxis* (Fig. 11).

Five floristic zones (A–E) were identified by cluster analysis. Zone A is characterized by the dominance of *Luticola andina*, followed by *Pinnularia borealis* and *Hantzschia amphioxys*. Zone B presents a sharp reduction of aerophiles (*L. andina*, *P. borealis* and *H. amphioxys*) and an increase of benthic taxa (*Navicula lauca*, *Nitszchia liebertrutti* and *Nitzschia palea*), which is indicative of a period of increased moisture in the site. The Zone C assemblage is similar to Zone A, although it incorporates the taxon *Luticola sp6*. Zone D is dominated by *L. subaequalis*, followed by *L. sp6*, *H. amphioxys* and *L. andina*. Lastly, *L. andina* is the most abundant species in Zone E, accompanied by *L. subaequalis* in the upper section of the zone and *H. amphioxys* in the lower section (Fig. 12).

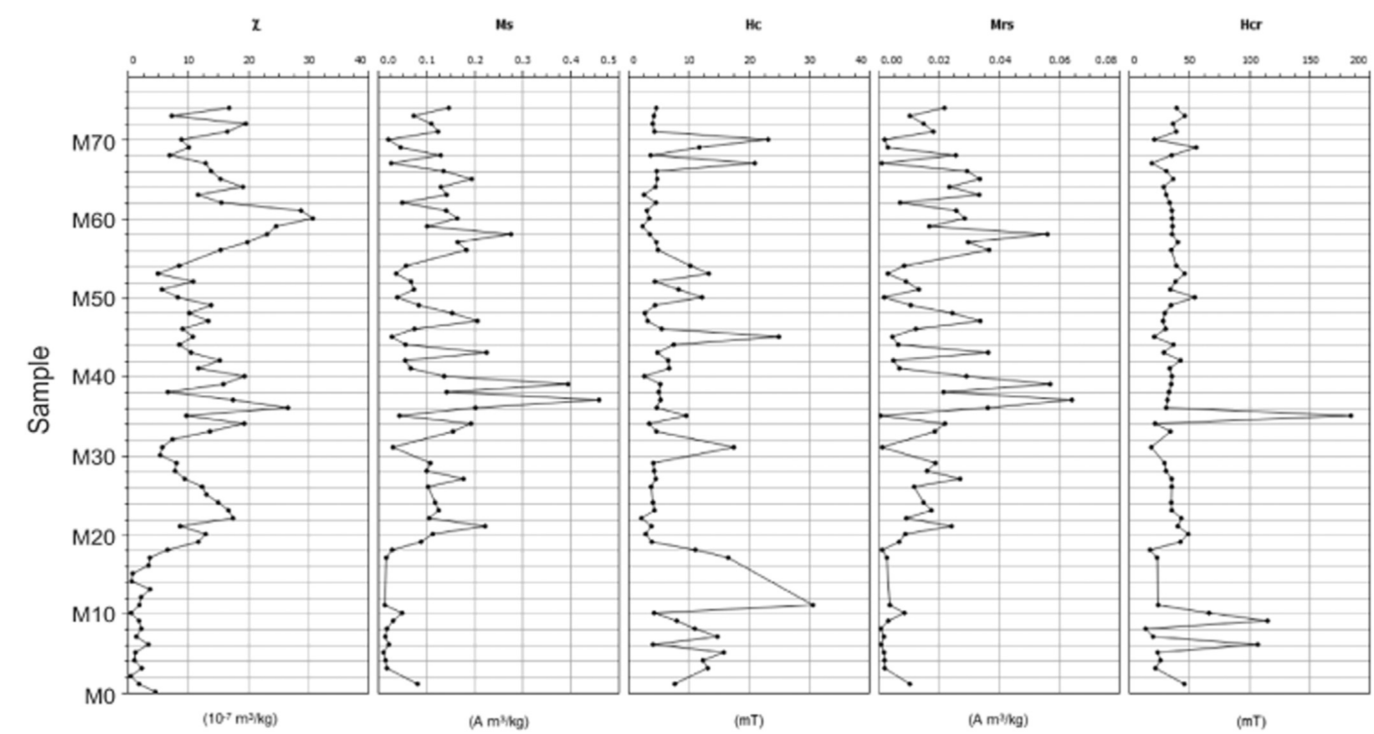

Fig. 8. Magnetic properties of PCC2 sediments.

