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Environmental trends between 2400 and 1200 BP in Barrancas, Argentinean Puna: Impacts on local resource variability and socioeconomic organization

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Abstract

This paper presents a multiproxy analysis—geomorphology, organic matter, and carbonate content, diatoms, pollen, and magnetic properties of sediments—of the Barrancas Pueblo profile, located in Barrancas, Jujuy, Argentina (S 23°18′08,7; W 66°05′15,2; 3666 m.a.s.l.) to explore local environmental change over the last few millennia. This study is part of a broader investigation of the environmental conditions that facilitated and/or triggered the development of a mixed herding and hunting economic strategy during the late Holocene. The results suggest ongoing local moisture availability for most of the late Holocene; between 2400 and 1500 BP there was a stable, low energy environment that supported a vegetated floodplain, resulting in high availability of pasture and water. However, throughout most of the studied period, there were punctual arid episodes and erosion of the river catchment. High environmental variability post-3000 cal BP could have put a premium on strategies to reduce the risk associated with resource unpredictability, such as economic specialization and intensification and storage practices designed to control and mitigate resource variability. This process could have ultimately lead to the consolidation of the Andean pastoralist way of life ca. 3000–2500 BP.

KEYWORDS

Andes, late Holocene, multiproxy analysis, paleoenvironment, Puna de Jujuy

1 | INTRODUCTION

One of the main objectives of the Barrancas Archaeological Project, launched in 2011, is to explore 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. The paleoenvironmental studies conducted so far have focused on the period 12 000–2200 BP (PCC2: 4510 ± 80 and 2180 ± 30; TC1: 11650 ± 62 and 4865 ± 37 BP; Morales, et al. 2018; Oxman, 2015; Oxman & Hoguin 2018; Pirola, et al. 2018). Here we present the results of a multiproxy analysis of the Barrancas Pueblo Profile (PBP) that sheds light on the environmental changes that occurred in the Barrancas river basin from 2500 to 1200 BP. There is very little local evidence regarding environmental conditions and changes during this time; however, traditionally known to Argentinean archaeology as the "Formative" period, it involved significant changes in subsistence and social organization strategies, including the consolidation of a pastoralist way of life, the adoption of agriculture, ceramic technology and increased social–political complexity.

1.1 | The Puna ecosystem

The study area is located in the Puna of Jujuy, that comprises the arid highlands of NW Argentina, between 22° and 24° S and 3000–4500 m a.s.l. This area is defined as a highland desert biome, traversed by several mountain ranges with a NNE-SSW direction. Plant communities present altitudinal variations. While the "tolar" (shrub steppe) is located between 3000–3900 m a.s.l, "pajonal" communities (highland grasslands) are located between 4100–4700 m a.s.l (Cabrera, 1976). Between 3900–4100 m.a.s.l there is an ecotone with a mixed grass and shrub-steppe. Wetlands, locally known as "vegas", present a patchy distribution and occur within both the shrub and grass steppes (Borgnia et al., 2006). The Puna is characterized by high solar radiation, wide daily thermal amplitude, marked seasonality of rainfall that never exceeds 400 mm/year, and low atmospheric pressure. Summer precipitation in Northern Argentina is largely governed by the South American Monsoon-like System (Garreaud, Vuille, Compagnucci, & Marengo, 2009), which produces about 80% of the annual precipitation in the Andes highlands between December and February (Vuille & Keimig, 2004). Primary productivity is focused on stable hydrological systems such as primary basins, high valleys (Olivera, 1997), and wetlands.

Several permanent freshwater basins, salt lakes, pans, and playas constitute the general hydrological network of the Puna. A few rivers and springs, irregularly distributed over the landscape, are the main sources of freshwater, which is a critical resource for human and ungulate populations. In turn, these conditions determine a heterogeneous distribution of plant and animal resources. Some patches contain the majority of the available regional biomass (Yacobaccio, 1994). The most important wild animal food sources for humans in the Puna highlands in the past included the camelids *Vicugna vicugna* -"vicuña"- and *Lama guanicoe* -"guanaco"; a few rodents: *Lagidium viscacia* -"vizcacha"- and Chinchillidae -"chinchilla", and a cervid, *Hippocamelus antisensis* -"taruca".

