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Exploring habitat diversity of mid-holocene hunter-gatherers in the South-Central Andes: Multi-proxy analysis of Cruces Core 1 (TC1), Dry Puna of Jujuy, Argentina

Marcelo R. Morales[a,b], Sabrina Bustos[a,b,*], Brenda I. Oxman[c], Malena Pirola[c], Pablo Tchilinguirian[d], Ma. Julia Orgeira[e], & Hugo D. Yacobaccio[c]

[a] CONICET - Universidad de Buenos Aires, Instituto de Biodiversidad y Biología Experimental y Aplicada – CONICET (IBBEA), Buenos Aires, Argentina
[b] Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Biodiversidad y biología Experimental, Buenos Aires, Argentina
[c] CONICET - Instituto de Arqueología, FFyL, UBA, 25 de mayo 221 3er piso (C1002ABE), C. A. Buenos Aires, Argentina
[d] CONICET, UBA - Instituto Nacional de Antropología y Pensamiento Latinoamericano, 3 de febrero 1378, (C1426BJN), C. A. Buenos Aires, Argentina
[e] IGEBA-FCEN, UBA-CONICET, Ciudad Universitaria, Pab. 2, 2° piso, (C1428EHA), C. A. Buenos Aires, Argentina

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A B S T R A C T

Over the past decade, most scholars in the field of paleoenvironmental studies have reached an agreement about the arid nature of the mid-Holocene in the South- Central Andes. However, the actual duration of arid conditions and their disparate effect in particular localities are still under discussion. This is particularly relevant in view that Mid-Holocene aridity is considered one of the main triggers of significant socio-cultural processes in the region, such as an increase in complexity among hunter-gatherers and camelid domestication. We contribute to this debate by presenting the results of a multi-proxy analisys of a 226 cm core (Cruces Core 1 or TC1) that includes geomorphology, diatoms, pollen, magnetic properties, organic matter and carbonate content of sediments. The analized record spans the late Pleistocene (*i.e.* 11,650 BP; *ca.* 13,400 cal. BP) to the onset of the Late Holocene (*i.e.* 4000 BP, *ca.* 4500 cal. BP).

Results show the presence of a fluvial system that progresively lost its energy along the Holocene, turning into a wetland *i.e.* fluvial-palustrine landscape. Humid conditions dominated the Barrancas basin since the late Pleistocene, with a higher energy during the early Holocene and the first part of the mid-Holocene up to 6000 BP. This environment was followed by a transitional period between 6000 and 5100 BP, characterized by an unstable wetland environment fluctuating between fluvial episodes and shallow paludal and evaporitic environments. A noticeable drop in local moisture is evident from 5100 BP on.

The Barrancas basin seems to have constituted a resilient habitat that alternatively offered circulation or settling possibilities for human populations throughout the Holocene, by providing dependable sources of water and prey. Its likely role as an ecological refuge even under the harshest conditions of the Holocene makes this locality highly relevant for archaeological studies.

1. Introduction

Mid-Holocene paleoenvironmental characteristics in the South-Central Andes were a subject of debate since the begginings of the XXI century (for instance Grosjean, 2001; Grosjean et al., 2003; Latorre et al., 2003). Currently, there is an extended consensus among most especialized scholars that the mid-Holocene was generally more arid than today in a regional scale (Ledru et al., 2013; Mayle and Power, 2008; Sáez et al., 2016; Tchilinguirian and Morales, 2013). However, the specific climate forcings behind this regional environmental change are elusive and several mechanisms have been proposed as responsible for these changes (Kull and Grosjean, 1998; Mayewski et al., 2004). Similarly, the actual duration of arid conditions and the uneven impact of these changes in particular localities across the South-Central Andes have become common topics in recent paleoenvironmental literature.

This paper seeks to contribute to this effort by presenting the results of multi-proxy analisys of a paleoenvironmental archive (Cruces Core 1, TC1) that includes geomorphology, diatoms, pollen, magnetic properties, and organic matter and carbonate content of sediments. The analized record begins at the Pleistocene-Holocene transition (*i.e. ca.*

* Corresponding author at: CONICET - Universidad de Buenos Aires, Instituto de Biodiversidad y Biología Experimental y Aplicada – CONICET (IBBEA), Buenos Aires, Argentina.
E-mail addresses: marcelomorales@conicet.gov.ar (M.R. Morales), sabrina.bustos.m@gmail.com (S. Bustos).

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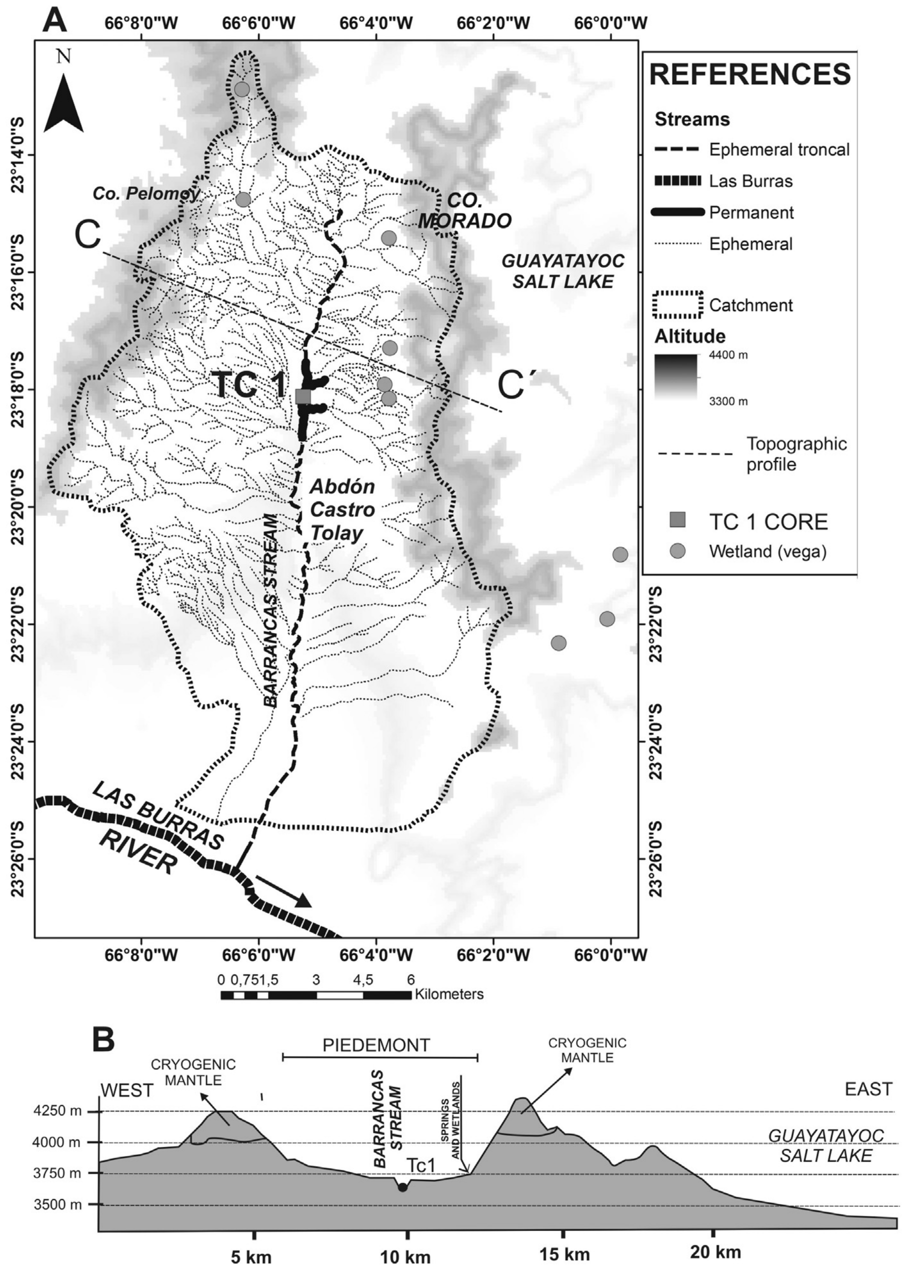

Fig. 1. A. Location of TC1, springs (wetlands) and catchment of Barrancas River Basin. B. Cross-section (W-E) of the Barrancas basin.

11.5 ka; 13.4 ka cal. BP) and ends at the onset of the late Holocene (*i.e. ca.* 4 ka, 4.5 cal. BP).

Environment is regarded as the main limiting factor of hunter-gatherers adaptations (Kelly, 1995; Binford, 2001), particularly when dealing with climate extremes, such as persistent droughts. Social mechanisms, including adjustments in mobility, social organization, development of new technologies, and change in the use of resources (Bar Yosef, 2014; Binford, 2001; Sandweiss, 2014), can be put in motion in order to mitigate the impact of climate changes for sustaining adaptation capacity.