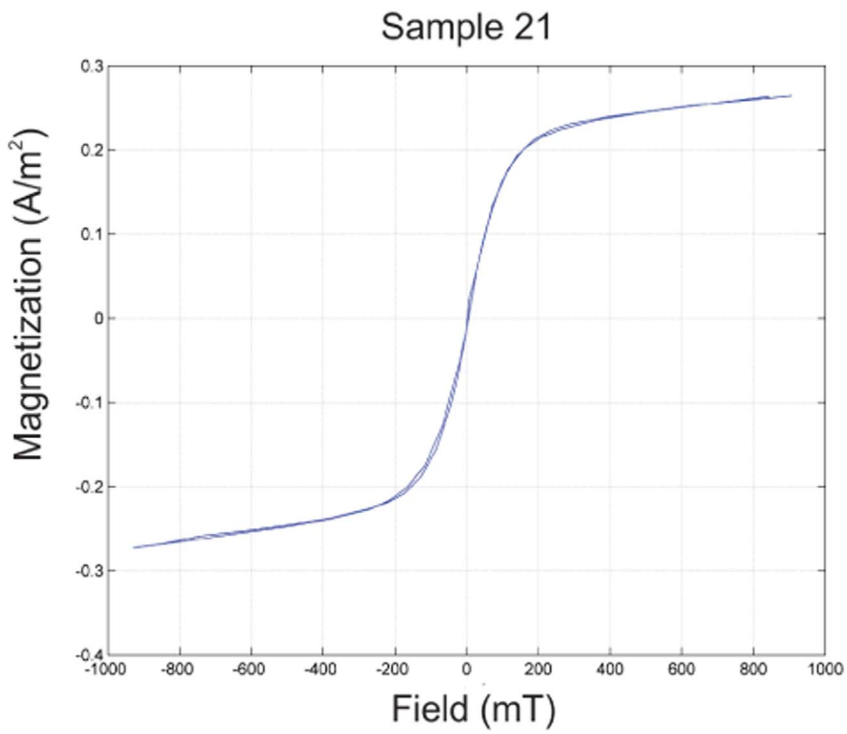

Fig. 9. Examples of most frequent shape in PCC2 hysteresis loops.

3.5. Pollen

A total of 11 taxa were identified at the family, genus and species levels (Poaceae, Ephedraceae, Pteridophyta, Asteraceae, Solanaceae, Chenopodiaceae, Cactaceae, Cyperaceae, Amaranthaceae, Malvaceae, and *Alnus acuminata*) (Fig. 13). Overall, TC1 pollen composition is dominated by the Poaceae family (40–90%), followed by Asteraceae (5–40%), Chenopodiaceae (5–40%), Ephedraceae (< 10%) and

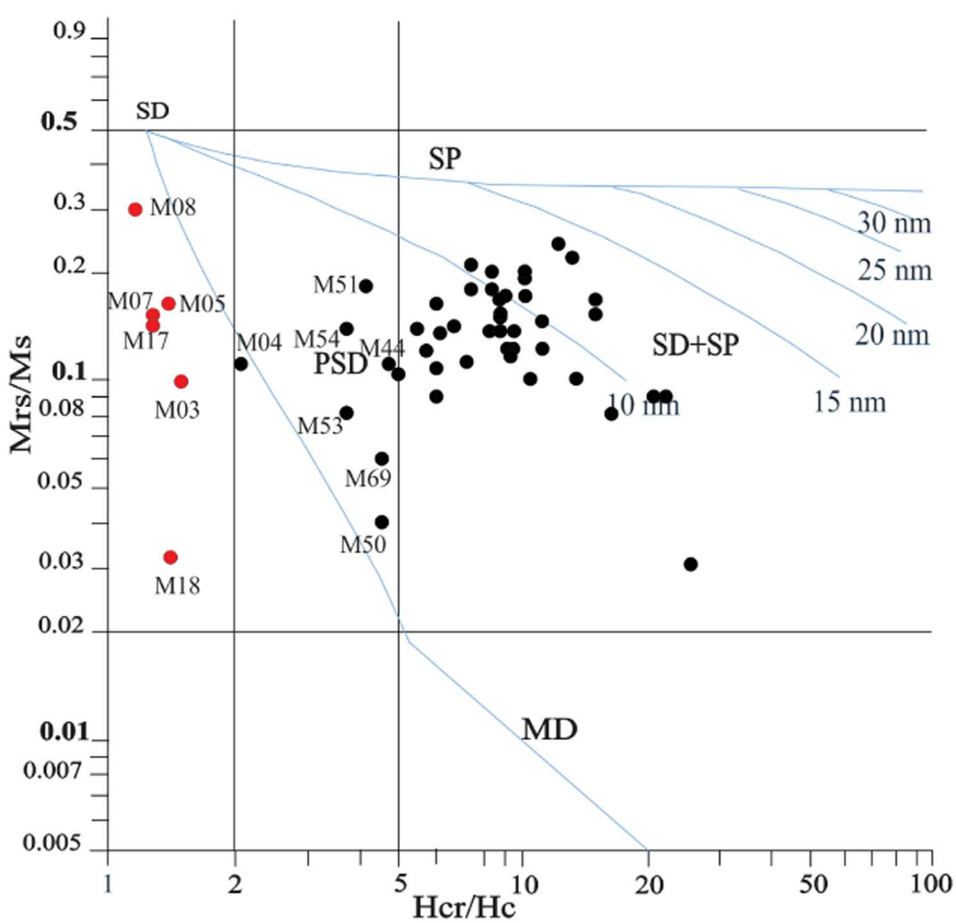

Fig. 10. Day Plot (Mrs/Ms vs Hcr/Hc) of PCC2 samples. Red dots represent mixed particle size assembles (SD + MD). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