1.2 | Archaeological background

Like all altitude deserts, the Puna constitutes a high-risk environment for human habitation due to resource unpredictability and patchiness, which has a profound impact on human adaptation to local environments (Winterhalder, Lu, & Tucker, 1999). However, there is a paucity of research on the relationship between environmental change and human strategies in this area during the past 2500 years BP, when strong changes in mobility patterns and social organization in hunter–gatherer societies took place (Morales, et al., 2009). This period, which traditionally has been defined as "Formative" (Castro & Tarragó 1992), related to societies which developed between 2500 and 1100 BP in NW Argentina, and which, according to the archaeological sites dated in this chronology, allows to infer prevailing agro-pastoral and/or pastoral practices, complemented with hunting strategies as from 2000 BP on (Escola, 2000; López, 2008; Muscio, 2004; Yacobaccio, Madero, Malmierca, & Reigadas, 1997-1998-98). In contrast with previous uses of the term to refer to a "cultural phase" (Willey & Phillips, 1958), we employ the concept "Formative" following Olivera (1992), to describe a specific way in which human populations applied certain adaptive strategies -for example, economic activities—in response to pressures caused by environmental -natural or social- change (Olivera, 1992, 2001).

Several agents of cultural change were active during this period in the Argentinean Puna, prompting local processes that increased social complexity, such as decreases in residential mobility in some areas and sedentarization and village settlement in others. In the Dry Puna, evidence of reduced mobility has been found in rock shelter and cave sites from 3000 BP on, and the earliest village-type settlements appeared by 2000 BP (Aschero, 1979; Fernández, 1988-89; Fernández Distel 1998; Muscio, 2004; Yacobaccio et al., 2011). Other indications of increased complexity include the expansion and intensification of long distance exchange networks (Aschero, 1994; López, 2008, 2013; Yacobaccio, 2001) through llama caravan trade (Muscio, 2001, 2004; Nielsen, 2003, 2007; Nielsen, Vázquez, Avalas, & Angiorama, 1999; Núñez, Cartagena, Carrasco, de Souza, & Grosjean, 2006; Tarragó, 1984, 1989; Yacobaccio, 2012), experimentation with new technologies such as pottery, metallurgy and textile production (Fernández Distel, 1998; García, 1997; González, 2004; Muscio, 2004; Olivera, 2001) and changes observed in rock art styles (Aschero, 1979, 1999; Aschero, 2006; Aschero, Martel, & López Campeny, 2006; Gallardo & Vilches, 1998; Gallardo & Yacobaccio, 2007; Gallardo, 2000; Gallardo, Castro, & Miranda, 1999; Hernández Llosas, 2001; Olivera & Podestá, 1993; Yacobaccio, Catá, Solá, & Alonso, 2008; Yacobaccio, et al., 2011). These societies had a mixed economy that focused on llama pastoralism with varying contributions of hunting and cultigen use - squash, quinoa, maize, and potato (Babot, 2004, 2006). Osteometry data obtained from archaeofaunal remains support these claims, since they record both llama and vicuña bone specimens, which suggests a mixed herding-hunting strategy (López, 2013).

In Barrancas, two sites were found that are relevant to this discussion of the Formative in the Dry Puna. The Morro Blanco rock shelter is located near the headwaters of the Barrancas river; three charcoal fragments obtained from archaeological excavation were dated to *ca.* 2250, 2800, and 3200 BP. Punta Motaite is an open-air site where 37 circular and square stone structures were identified; one of its occupations was dated to ca. 1800 BP (Pirola et al. 2018).

1.3 | Paleoenvironmental background: The Puna ecosystem during the late holocene (5000-1000 BP)

In the tropical and subtropical Andes highlands, a transition toward more humid conditions occurred between *ca.* 5000–3500 cal BP (Abbott et al., 2003; Bird, Abbott, Rodbell, & Vuille, 2011; Thompson et al., 1995; Thompson et al., 1998; Thompson, Mosley-Thompson, & Henderson, 2000) which has been considered to signal the onset of the late Holocene in the region. This general pattern could be explained by the progressive strengthening of the South American Summer Monsoon (SASM) driven by increasing SH summer insolation since 9500 cal BP (Bird, Abott, Rodbell, et al. 2011; Kanner, Burns, Cheng, Edwards, & Vuille, 2013). However, this millennial-scale, orbitally-driven process cannot account for short-term variability during the late Holocene (Bird, Abott, Vuille et al., 2011; Kanner et al., 2013; Vuille et al., 2012) which, in turn, has been attributed to the interplay of changes in the intensity and frequency of the El Niño Southern Oscillation or ENSO (Kanner et al., 2013), NH temperature, and Pacific SST gradient variations (Vuille et al., 2012).