The characteristics of mid-Holocene climate conditioned the availability of suitable habitats for the extractive societies that lived in the South-Central Andes since the Pleistocene/Holocene boundary (*i.e. ca.* 10.5 ka, 12.4 ka cal. BP). Traditionally, the mid-Holocene has been considered a period of regional occupational hiatus in most of the Andes highlands (*i.e.* "Archaeological Silence" *sensu* Núñez and Santoro, 1988). New evidence suggests that the environmental constraints imposed by mid-Holocene conditions could have been responsible for one or more demographic bottlenecks in the arid Andes (Barberena et al., 2016). However, several archaeological occupations have been detected at both flanks of the Andes with a mid-Holocene chronology, which has driven scholars to abandon the idea of a general depopulation of the area for this period. Moreover, the mid-Holocene archaeological record suggests that hunter-gatherer organization was undergoing profound and sustained changes at this time (*v.g.* Núñez and Meggers, 1992, De Souza, 2004, Hoguin et al., 2012, López, 2008, Pintar, 2009, Yacobaccio et al., 2013). Thus, mid-Holocene aridity is currently considered one of the main triggers of significant socio-cultural processes in the region, such as changes in mobility patterns (Yacobaccio and Morales, 2005), hunting techniques (Aschero and Martínez, 2001), technological organization (Restifo and Hoguin, 2012), and economic intensification, including camelid domestication (Yacobaccio, 2012; López and Restifo, 2012), which resulted in a general rise in complexity among Andean hunter-gatherer societies.

In this context, understanding and modeling the duration and nature of mid-Holocene climate impacts on localities with diverse altitudinal, hydrological and geomorphological characteristics are primary research tasks for archaeology in the Andes. As we proposed in a recent paper (Yacobaccio et al., 2016b), mid-Holocene conditions caused habitat fragmentation and habitat loss, while also generating ecological refugia in resilient localities. These "niches of moisture" (*sensu* Ledru et al., 2013) were probably not only critical for the survival of hunter-gatherer groups during the driest phases of this lapse, but they may also have had a significant effect on different aspects of social organization among hunting-gathering societies. An accurate account of mid-Holocene climate impacts on human habitats – in terms of the temporal and spatial abundance, distribution and predictability of resources – will allow us to improve our models about change in economic, social and symbolic traits of the hunting-gathering societies that inhabited the Puna region. This paper adds to our effort to gain spatial coverage in paleoenvironmental studies in order to enhance our previous models about mid-Holocene environmental diversity in distinct localities (*e.g.* Morales, 2011, Tchilinguirian and Morales, 2013, Tchilinguirian et al., 2014, Yacobaccio and Morales, 2005).

2. Setting

The Puna of Argentina, as the eastern slope of the Puna de Atacama, comprises the arid highlands above 3000 m asl (and below 4500 m asl) between 19° and 27°S. This highland desert biome presents a marked seasonality in rainfall, due to the control of South American Monsoon System (Zhou and Lau, 1998). This system produces about 80% of annual precipitation between December and February (Vuille and Keimig, 2004). These conditions set a heterogeneous distribution of vegetal and animal species, where scarce scattered patches contain most of the available regional biomass. A small number of wetlands related to permanent freshwater basins, salt lakes, pans and playas constitute the general hydrological network that concentrate primary productivity and, consequently, most part of animal species that constitute a valuable resources for human populations. A few rivers and several springs scattered in the landscape are the only sources of freshwater.

Precipitation across the Puna region also shows a latitudinal gradient that defines two sub-regions: 1) the Dry Puna, north of 24°S, with a mean annual precipitation of 340 mm/yr (reaching even 400–500 mm/yr in some localities of the northern-western sector), and 2) the Salt Puna, south of 24°S, in which precipitation barely reaches an average of 100 mm/yr, producing an even more heterogeneous landscape than the Dry Puna.

Barrancas village (formally called Abdón Castro Tolay) is located in Cochinoca, Jujuy Province, in the Dry Puna and its summer precipitation reach 180 mm/yr. Barrancas is located in the right margin of the Barrancas River, a tributary of Las Burras River, which drains into Salinas Grandes basin. The Barrancas River catchment has 190 km^2 (Fig. 1a) and its flow depends heavily on the seasonal precipitation regime. This river presents sharp flow increases during summer, but it remains dry for the most part of the year with the exception of its mid-section, which presents a limited but permanent flow (100 to 500 l/s.). This permanent flow develops 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 Cerro Morado where groundwater surfaces along fractures in the igneous rocks, creating small wetlands spanning an approximate 0.8 km^2 each (Fig. 1a).

The Barrancas River flows on the base of a canyon formed by the Pelomoy and Volcan mountains (4200 m asl, Ordovician, Santa Victoria Group) to the west, and Cerro Morado (4300 m asl, Jurassic, Aguilar Fm.) to the east (Fig. 1a). Between these two mountain systems there is a depressed area composed by Miocene ignimbrites (Coranzuli Fm.) 30 m to 100 m deep, overlain by 5 m to 30 m of Quaternary alluvial conglomerates (Figs. 1b and 2). Three Pleistocene pediment levels and several Holocene alluvial fans that reach Barrancas River were detected (Figs. 1b and 2). The fluvial erosion has exposed the underlying ignimbrites, which form structural plateaus and erosive features such as scarps and gullies. The mid-section of the Barrancas River cuts into the piedmont deposits and the Miocene ignimbrites, giving rise to 30 m-deep and 200–300 m-wide ravines. An 11 km-long paired terrace of Holocene fluvial-palustrine accumulation is also present in the Barrancas River. The TC1 core, which is described and analyzed in this paper, was drilled into these Holocene deposits.

Finally, a rich, chronologically and stylistically diverse repertoire of archaeological sites and rock art panels are located along the Barrancas River terraces and ignimbrite valley walls. This evidence supports a human presence in the area along the entire Holocene, with particular continuity and intensity in the past 3000 years (Yacobaccio et al., 2016a).

2.1. General paleoenvironmental trends since the end of Pleistocene in the South-Central Andes

The process of human dispersal into the highlands of northwestern Argentina and northern Chile *ca.* 11 ka (13.3 ka cal BP) seems to have occurred in favorable habitats, during the cold and humid conditions (*v.g.* Grosjean et al., 2005, Yacobaccio and Morales, 2013, Latorre et al., 2013, Santoro et al., 2016) of the CAPE II phase, between 13.8 ka and 9.7 ka (Central Andean Pluvial Event, Quade et al., 2008). This event seems to have fostered changes in the altitudinal arrangements of flora (*v.g.* Fernandez et al., 1991, Betancourt et al., 2000, Latorre et al., 2002, 2003, 2006), a rise of regional water tables and enhanced fluvial flow (*v.g.* Rech et al., 2002, Gayo et al., 2012). This was reflected in higher lake levels across the region (*v.g.* Geyh et al., 1999; Baker et al., 2001; Bradbury et al., 2001; Abbott et al., 2003, Placzek et al., 2006, 2009) commonly known as the Coipasa phase (between *ca.* 12 ka and 9.5 ka, *sensu* Sylvestre et al., 1999).

During the early Holocene − 10 ka to 8.2 ka (*ca.* 11.5 ka to 9 cal BP) - the mean conditions in the Andes were more humid, and landscapes were probably more homogeneous than today (Thompson et al., 1995, 1998, 2006; Bradbury et al., 2001; Ramirez et al., 2003). These conditions seem to have facilitated a continuous human presence in the area, triggering a colonization process that included high altitude locations (*i.e.* above 4000 m asl, Yacobaccio and Morales, 2013). The end of these environmental characteristics occurred non-synchronously, being somewhat later (at least *ca.* 7 ka or 7.8 ka cal BP) in the South Central Andean region (northern Chile and NW Argentina). This late chronology is mainly evidenced in water bodies with broad moisture catchment areas or wetlands located in the headwaters of fluvial systems above 4000 m asl (Morales, 2011).

As we previously mentioned, an extended agreement between paleoenvironmental researchers states that the mid-Holocene was more arid than today in the Andes (Mayle and Power, 2008; Sáez et al., 2016; Tchilinguirian and Morales, 2013). During this period (8.2 ka to 4.2 ka, *sensu* Walker et al., 2012) the climate seems to have been warmer and dry, with a marked seasonality in rainfall. Mid-Holocene records show that several lakes and "lagunas" dried out (*v.g.* Geyh et al., 1999; Bradbury et al., 2001); numerous wetlands disappeared due to the moderated groundwater levels (Rech et al., 2002) and the grassland steppe was displaced upwards, above the 4000 m asl altitude contour (*v.g.* Markgraf, 1985, Fernandez et al., 1991). The ecological impact of changes in the amount of moisture and its spatial and temporal distribution also caused significant drops in the regional abundance of pack-rat middens (Latorre et al., 2003, 2006; Grosjean et al., 2003) and paleosoils (Rech et al., 2002; Morales, 2011; Yacobaccio et al., 2016b). However, it was neither spatially nor chronologically homogeneous (Rech et al., 2002, 2003; Tchilinguirian and Morales, 2013). At least two different phases could be identified. The 8.2 ka to 6 ka (9 ka − 6.8 ka cal BP) span, or mid-Holocene I (MH I), was moister and colder than the dry, less stable and warmer mid-Holocene II (MH II, 6 ka to 4.2 ka or 6.8 ka − 4.5 ka cal BP). During MH I, the high groundwater levels achieved during the early Holocene allowed the retention of wetland characteristics in several localities until *ca.* 7 ka (7.8 ka cal BP), (Servant and Servant-Vildary, 2003, Rech et al., 2003,