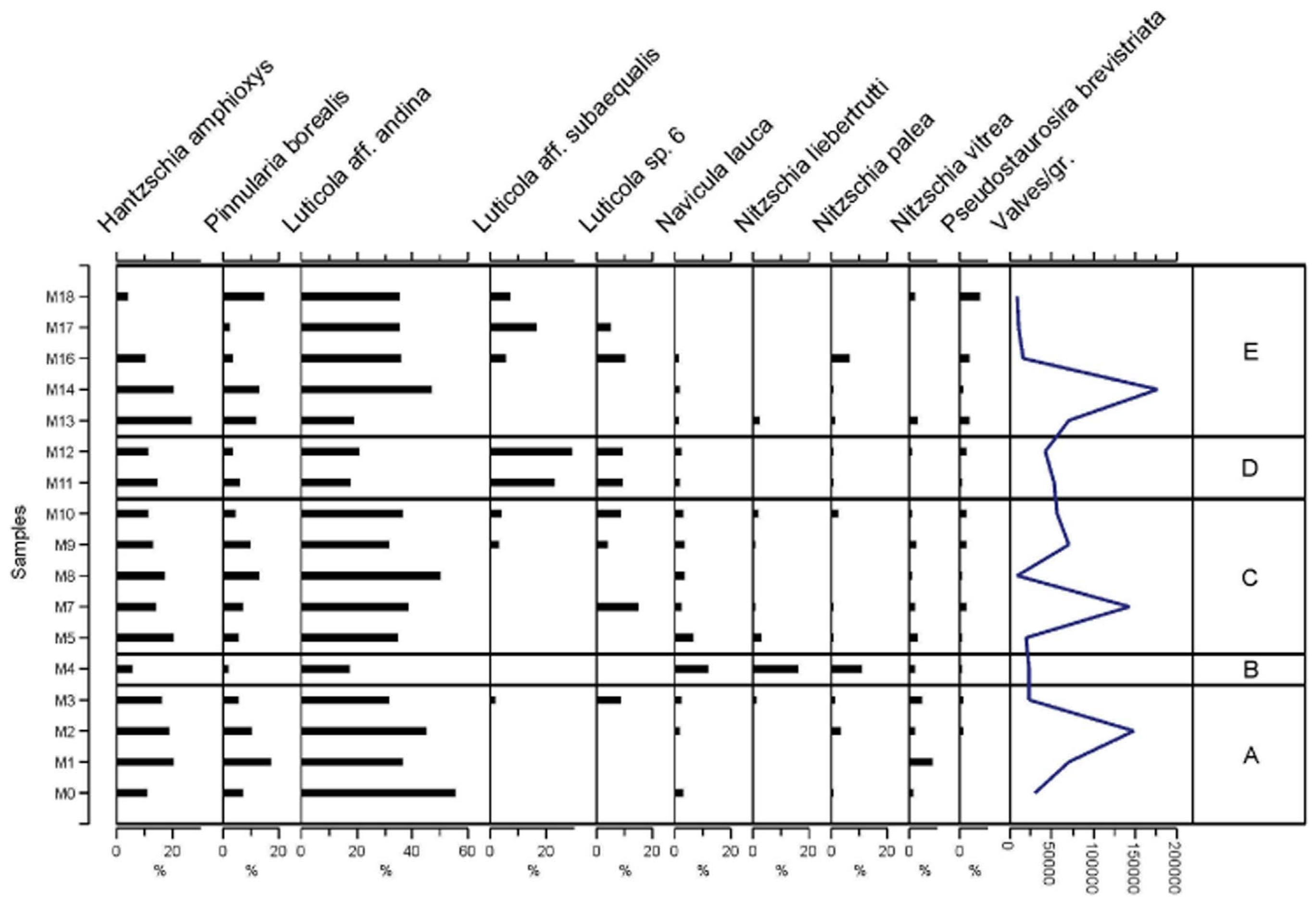

Fig. 11. Most frequent (> 5%) diatoms taxa, diatoms concentrations and floristic zonation.

Pteridophyta (5–20%) (Fig. 13). Other taxa were identified but in very small frequencies (< 5%).

Stratigraphically-constrained cluster analysis determined 6 main pollen zones (Fig. 14). Zone 1 (M0 - M3) is dominated by typical herbaceous steppe taxa, such as Poaceae (60–70%) and Ephedraceae (< 10%), coupled with shrub steppe taxa (Asteraceae, 20–40%) that was particularly high in M0 (40%). Low proportions of Pteridophyta, Amaranthaceae, Chenopodiaceae and Malvaceae (< 10% each) were also identified in this zone. Zone 2 consists of a single sample (M8) with a high pollen concentration value and dominated by Poaceae (40%), Ephedraceae (< 10%) and Asteraceae (20%). Local humidity indicators (i.e. Pteridophyta) presented very low frequencies (< 5%). Zone 3 (M9 - M15) included high proportions of Poaceae (60–80%), followed by Asteraceae (20–40%) and local humidity indicators (< 10%). Zone 4 consists of a single sample (M16) with a particularly high pollen count. It is also distinctive because of its high proportion of shrub steppe components (60%) vs. herbaceous steppe taxa (Poaceae). This zone further presents a sharp increase of Chenopodiaceae (40%) and a small proportion of Malvaceae. Although the presence of Chenopodiaceae may be interpreted as related to anthropogenic impact, according to studies of current pollen influx this family is part of the natural shrub steppe assemblage of the area. Only when Chenopodiaceae proportions reach high values and are accompanied by Malvaceae and Amaranthaceae (above 20% of the total pollen count) it may be considered as indicative of anthropogenic disturbance (Lupo, 1998, Oxman, 2016). Zone 5 (M17 – M32) herbaceous steppe elements increased again (70–80%) and Chenopodiaceae decreases (5–20%) and also the pollen concentration presents a low values.

In Zone 6 (M32-M72) herbaceous steppe components increase up to sample M58, and then decrease gradually. Also, a slight increase in shrub steppe species is detected, accompanied by an increase in local humidity indicators (Pteridophyta, ~25%) between samples M45-M51. There is also an increase in Chenopodiaceae between samples M62-M66. After M36, pollen concentration values decrease are lowered and they remain in those values.

This zone also presents *Alnus acuminata* pollen recurrently from M36 onwards. This species is only present in the montane tropical forest or *yungas*; its occurrence in high Andean paleoenvironmental archives is due to aeolian transport and is interpreted as indicator of intensification of easterly winds.

4. Discussion

The evidence presented in this article indicates that, although the energy of the hydrological system of Barrancas varied throughout the late Holocene, humid conditions were present during most of the time span represented in the PCC2 sequence. During the mid- to late Holocene transition (since before 4500 BP and up to 2000 BP) the Barrancas river system constituted a relatively stable, low-energy, fluvial/marshy environment, with a shallow water table, which supported abundant riparian vegetation and the formation of paleosoils. This fluvial paleowetland extended along 1300 m of the mid-section of the Barrancas river course. The composition of diatom assemblages in PCC2 during this moment is consistent with a mostly hydrologically stable environment, with the exception of diatom zone B (ca. 4500 BP). The decrease of aerophiles and increase of benthic taxa suggests more humid conditions (increase of water level) than in the rest of the section; this chronology also presents one of the highest OM content of the series and an increase in pollen local humidity indicators. However, increased carbonate content in several samples (M24-M32) just before