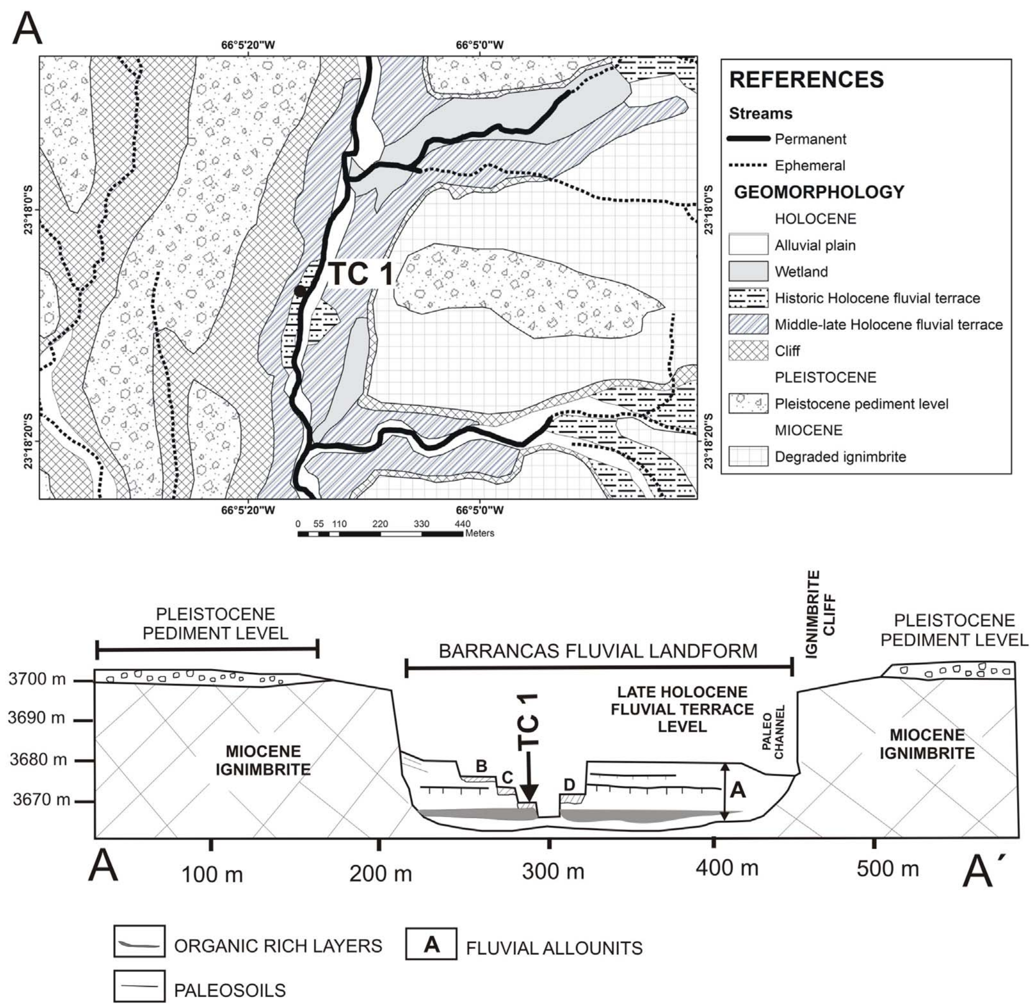

Fig. 2. Geomorphology of Barrancas River mid-section (plain-view) and cross-section of the Barancas basin, including TC1 location and main fluvial allounits.

Grosjean, 2001; Yacobaccio and Morales, 2005; Morales, 2011; Tchilinguirian, 2009; Tchilinguirian et al., 2014). In turn, the MH II seems to have been extremely arid in the regional scale. Locations above 3000 m asl present evidence of a more or less synchronic interruption in moisture input at about 6.2 ka (7.1 ka cal BP), and a strong desiccation event around 5 ka (5.7 ka cal. BP) (Tchilinguirian and Morales, 2013).

3. Material and methods

A 226 cm long core was drilled in the Holocene terrace of the mid-section of Barrancas River in a place locally known as "Cruces" (Fig.2). A relatively constant and regular sedimentation of fine grain (silts to fine sands) was observed in TC1, with the exception of a 15 cm-section in the bottom of the core, between 225 cm and 210 cm deep, composed by upward coarsening sands (Fig.3). Four AMS radiocarbon dates were obtained from bulk OM of organic layers, which were consistent with our sediment observations (Fig. 3), indicating: a) a sedimentary unconformity at 210 cm (Fig.3), probably caused by fluvial erosion activity, between a final Pleistocene date and a mid-Holocene date, and b) a relative stable sedimentation rate (between 11 yrs/cm and 15 yrs/cm) during the mid-Holocene (see below). The geomorphology of the Barrancas River basin was studied through satellite imagery interpretation (Landsat and higher resolution Google Earth TM images) and terrain survey, allowing the identification of different levels and types of fluvial terraces. Several naturally exposed sediment sequences of the terraces were studied along the basin. The stratigraphy of TC1 was studied following Miall (1982, 1996) and Friend (1983), describing the lithofacies grain size (Fig. 4), sedimentary and soil structures and color. Those lithofacies were associated to local sedimentary facies in order to interpret the general sedimentary environment. These dates indicate that the core spans the 11.5 ka to *ca.* 3.5 ka (*ca.* 13.4 ka and 3.8 ka - cal. BP) period.

Several proxies were studied at different intervals in Cruces Core 1. Diatoms and pollen were analyzed in 4 and 8 cm intervals, respectively. This implies a 40–60 years resolution for the diatoms record, and 80–120 years for pollen, as indicated by the linear interpolation age-depth model developed using Clam v.2.2 (Blaauw, 2010). Organic matter and carbonate content and magnetic properties of sediments were analyzed in each centimeter of the core resulting in records with decadal resolution.

3.1. Techniques

Samples for organic matter (OM) and carbonate content determination and magnetic properties measurement were air-dried and pulverized in a ceramic mortar. Organic matter (OM) and carbonate content (% w/w) was determined by LOI using a muffle furnace at 390 °C for 16 h (OM) and 950 °C for 2 h (Ct) (Pirola, 2014). Samples were previously dried overnight at 95 °C.

Initial 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) (Evans and

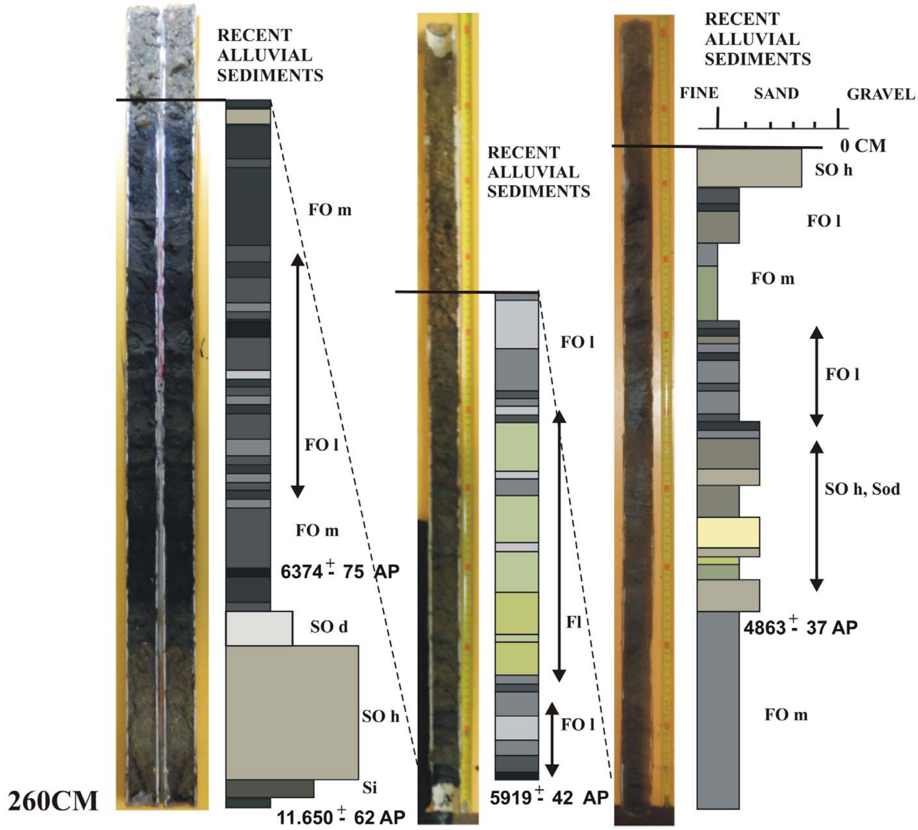

Fig. 3. Scheme of the core (including pictures) with stratigraphic and grain size scheme, sediment facies and location of AMS dates.

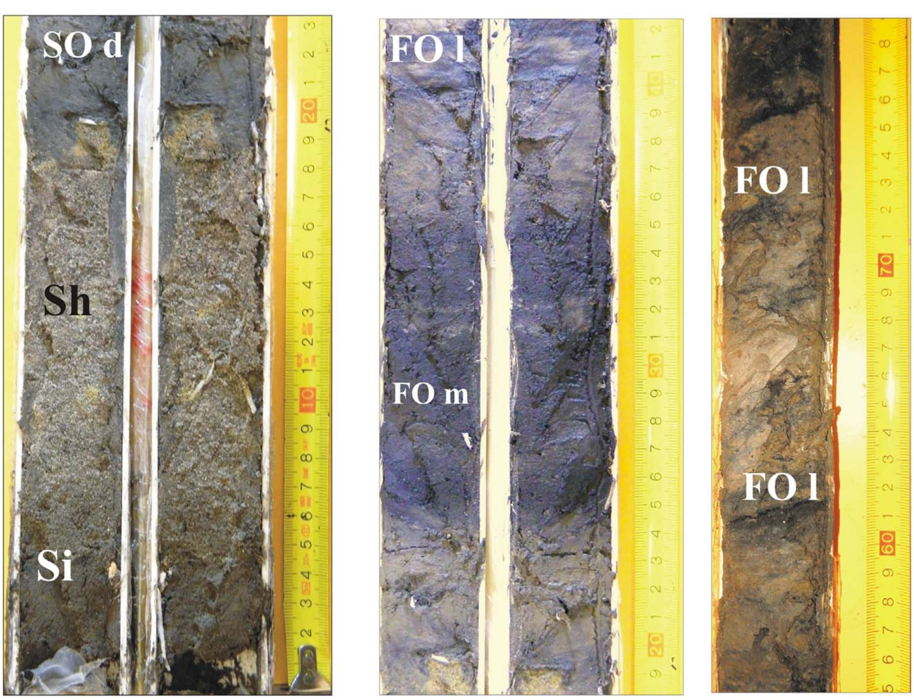

Fig. 4. Details of the different sediment facies.

Heller, 2003).

Diatoms samples were treated following standard procedures (Battarbee, 1986), mounting the material in permanent slides with Naphrax®. Diatoms valves were identified and counted (300–400 valves per slide) with OM (Reichert-Jung Polyvar, 1000 ×) and SEM (Zeiss Supra 40, up to 30,000 ×). Latter observations in SEM were performed in the CMA (*Centro de Microscopía Avanzada*), FCEN, Buenos Aires University. Taxonomic determinations were bases on Levkov et al. (2013), Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b), Round et al. (1990), Rumrich et al. (2000) monographic works and several studies about diatoms biodiversity in Argentinean Puna ecosystems (Maidana and Seeligmann, 2006; Maidana and Mascitti, 1998; Maidana et al., 2009, 2011; Seeligmann and Maidana, 2003; Seeligman et al., 2008; Grana et al., 2016). Ecological affinities of diatoms were obtained from Lowe (1974), De Wolf (1982), Vas and De Wolf (1993) and Van Dam et al. (1994) and specific papers about several taxa (e. g.

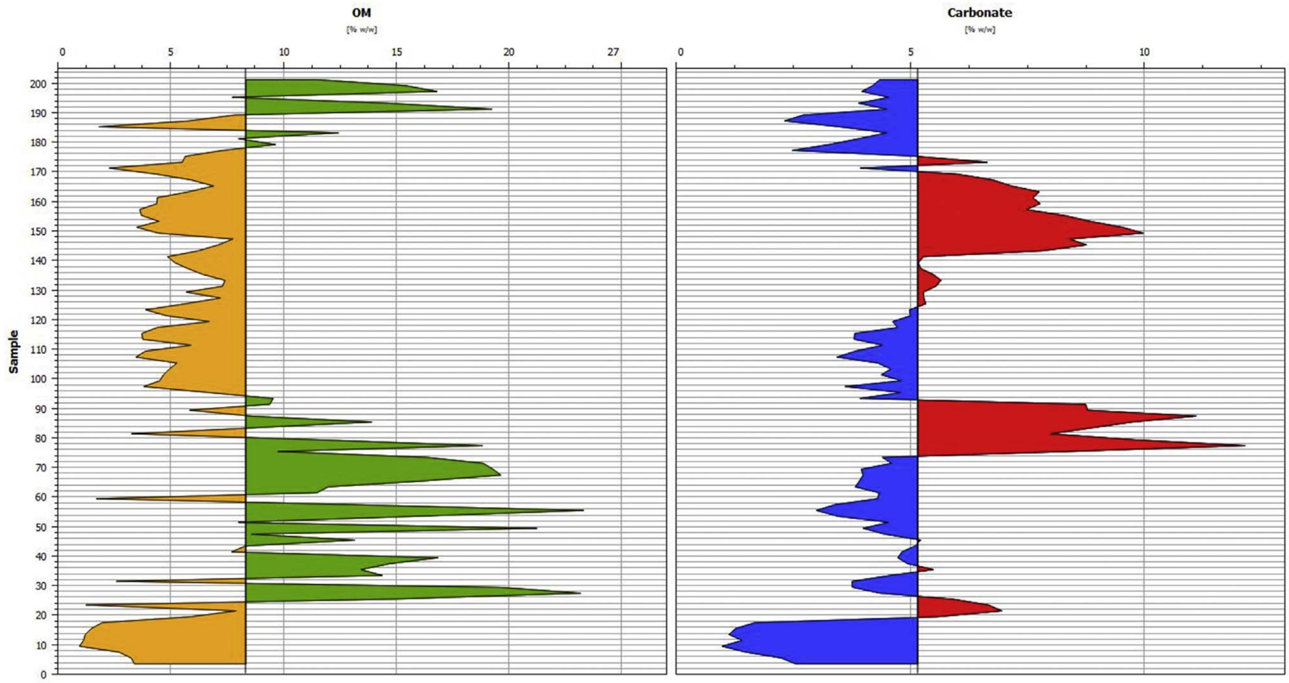

Fig. 5. Organic matter and carbonate content of the TC1 profile.

Levkov et al., 2013). As in previous works, (*e.g.* Tchilinguirian and Morales, 2013; Morales et al., 2015) our general paleoenvironmental interpretations rest on a moisture index, based on a ratio of diatom life-form affinities (*i.e.* Benthic + Epiphitic + Planktonic / Aerophiles).

Pollen samples were processed following the standard techniques for Quaternary sediments (Erdtman, 1960; Gray, 1965; Faegri and Iversen, 1989). Processing included determining of sample volume by volumetric displacement and the addition of two *Lycopodium clavatum* tablets (x = 12,450) per sample to calculate pollen concentration (grains/ml) (Bennett and Willis, 2001). Standard palynological techniques were applied for pollen analysis, which includes the use of KOH, HCl, HF and acetolysis processing (Faegri and Iversen, 1989). Microfossil samples were mounted in glycerine and pollen was counted under × 400 and × 1000 magnification. For pollen identification, our own reference collections and published atlases and keys were used (Heusser, 1971; Markgraf and D'Antoni, 1978; Torres et al., 2012). Regional pollen types were counted until the sum of 200 was reached in each sample. Plotting and zonation are based on a Cluster Analysis carried out with Tilia 2.0.2 software (Grimm, 2004). Pollen zones were determined by CONISS stratigraphically constrained Cluster Analysis (Grimm, 2004). The pollen taxa selected for this analysis were Poaceae, Chenopodiaceae, Asteraceae and Celtis. The TGView program was used for plotting diagrams (Grimm, 2004). CONISS cluster dendrograms are displayed on the right side of the palynological diagram, showing the pollen zones. In order to interpret this diagram, the characteristic pollen types for each geological and ecological Puna belt were grouped based on Cabrera's (1976) phytogeographic classification: shrub steppe (Puna), herbaceous steppe (High Andean steppe), disturbance indicators, local humidity (wetlands) and trees (in this case, from the tropical montane forest, known as *Yungas*).

4. Results

4.1. Geomorphology and sediments

The TC1 core was recovered from the mid-section of the Barrancas river (23°18′7.10″S, 66° 5′13.95″O, 3670 m) which has a 54 km^2 catchment at the sampling locus. In this section the river cuts deeply (20 m) into Miocene ignimbrites and Pleistocene piedmont conglomerates, forming a narrow valley 450 m-wide (Fig. 2). At both sides, four fluvial terrace levels were detected. The highest terrace (+ 9 m above riverbed, A, Fig. 2) is the most extended. The other terraces, intermediate (+ 6 m, B, Fig. 2) and low (+ 3 and + 2 m, C and D, respectively, Fig. 2) are odd erosion terraces associated to fast late Holocene excavation by the fluvial system.

Holocene deposits are represented by four allo-units separated by erosive surfaces (unconformities type 4, Miall, 1982, 1996, Fig. 2). The deposits formed by paleo-soils and fluvial sediments of the terrace of + 9 m corresponded to allounit A. Allo-units B, C and D corresponded to coarse well stratified sediments that form the intermediate and low level terraces. They are deposits of 1 to 2,5 m thick that lie on an erosive unconformity over allo-unit A. These sediments have been estimated (by stratigrafic correlation) as post 1000 years BP.

TC1 is stratigraphically located below the level of the current Barrancas River bed and constitutes the lower, non-exposed section of the Cruces 2 profile (PCC2), formed by the bottom section of allounit-A (*i.e.* Allounit A1 and the bottom half of A2). This means that a substantial section of TC1 (*ca.* the upper half) constitutes the lower section of the PCC2 profile, located in the left margin of the river, whereas the lower section of TC1 (located in the right margin) remains buried in PCC2. Allounit A has been exhaustively described in another paper in this volume (Pirola et al., in this volume) (Fig.1).