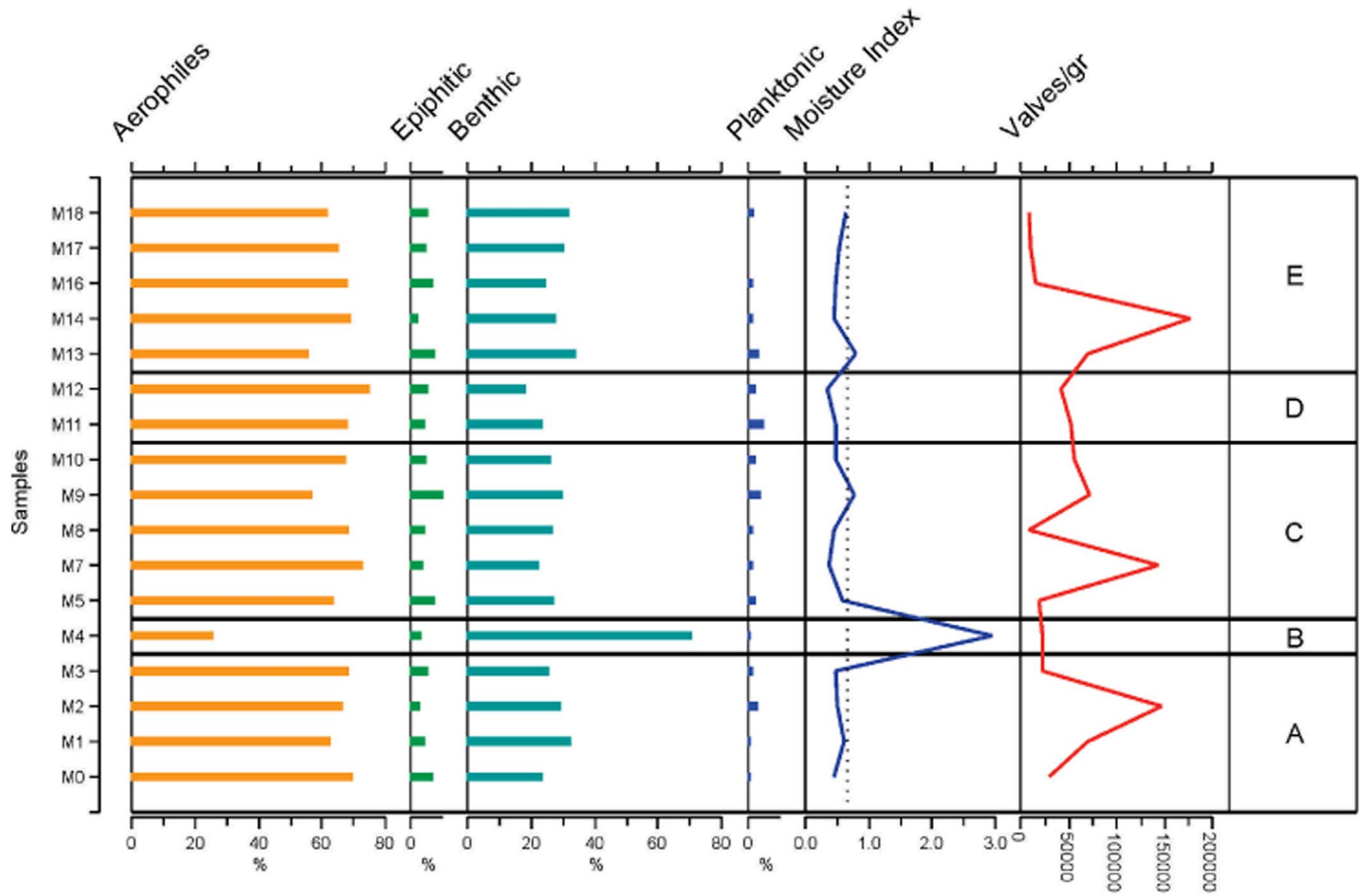

Fig. 12. Diatom life-form affinity spectra, moisture index and diatoms concentrations.

2000 BP suggests that these wetlands might have been subject to frequent and/or intense evaporation episodes. Likewise, pollen concentrations suggest variable vegetation coverage, mainly dominated by herbs, for this period. OM content is low (< 5%) during most of the period but, in light of the other proxies analyzed here, low OM values could be related to a higher detrital input rate and may not be indicative of bioproductivity conditions in the PCC2 catchment.

At 2000 BP, the formation of a short-lived humic soil along the entire river's mid-section (Allounit A3) suggests an event in which the hydrological system lost energy and gained stability. After this date and up to 1500 BP, as suggested by available dates in Trono del Inca (PTI) and Perfil Barrancas Pueblo (PBP) within the Barrancas basin, the fluvial system increased its energy again (Allounit A41), which explains very low OM and carbonate content values post-2000 BP. However, the presence of high-coercivity magnetic minerals during this phase is indicative of fluctuating wet and dry conditions. Post-2000 BP the prevalence of torrential events also increased.

At ca. 1500 BP another short, hydrological low-energy episode allowed the formation of ephemeral ponds and mineral soils (Allounit A42). The pollen record also indicates high local humidity for this time span. From 1500 BP on, the fluvial system presented an ephemeral regime dominated by detritus flow, with scarce vegetation and edaphization (Allounit A5). This is consistent with the increase of extensive magnetic parameters that indicate a higher detrital input. At some point in time post-1100 BP (by correlation to a date obtained from PTI), the fluvial system cut down 2 m, creating a sinuous drainage pattern with associated mineral soils and profuse vegetation, described as Allounit A6 in the PCC2 profile. After Allounit A6, successive eroding stages created 3 levels of alluvial terraces (Allounits B, C and D) that did not create the conditions for development of rich organic soils.

PCC2 sheds some light on late Holocene paleoenvironments in this area of the South-central Andes; to date, evidence of this period is scarce and fragmentary in the Dry Puna of Argentina (Markgraf, 1985; Lupo, 1998; Oxman, 2010; Oxman et al., 2013; Morales et al., 2015; Schittek et al., 2016). Due to an erosion unconformity in the PCC2 sequence and the low quantity of organic matter available for conventional radiocarbon dating we are unable to provide a more precise chronology at this time. However, the presence of this unconformity, as well as the coarse-grained, fluvial deposits that overlie it, implies that at some point in time after 4500 BP and before 2400 BP the hydrological system of Barrancas increased its flow energy and coarse sediment budget, which suggests a regional increase in humidity, signaling the onset of late Holocene conditions in the Dry Puna of Jujuy. We propose that these conditions were already present in the Barrancas basin by at least 2410 BP because we dated a paleosoil 3 km downstream from the PCC2 site (PBP) that appears within a generally fluvial (i.e. higher energy) context.

However, these conditions of increased regional humidity were punctuated by repeated dry events that manifest as flow energy lows in Barrancas, represented by episodes of paludization and paleosoil formation. These environments are similar to those described for Barrancas during the mid-Holocene (Morales et al., this volume). Thus, these features could be considered local signs of intense droughts occurring at a regional scale. PCC2 presents such conditions at ~2100 BP (2100 cal BP); PBP at ~2400 BP (2500 cal BP) and at ~1570 BP (1490 cal BP), and Trono del Inca (PTI, 1.5 km downstream from PCC2), at ~1580 BP (1460 cal BP) and ~1100 BP (1050 cal BP) (Morales et al., 2014). The research team has also found evidence of similar events in other localities of the Dry Puna as early as 2900 BP/3000 cal BP and 3070 BP/3260 cal BP in Pastos Chicos (Tchilinguirian et al., 2014a) and at 2100 BP/2100 cal BP in Azul Pampa (Yacobaccio, pers. com., 2016). In all cases, these dated paleosoils can be associated to