Sands are the main grain size in the TC1 core. Downward fining, coarse brown-greenish (2,5Y 6/2) sands (Si) are dominant at the base of the core. These sediments present roots traces and mottles and were interpreted as moderate-energy fluvial channel deposits (Figs. 3 and 4). The rest of the core is dominated by very fine sand and diatomaceous silt. These facies are detritic-organic (F) and organic (FO) when OM reaches 15%. It also presents thin layers (1 to 5 cm) with different colors: black (2,5Y 2/1 or 7Y 2/1), dark grey (5Y 3/1), light grey (5Y 6/1) and olivaceous (5Y 7/2) (Figs. 3 and 4). The main sediment structure present in these facies is thin flat horizontal lamination. Permanently high and stagnant groundwater causes the developments of the layers of organic or peaty material (Fen) and reduced green olive colors, corresponding to Fe^{2+} and Fe^{3+} hydroxyl salts. For this reason, we consider that these organic-rich alluvial layers correspond to a permanent fluvial environment with several small channels, ponds with periphitic vegetation, and "vega"-like environments (*i.e.* peatlands).

4.2. Organic matter and carbonate

Mean OM content was relatively high along the core, although OM % values presented a high variability (mean 8.75%, SD 5.60%), ranging from 0.94% at its lowest to 23.34% at its highest (Fig. 5). The inferior segment of the core is characterized by anomalous, low values, which coincides with the more coarse-grained fluvial sediments in the sequence. Between samples M177 and M81 (5943–4629 BP; 6774–5350 cal BP), OM% values were generally lower than the mean of the series (Fig. 5). In contrast, above average OM% values characterize the top-most section between samples M201 and M189 (4463–4296 BP; 5171–4991 cal BP) and the segment between M77 and M28 (6374–5975 BP; 7310–6815 cal BP), including anomalous or extremely high OM content (Fig. 5). Carbonate content presented a mean of 5.10% with a SD of 2.27%, ranging from 0.97% to 12.16%. Three segments presented values below the mean of the series: M201–M171 (4712–4296 BP; 5440–4991 cal BP), M123 - M93 (5794–5378 BP; 6609–6160 cal BP), and M73 - M31 (6343–6007 BP; 7280–6855 cal BP). As was the case for OM content, anomalously low values were prominent in the bottom-most segment of the core. Two segments were characterized by high carbonate content, including anomalous values: M91–M75 (5991–5822 BP; 6835–6639 cal BP) and M173–M125 (5350–4685 BP; 6130–5410 cal BP) (Fig. 5).

4.3. Magnetic properties

The shape of hysteresis loops (Fig. 6) and the measured magnetic parameters (Fig. 7) indicate that the prevailing magnetic mineral throughout the sequence is magnetite or titanomagnetite, although paramagnetic minerals are also abundant. These contents are consistent with the source areas that surround the studied profile. These are mainly Miocene ignimbrites, which are frequently impoverished in ferrimagnetic minerals and enriched in paramagnetic ones.

The bottom section of the sequence, which has been assigned to a fluvial phase on the basis of stratigraphic description, presents an upward-coarsening tendency observed in the increase of extensive magnetic parameters (χ, Ms and Mrs) and decrease of intensive properties (Hc and Hcr) (Fig. 7), which indicates that magnetic results are in agreement with the general geological description of the core.

A peak of χ, Ms and Mrs, indicative of an increase in magnetic content and/or grain size, is observed in the M81 sample (*ca.* 6 ka or 6.8 ka cal. BP) (Fig. 7). This could be interpreted as a discrete event of volcanic ash input into the sedimentary sequence. Considering that a few kilometers upstream from the TC1 site there are tufa outcrops, locally known as Morro Blanco, this magnetic signal could indicate a period of enhanced local erosion, possibly caused by intense torrential events. Well within a late Holocene chronology, in M148 and between M173 and M163, (Fig. 7) there is a similar increase of extensive magnetic parameters consistent with increased magnetic grain size (χ/Mrs ratio), possibly related to the intensification of prevailing winds.

Day plot (Mrs/Mr *vs.* Hcr/Hc, Fig. 8) determination shows a diversity of magnetic particle groups, two of which represent mixed grain size and mineralogy populations. One of these groups (red stars, Fig. 8) belongs to the M09–M18 segment and is consistent with a single domain (SD) + 10 nm superparamagnetic (SP) grain-size distribution (Dunlop, 2002). This segment is located below the levels with the highest OM values in the TC1 core. SP particles may have both an organic or inorganic origin, typical of reducing environments punctuated by intermittent oxidating conditions (Orgeira et al., 2011). Therefore, the SP fraction between M09 and M18 may be the product of lixiviation from the overlying, organic-rich layers. Another group (green dots, Fig. 8) consists of samples with Mrs/Ms ratios between 0.1 and 0.5 and Hcr/Hc values between 1 and 2, which were obtained mainly from the top half of the TC1 core. These ratios have been assigned by Dunlop (2002) to a mix of SD + multidomain (MD) particles, of which one fraction consists of titanomagnetite TM60 (*i.e.* 60% of Ti content).

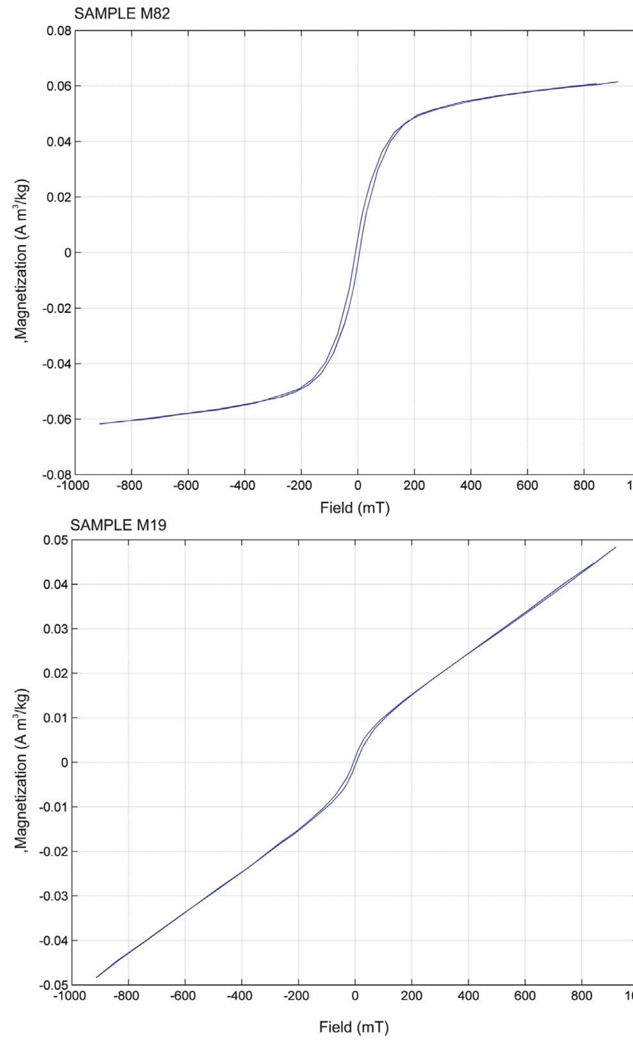

Fig. 6. Examples of TC1 hysteresis loops obtained that indicate significant magnetite content (sample M82) or a predominantly paramagnetic composition (sample M19).

Titanomagnetites with high Ti-content are typically associated with basic rocks, which are scarce at best in the water catchment area of TC1. This suggests that titanomagnetite particles were transported to the TC1 site by the wind. The most likely source of these minerals is a basalt outcrops in the Cerro Coranzulí. There are other possible sources, such as basalt flows in the Rachaite and Tuzgle mountains (Sola, P., pers. communication, 2016). However, the direction of prevailing winds in the region today and up to at least 150 Kyrs (Bailey et al., 2007; De Silva et al., 2010) was NW-SE. The Coranzuli basalt flows, located < 50 km away to the NW of the locality of Barrancas, are therefore the most likely candidate as source of the titanomagnetite detected in the TC1 core.

4.4. Diatoms

A total of 140 taxa were identified in the 56 fertile samples analyzed. 65 of them were frequent (> 5% in at least one sample). Only a few of them were sufficiently frequent in many samples to let us statistically identify floristic zonations: *Denticula valida*; *Denticula aff. sundayensis*; *Diadesmis gallica*; *Hantzschia amphyoxis*; *Humidophila contenta*; *Luticola andina*; *Luticola subaequalis*; *Navicula lauca*; *Navicula libonensis*; *Nitzschia halloyii and Pinnularia borealis* (Fig. 9). Five zones (A to E) were identified using this method (Fig. 9). A and B have also been subdivided in two (A1 and A2) and three (B1 to B3) sub-zones, respectively. Sub-zone A1 (M0-M17) was dominated by *D. gallica*, a

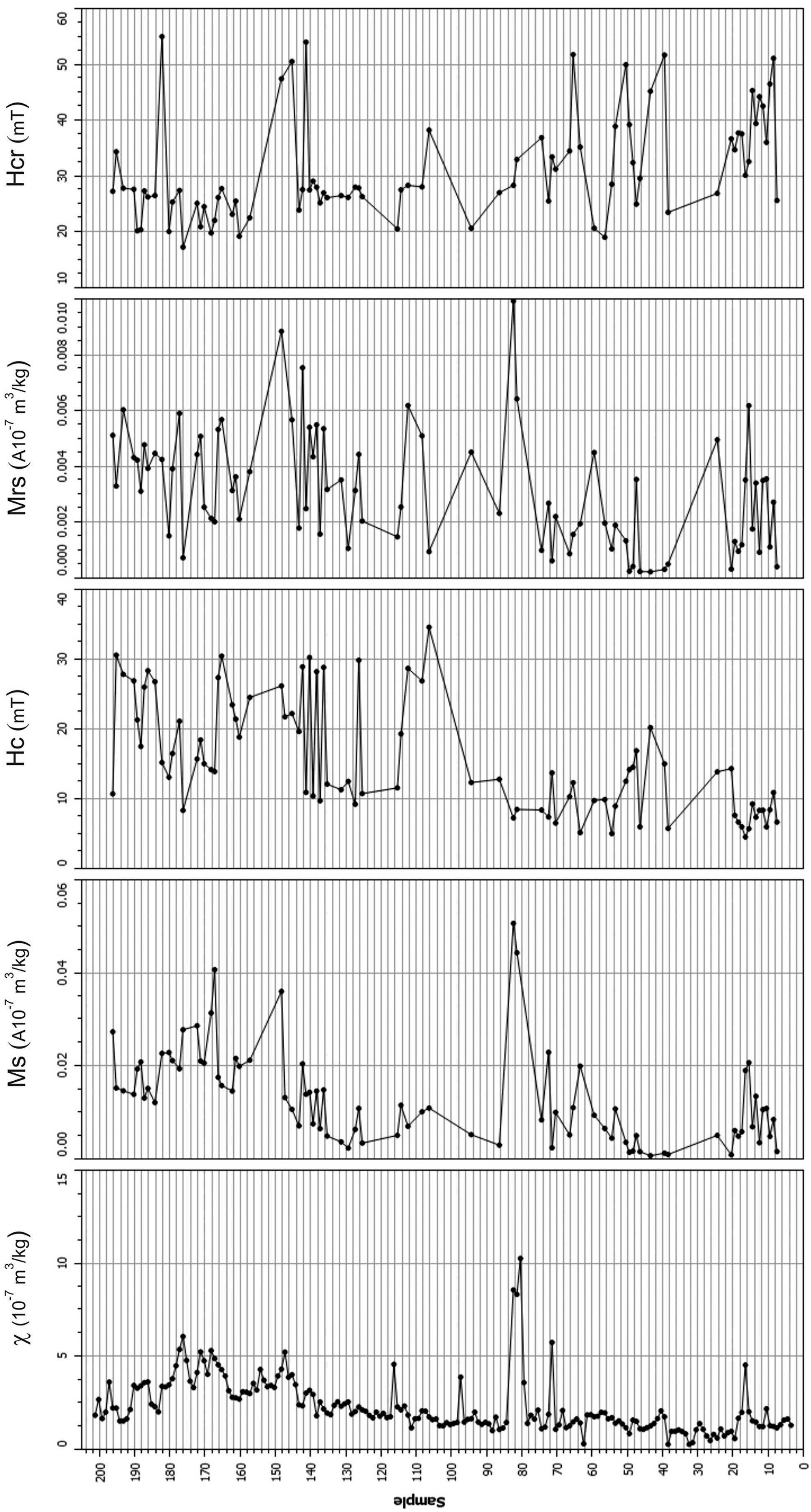

Fig. 7. Magnetic properties of the TC1 sediment record: χ (mass magnetic susceptibility); Ms (saturation magnetization); Hc (coercive force); Mrs (saturation remanence); and Hcr (coercivity of remanence).

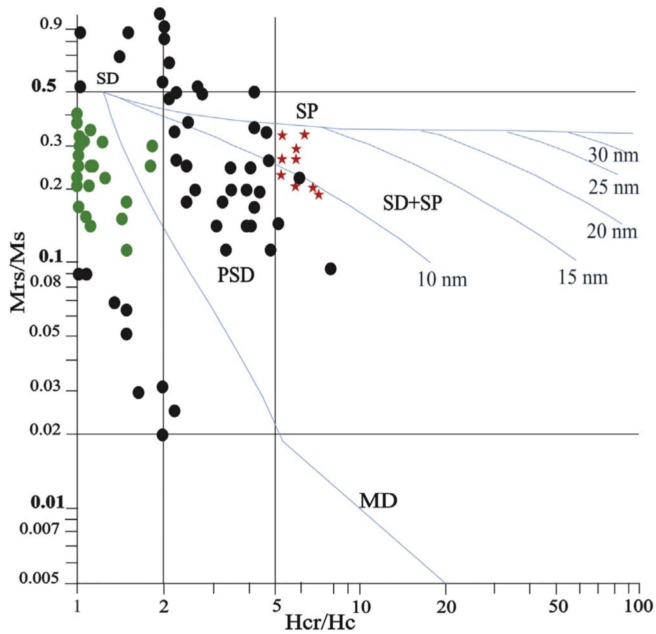

Fig. 8. Magnetic particle size distribution of TC1 (Day plot). Red stars indicate SD + SP magnetic particle size distributions within the M9–M18 section of the core. Green dots indicate samples with a SD + MD magnetic particle size distribution. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

species usually found in shadowed areas (*e.g.* under plants with dense coverage). This species was followed by *D. valida*, *N. lauca* and *L. andina*, while *L. subaequalis* and *N. halloyii* completed this assemblage in the lower part of this segment. This sub-zone also presented other species frequently found in floodplain areas such as the planktonic *Cyclotella meneghiniana* and *Cyclotella agassizensis*. In sub-zone A2 (M21–M53), valve abundance/g was noticeable higher and the dominant assemblage included *N. halloyii*, *N. lauca*, *N. libonensis y H. contenta* (the latter was remarkably abundant the initial samples of this sub-zone); these species were followed by *D. gallica* and *L. andina* only in the upper part of the sub-zone (Fig. 9). A2 could be considered as the more humid moment in the sequence, particularly between 6374 BP (7289 cal BP) y 6308 BP (7138 cal BP), as indicated by the dominance of benthic species coupled with an increase in diatom valve concentration (Fig. 10). Sub-zone B1 (M57–M81) was dominated by *D. valida*, *D. gallica* and *L. andina*, followed by *N. halloyii* and very low frequences of *L. subaequalis*, *P. borealis* and *H. amphioxys*. This section (more precisely between 6308 and 5919 BP or 7138–6698 cal BP) presented similar conditions and diatom assemblages to sub-zone A1, suggesting more arid conditions, such as those prevailing during the late Pleistocene (Figs. 9 and 10). Sub-zone B2 (M85–M109) was very similar to B1, but with different low frequency taxa, particularly *D. sundayensis* and *N. libonensis*. Sub-zone B3 (M113-M145) registered a rise in the frequency of *L. andina*, *L. subaequalis* and *N. lauca* and a drop of *D. valida*. Zone C (M149-M185) was dominated by *L. andina* followed by *L. subaequalis*, *P. borealis*, *H. amphioxys*, *N. haloyii* and *N. lauca*. During the ~1000-year span between M85–M157 (5919–4919 BP or 6698–5569 cal BP) –which includes sub-zones B2 and B3 – we observed unstable but more humid conditions than the observed in the previous section (B1) (Figs. 9 and 10). However, those conditions were still less humid than those registered between 6374 y 6308 BP (A2). The recurrence of planktonic species such as *Discostella stelligera* in this period – particularly between M93 and M125 in B3 (Fig. 10) – possibly indicates a rise in the frequency of ephemeral fluvial events in this locality. Zone D (M193–M213) was dominated by an assemblage including *D. valida*, *N. lauca* and *L. andina*, followed by *H. amphioxys*, *P. borealis*, *L. subaequalis* and *D. sundayensis* (the latter only in the lower section of the zone). Finally, zone E (M217–M225) was broadly dominated by *L. andina*, followed by *L. subaequalis*, *P. borealis* and *H. amphioxys* in low frequencies. The top section of the core (M157–M225), after 4863 BP (5506 cal BP), was the driest of the series as shown by low values of the moisture index, particularly after 4000 BP (Fig. 10).