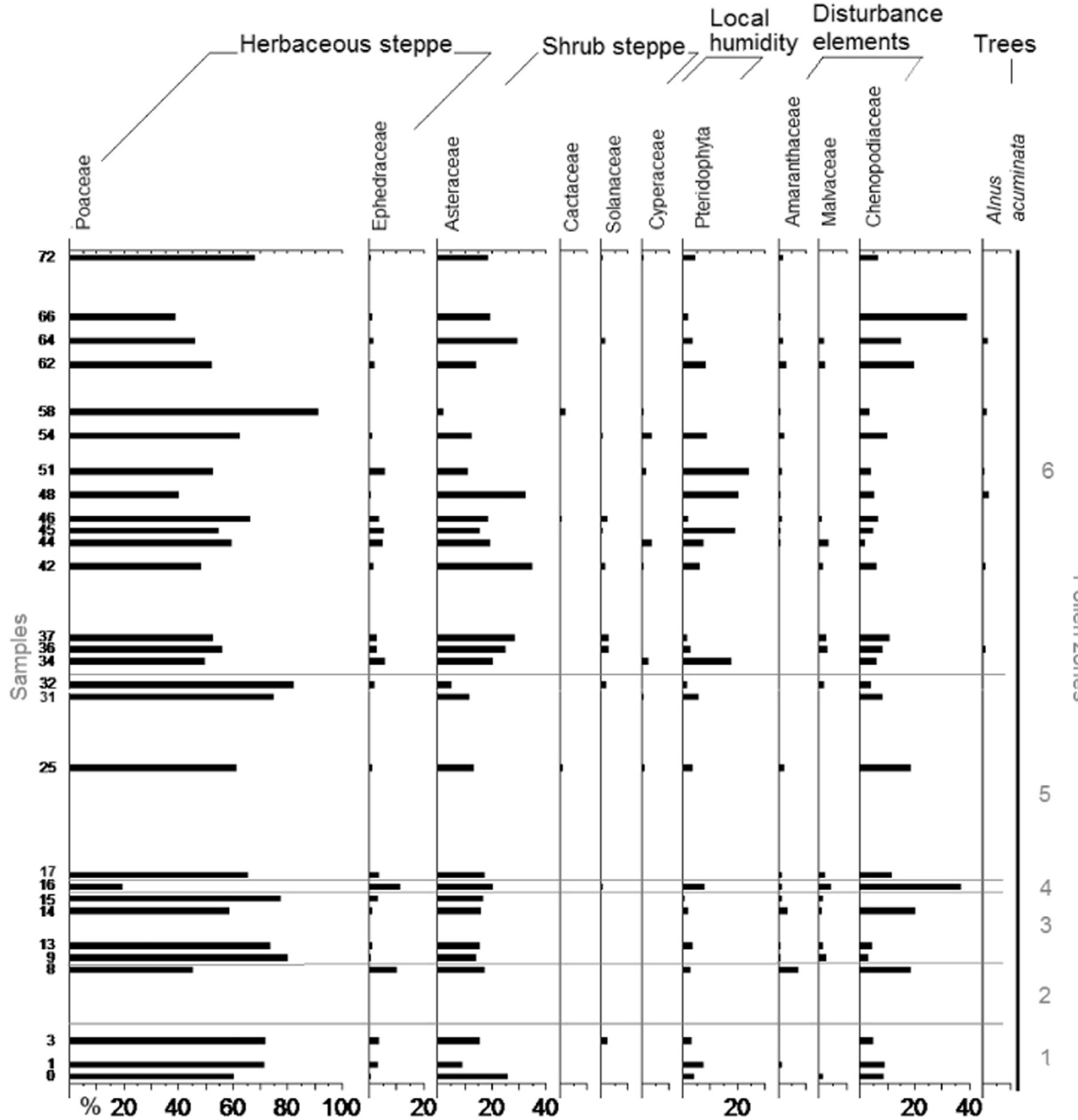

Fig. 13. Most frequent pollen taxa in the PCC2 sequence.

discrete episodes of lower hydrological energy within an otherwise predominantly fluvial sequence. This probably pushes back the onset of late Holocene characteristics in the Argentine dry Puna to at least 3500 BP, rather than 2500 BP.

Evidence from Tropical Andes ice cores provide support to the claim that these episodes of paleosoil formation were related to regional high temperature/dry episodes. Oxygen isotope composition values ($\delta^{18}O$) in the Quelccaya ice core for the two PTI dates − 1460 and 1050 cal BP; $\delta^{18}O$: − 17.25‰ and − 17.20‰, respectively- are above the overall average for the last 1800 years ($\delta^{18}O$: − 17.92‰, Thompson et al., 2013). Similarly, $\delta^{18}O$ values at 2500 (paleosoil dated at PBP; $\delta^{18}O$: − 17.99‰) and 2100 cal BP (paleosoil dated at PCC2 and Azul Pampa, $\delta^{18}O$: − 18.13‰) were above late Holocene average (− 18.31‰) in the Huascarán ice core (Thompson et al., 1995) even when removing the extremely low Little Ice Age values from the series (mean $\delta^{18}O$: − 18.25‰).