4.5. Pollen

According to the cluster analysis, the palynological spectra can be divided in 5 pollen zones (Fig. 11). Zone 1 (*e.g.* M1, *ca.* 11.5 ka or *ca.* 13.4 ka cal. BP) presents high values of Asteraceae (50%) and low frequencies of Pteridophytes (< 5%) (local moisture indicator) and Chenopodiaceae-Amaranthaceae and Malvaceae (< 5–20%) (indicators of disturbance), suggesting regional dry conditions. Zone 2 (*e.g.* M9–M25, post 11,650–pre 6374 BP or post 13,400–pre 7289 cal. BP) presents a

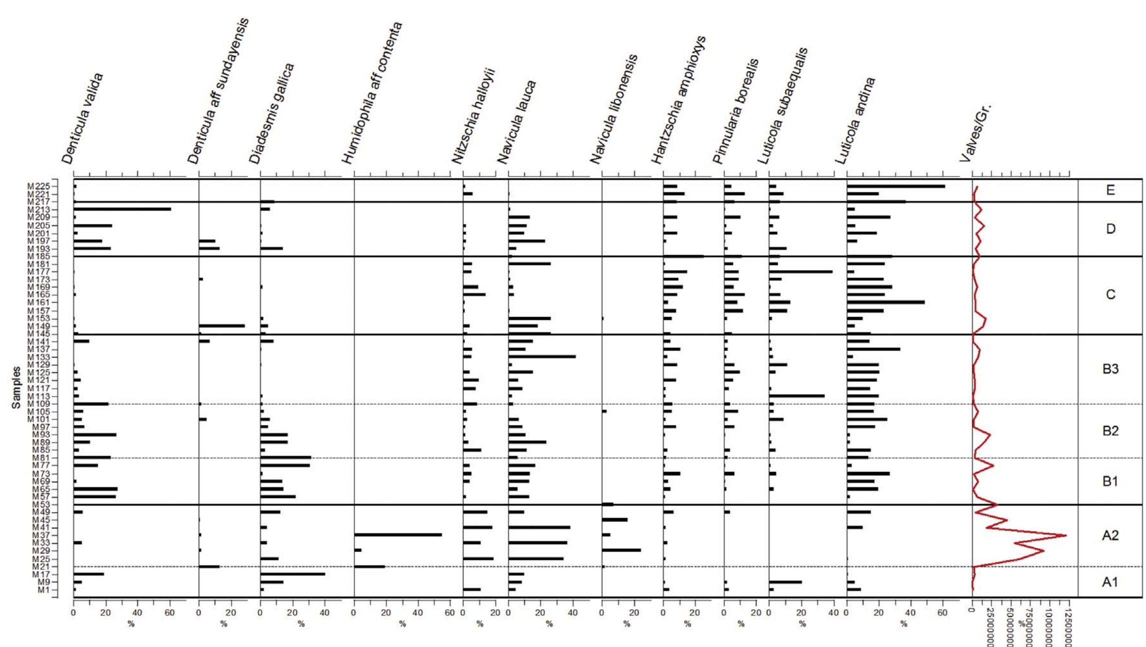

Fig. 9. Most frequent (> 5%) diatoms taxa, diatoms concentrations and floristic zonation.

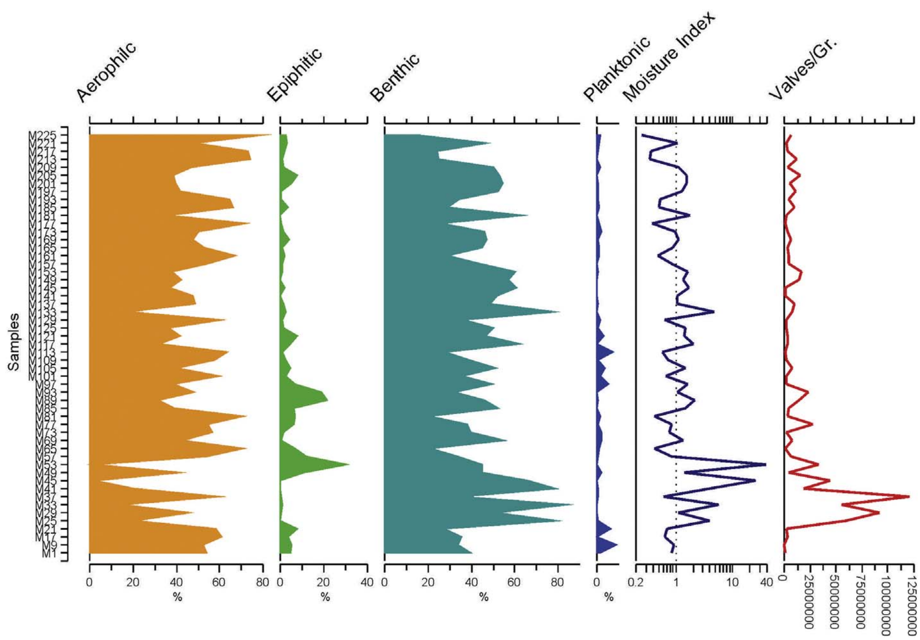

Fig. 10. Diatom life-form affinity spectra, moisture index and diatoms concentrations.

marked increase in the frequency of herbs (50–90%) and the core's lowest values of pollen concentration (Fig. 12). The herbs signal suggests a steady increase in local moisture availability, while the low pollen concentration could be associated to fluvial activity – *e.g.* erosion- in this locality. Zone 3 (M33 - *ca.* 6374 BP or 7289 cal. BP) can be considered a different zone due to the presence of Caryophyllaceae (Fig. 12), another indicator of local moisture availability, suggesting moister conditions than Zone 1. Zone 4 (M57–M89, 6374–5919 BP or 7138–6698 cal. BP) shows the dominance of herbs with a moderate increase of shrub steppe components (10–30%) towards M73, then decreasing near 5919 BP (6698 cal. BP), while herb frequency rises again (Fig. 11). Zone 5 (M97–M217, post 5919 BP or 6698 cal. BP) shows a new drop in herbaceous steppe components (30–60%), followed by a rise in shrub steppe elements (20–40%) (Fig. 11). A broader diversity of shrubs was also identified during this span, including Rosaceae, Solanaceae and Portulacaceae (Fig. 12). The frequency of local moisture indicators remains relatively stable (5–15%) from M33 to M201, with the exception of the M89–M97 section (*ca.* 5919 BP or 6698 cal. BP) where they almost disappear (Figs. 11 and 12). The highest pollen concentration values of the series were observed after M145 (Fig. 11).

5. Discussion

During the period under study, the Barrancas River registered a general evolution between a permanent fluvial system towards an ephemeral one. At the end of the Pleistocene -*ca.* 11.5 ka (13.4 ka cal. BP)- sands and OM points to the presence of a low-energy but permanent river system (Fig. 13). Since then and until approximately 6.4 ka (7.3 ka cal. BP) the system increased its energy, as evidenced by the presence of fluvial erosion, low pollen concentration, low abundance of diatom valves, low OM/carbonate content, and magnetic

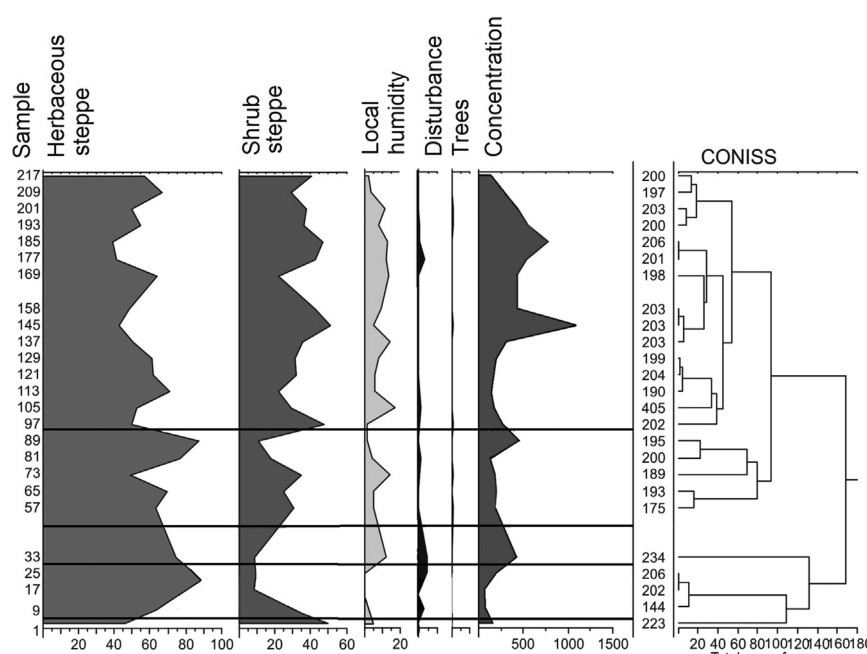

Fig. 11. Most frequent pollen taxa.

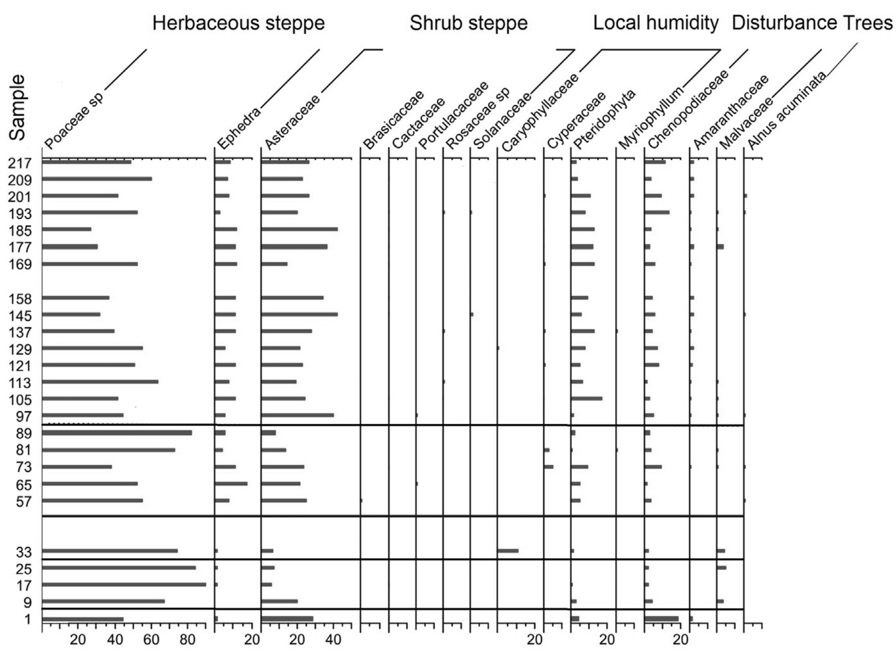

Fig. 12. Pollen ecological spectra, zonation (CONISS) and pollen concentration.