Lake Pumacocha in the Peruvian Andes has provided further data on changes in precipitation governed by the South American Monsoon System (SAMS) over the past 2300 years (Bird et al., 2011), based on high-resolution $\delta^{18}O$ values of authigenic sedimentary calcite. Higher δ18O are interpreted by the authors as representing a lower intensity of the SAMS and therefore reduced precipitation. In general terms, the values were very variable over the lapse analyzed, but the series presents mostly above-average values (mean $\delta^{18}O$: − 13.40‰) - between 850 and 1500 cal BP (and particularly the span between 800 and 1050 cal BP). This period fits the chronology of paleosoil formation episodes detected at PBP and PTI in the Barrancas basin. In contrast, the 1500–2300 cal BP lapse is highly variable in terms of above and below average values. However, between 2080 and 2140 cal BP, $\delta^{18}O$ values were above average, in coincidence with the 2100 cal BP paleosoil at PCC2.

Schittek et al. (2016) have also found local evidence of variable wet/dry conditions for the past 2100 years in the Cerro Tuzgle peatlands, located in the dry Puna of Jujuy and 90 km away from the Barrancas area. Cerro Tuzgle data suggests drought periods at 2100–1800 cal BP, 1300–1150 cal BP, and 1050–1000 cal BP. The first and last of these periods coincide with paleosoils dates in Barrancas, thus supporting our hypothesis of paleosoil formation in the Barrancas

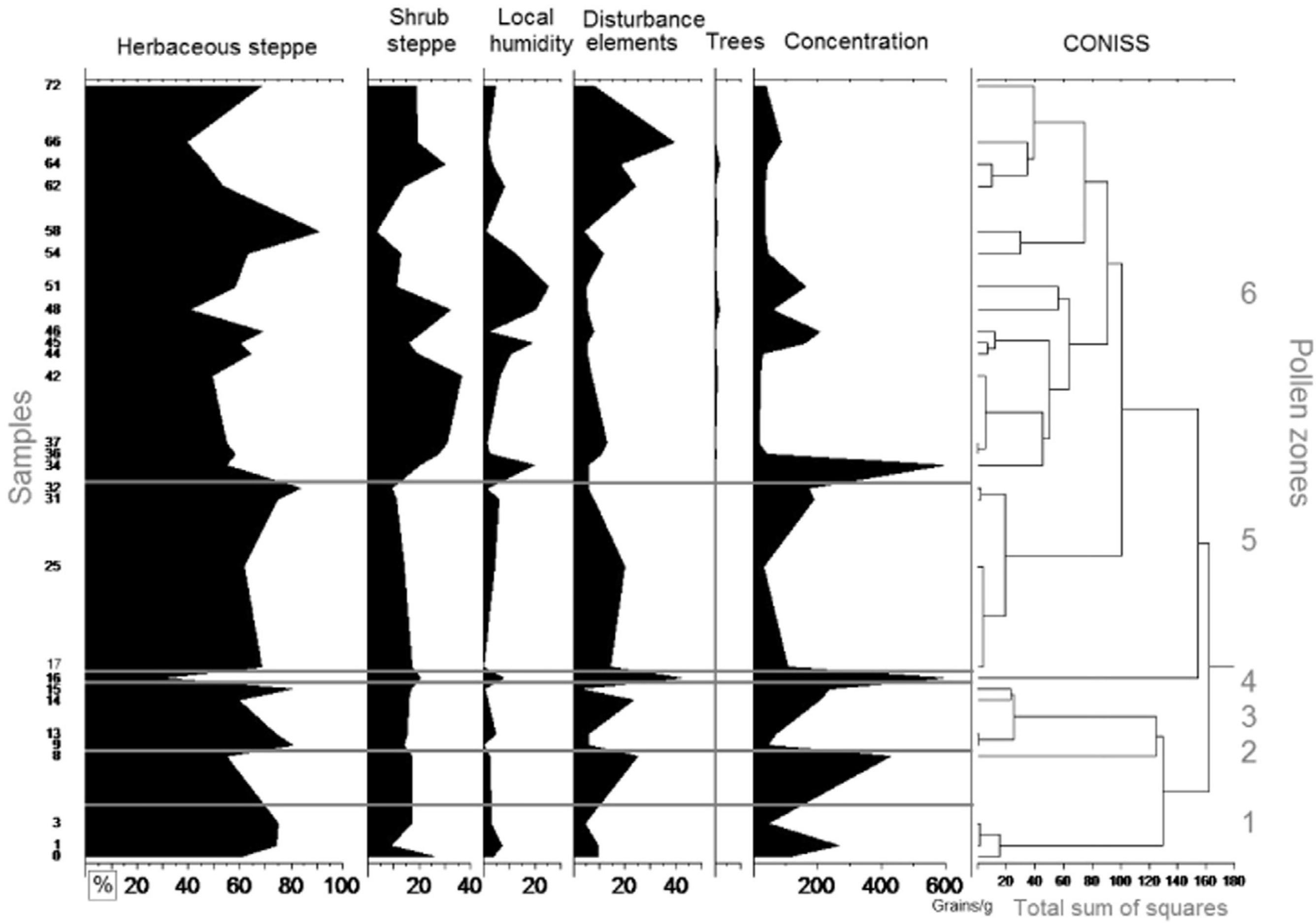

Fig. 14. Pollen ecological spectra, zonation (CONISS) and pollen concentration.

river basin during regionally dry periods.

There is further evidence that supports our interpretation of unstable late Holocene environments. Summer precipitation volume in the South-central Andes is a function of SAMS intensity, which has been highly variable during the late Holocene not only in centennial or millenial scales (v.g. Vuille et al., 2012; Kanner et al., 2013; Novello et al., 2016), but also in terms of decadal (v.g. Pacific Decadal Oscillation) and interannual variability (i.e. ENSO) (Garreaud et al., 2009). This sub-centennial variability is of special interest when dealing with human responses to environmental change, particularly those that could be clearly perceived or identified over time (i.e. inter-annual). For this reason we discuss some issues about ENSO and its variability over time.

On one hand, Carré et al. (2014) have stated that El Niño/La Niña events, which in the Dry Puna of Argentina are associated to anomalous dry/wet conditions, reached its current periodicity − 2 to 8.5 years - between 4500 BP and 3000 BP. This date coincides with the earliest possible date of the mid to late Holocene transition in PCC2, when both energy and instability started to rise in the Barrancas system. On the other hand, the intense regional droughts events evidenced in PCC2 and other records studied by the team fit well with other records that suggest an increase in the frequency and intensity of El Niño-events since 3000 BP (Riedinger et al., 2002) or 2000 BP(Kanner et al., 2013).

The archaeological record in Barrancas is still under study but preliminary results suggest that the locality was used by human occupations throughout most of the mid and late Holocene (Yacobaccio et al., 2016a). Paleoenvironmental evidence also indicates that even during the driest moments of the mid-Holocene, the locality might have functioned as an ecological refuge, providing a locus of water and/or pasture for camelids, and therefore, a dependable source of prey for human groups (Morales et al., this volume). The mid- to late Holocene transition in this locality implied a change from predominantly low-energy, more stable hydrological systems – i.e. *vega*-like wetlands, to mainly fluvial, unstable hydrological landscapes.

While mid-Holocene spatial heterogeneity and relative temporal stability might have triggered the domestication of camelids and the increase of complexity in hunter-gatherers' organizational traits (Yacobaccio and Vilá, 2013), the more humid but unstable conditions of the late Holocene might have put a premium on the further development of these and other risk-buffering mechanisms, such as resource intensification and suitable technologies to store surplus for deferred consumption. Thus, the "Formative period" and most of its related innovations – e.g. pottery, pastoralism, agriculture, etc. - may be interpreted as integrated cultural strategies to manage the risk related to uncertainty in resource availability, a defining characteristic of the late Holocene. For this reason, whereas at least a few of these innovations (e.g. the camelid domestication process) may have had an early start during the mid-Holocene, the consolidation of risk-buffering social traits seems to have occurred systematically along the Andean highlands of Argentina only after 3500 BP, framed in late Holocene environmental instability that generated resource uncertainty.

5. Conclusions

The Perfil Cruces 2 paleoenvironmental record suggests that the mid- to late Holocene transition in the locality implied a change from more stable to unstable conditions. While mid-Holocene regional aridity prompted the formation of vega-type wetlands in Barrancas – i.e. low energy/paludal environments, with high-coverage, riparian vegetation - the more humid late Holocene increased the energy of the hydrological system, including frequent torrential events. However, these conditions were punctuated by discrete episodes of paleosoil formation in several localities of the dry Puna, very matching those characteristic of the mid-Holocene: low energy, richly vegetated *vega*-type wetlands. These episodes took place at approximately 2500, 2100, 1490/1460, and 1050 cal BP in Barrancas, 3000 and 3260 cal BP in Pastos Chicos and at 2100 BP/2100 cal BP in Azul Pampa. Due to similarities with mid-Holocene conditions and evidence from ice core records, we suggest that the formation of these low energy wetlands was a local signal of intense regional drought events within the generally more humid late Holocene.

This centennial environmental instability coupled with ENSO-related inter-annual variability might have fostered the consolidation of social and cultural mechanisms to cope with resource uncertainty and economic risk, such as pastoralist/agricultural components in the economy, pottery, and other features that facilitated the production of surplus and its storage for later use. Thus, it was only from 3500 BP on - with the onset of late Holocene environmental conditions - that these socio-cultural features, usually used to identify the "Formative Period", were consolidated and expanded throughout the Andes highlands in Argentina.

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