properties of sediments (Fig. 13). This erosive process appears to have occurred during a regional arid phase that ends with the onset of late Holocene conditions (see above). This regional trend towards aridization is widely supported by regional paleoenvironmental information (Mayle and Power, 2008; Sáez et al., 2016; Tchilinguirian and Morales, 2013), as well as by the TC1 multi-proxy record. For example, after 6.4 ka (or 7.3 ka cal. BP) the pollen record clearly shows the presence of a herbaceous steppe that dominated the local landscape until *ca.* 5.4 ka or 6.1 ka cal. BP (*i.e.* M97–105), when shrubs began to increase their signal substantially (Fig. 13). However, as suggested by local pollen, geomorphology and diatom indicators, around this date and until 5 ka (about 5.6 ka cal. BP), the local landscape presented a wetland environment, dominated by a relatively low energy fluvial-palustrine system with shallow ponds and abundant periphytic vegetation (Fig. 13). These characteristics suggest spatial and temporal environmental stability that supported the development of organic rich soils. This wetland environment also contained a small but permanent river flow and a shallow or even overflowing water-table during most of the year. Nevertheless, it is worth noting that, at least between 6.4 ka and 5.9 ka (or between ~7.3 ka and 6.7 ka cal. BP), dry episodes might also have increased their frequency or intensity, as indicated by magnetic properties of sediments and fluctuating carbonate contents (Fig. 13).

Some particularly wet and dry phases or events were detected in the TC1 record (Fig. 13). On the one hand, humid episodes were particularly frequent and intense up to 6 ka (approximately 6.8 ka cal. BP). Other less intense wet events, possibly related to the intensification of fluvial activity – as indicated by geomorphology, OM and carbonate content in sediments – were detected between 5.8 ka and 5 ka (~6.6 ka and 6.1 ka cal. BP) (Fig. 13). On the other hand, a sustained dry phase was evident since 5 ka, only interrupted by the scattered slightly moister events that occurred between 4.7 ka and 4.2 ka (or *ca.* 5.3 ka and 4.8 ka cal. BP) (Fig. 13).

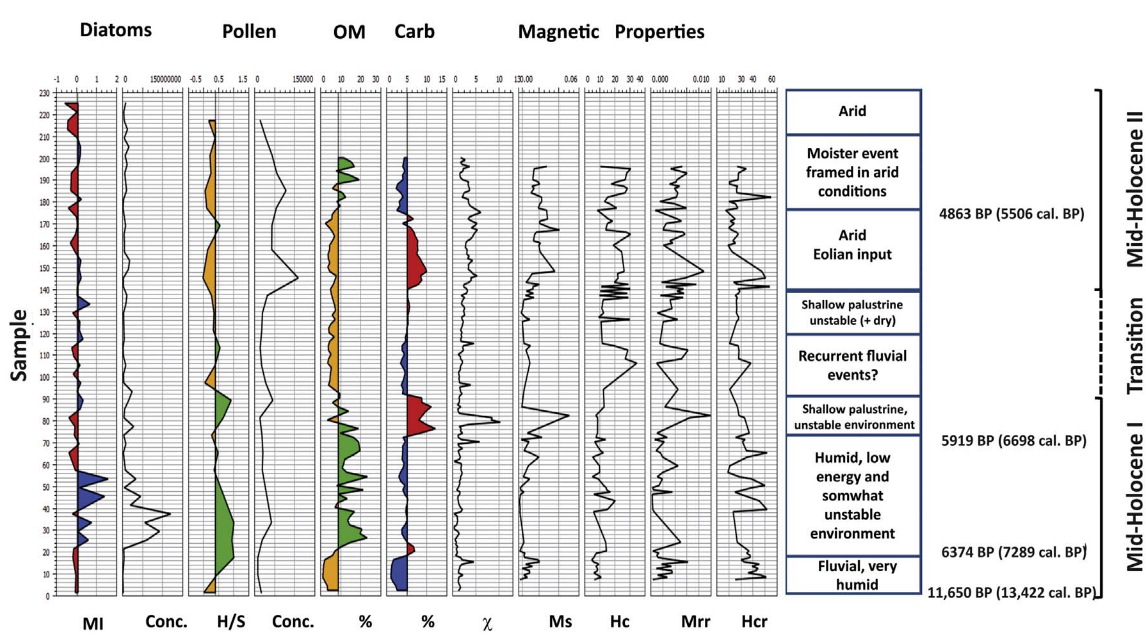

Fig. 13. General synthesis of multi-proxy signals: paleoenvironmental interpretation.

This general paleoenvironmental characterization reinforces the idea of a non-homogeneous mid-Holocene, possibly showing two different moisture "phases" (Fig. 13). An early one, more humid, unstable and heterogeneous, that we have previously defined as mid-Holocene I (*e.g.* Yacobaccio et al., 2016a), between 8.2 ka and 6 ka. The second phase more arid, stable and homogeneous, the mid-Holocene II, developed between 6 ka and 4.4 ka. A gradual transition between both is expected, but with chronological variation depending on the nature of the system in terms of its catchment (*i.e.* size, altitude, hypsometry), local geomorphology (depth to impermeable layer; hydric section) and elevation (Grana et al., 2016). In the Barrancas case, the transitional phase seems to have occurred between 6 ka and 5 ka, including fluvial wet episodes and saline dry events (Fig. 13).

Additionally, some remarks should be made in terms of the ecosystem services of this locality for hunter-gatherer populations during the period. As we mentioned in previous papers (Yacobaccio, 2013; Yacobaccio et al., 2016b, 2017), the mid-Holocene could be characterized as a moment of habitat fragmentation and habitat loss for hunter-gatherers; however, these processes were probably gradual. Although some environments may have been subject to discrete arid events during MH I, it was only during MH II that substantial habitat loss occurred in the area. Despite these adverse conditions, a few scattered, highly productive landscapes – in terms of primary and secondary biomass and water accessibility - remained available during the MH II. These *loci* are commonly characterized as resilient environments that constituted ecological refugia, "niches of moisture" (*sensu* Ledru et al., 2013) or nodes that nucleated human groups and animal populations (Yacobaccio et al., 2016b). In other words, the hostile conditions of MH II forced a close cohabitation between humans and animal species -particularly camelids- fostering complex ecological interactions such as protective herding (Yacobaccio and Vilá, 2013), which would eventually lead to the domestication of the species. The recurrent –or even periodical - occupation during MHII of these stable landscape features could also triggered density-dependent processes such us the increase of complexity in hunter-gatherers' organizational traits and the consolidation of formal, long-distance social and goods' circulation networks (probably emerged during MH I).

The Barrancas basin seems to have been one of these "niches of moisture" in the Dry Puna landscape, however fluctuating its resources offer over time. During the early Holocene, the Barrancas hydrological system seems to have supported a permanent river that probably offered little in the way of development of pasture for camelids; however, such an environment surely provided good opportunities for water provisioning and circulation. Framed in extremely arid regional conditions, during the mid-Holocene, Barrancas turned into an extensive, highly productive and stable wetland environment, available for recurrent/permanent occupation/exploitation for humans and other species. It is remarkably that even in the harshest phase of the mid-Holocene (*i.e.* MH II) this locality seems to have retained enough moisture to maintain a low energy fluvial flow, enable soil development and sustain significant vegetation coverage. These elements provide support to our proposal of Barrancas as a resilient habitat –*e.g.* a system with some degree of resistance and spatial-temporal stability (Davis et al., 2013), It also fits well with the concept of ecological refugia proposed by Keppel et al. (2012), - *i.e.* a site to which biota retreat, persist in, and potentially expand from, under changing environmental conditions.

6. Conclusion

Taking the Cruces Core 1 record as a whole, we can interpret this environment during the studied span as a fluvial system that progressively lost its energy along the Holocene, turning into a wetland or a vega-type landscape environment with several shallow ponds and a small, low energy river flow. In this process we can distinguish two general environmental phases and a transitional span. The record begins with a relatively wet environment during the late Pleistocene that increased its energy during the early Holocene and the first part of the mid-Holocene, both absent in the record due to fluvial erosion. This environment was followed by a gradual transitional between 6 ka and 5.1 ka characterized by an unstable wetland environment fluctuating between fluvial wet episodes and shallow paludal and brackish environments. Finally, since 5.1 ka, a noticeable drop in local moisture availability was evident, as shown by a shrub steppe pollen rise, low diatom moisture index and high values of carbonates. An intensification of aeolian input is also evident during this moment, as shown by magnetic properties. The characteristics of this paleo-landscape is clearly different to current conditions in the basin, where the fluvial system follows braided channels, with fine gravel and coarse and medium sand bars and high detritic input from highlands, unable to support organic rich soils development (peatlands) or dense riparian vegetation. The archaeological relevance of Barrancas is related to its likely function as a resilient habitat, suited for circulation and/or settling of human populations throughout the Holocene. Barrancas probably played a key role for human populations in the area, offering significant chances for water and food-prey provisioning even during the harshest moments of the Holocene, thus constituting an ecological refuge for mid-Holocene hunter-gatherers in the Dry Puna.

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