Because most of the rainfall in the dry Puna of Argentina is related to the SASM, regional records of SASM intensity are useful to shed light on broad, coarse-grain climate change trends in the area, particularly because there are few sedimentary archives suitable to explore environmental change at the local scale. Because the PBP sequence was deposited between at least 2800 and 1000 cal BP, the following review focuses on this period, as represented in high-resolution paleoenvironmental records in the tropical and subtropical Andes.

One of the main features of the paleoenvironmental records of SASM intensity in the late Holocene post-3000 cal BP is its high variability at decadal and centennial time scales; moreover, the amplitude of short-term variability seems to have increased after 2200 cal BP (Bird, Abott, Rodbell, et al. 2011), possibly as a response to an increase in the frequency and intensity of ENSO events (Kanner et al., 2013). Oxygen isotope composition—$\delta^{18}O$ values—in authigenic calcite from Laguna Pumacocha in northern Peru indicates an intensification of the SASM from 2200 to 1500 cal BP, followed by weakening of the SASM from 1500 to 900 cal BP (Bird, Abott, Rodbell, et al. 2011). Similarly, the $\delta^{18}O$ record measured in speleothems of Huagapo Cave in the central Peruvian Andes show a short period of weakened SASM at 2600 cal BP, followed by a period of strong SASM -2500–1900 cal BP. After this, $\delta^{18}O$ values indicate a steady decrease of SASM intensity, reaching its lowest at 1500 cal BP (Kanner et al., 2013).

Multiproxy environmental research in the arid highlands of Catamarca supports the notion of a regional-scale humid phase from 3500 to 1600 cal BP, followed by a drier period (Grana, Tchilinguirian, Hocsman, Escola, & Maidana, 2016; Tchilinguirian, Grana, & Olivera, 2018; Valero-Garcés, Delgado-Huertas, Ratto, Navas, & Edwards, 2000). Evidence from the western slope of the Andes range is consistent with this proposal, where a significant glacial advance in northern Chile between 3100 and 1700 cal BP suggests an increase in effective moisture input (Grosjean, Geyh, Messerli, Schreier, & Veit, 1998).

Over the last few years a growing body of research conducted in the Dry Puna of Jujuy has provided valuable information regarding local variations in moisture availability. In the Yavi river, in the eastern border of the Puna of Jujuy, multiproxy research supports the notion of a period of increased moisture availability between 3900 and 2000/1500 cal BP (Lupo, Kulemeyer, Sánchez, Pereira, & Cortés, 2015). In turn, the Cerro Tuzgle high-resolution peat core suggests great variability between wet and dry conditions in this high-altitude wetland over the past 2100 years, including a predominantly dry phase between 2000 and 1850 cal BP and wet phase from 1850 to 1400 cal BP (Schittek et al., 2016).

1.4 | Environmental change in Barrancas

To date, two sedimentary records of local environmental change—Cruces core 1 and Cruces 2 profile—have been studied in the Barrancas locality through geomorphology and sedimentological analysis, pollen and diatom studies, geochemical indicators, and magnetic properties.

The 2.3 m long Cruces 1 Core was extracted from the current river bed and dated to between the end of the Pleistocene (ca. 12800 BP) and the mid to late Holocene transition (ca. 4800 AP). Humid conditions dominated the Barrancas basin since the late Pleistocene, with a higher fluvial 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 (Morales et al. 2018). The Cruces 2 profile was dated to between ca. 4500 and 1000 BP. Its study suggests that the mid- to late Holocene transition in the locality implied a change from a more regionally dry but mostly stable setting to more humid but unstable conditions. During the regionally wetter late Holocene, the energy of the Barrancas hydrological system increased, including frequent high flow events caused by torrential rain, but these conditions were punctuated by discrete, recurrent and/or intense regionally dry episodes. Locally, these drier events manifested as episodes of paludization/paleosol formation in Barrancas and other localities of the dry Puna, which took place at 3260, 3000, 2500, 2100, 1490/1460, and 1050 cal BP (Pirola et al, 2018).

2 | MATERIALS AND METHODS

2.1 | Geological setting and the PBP profile

The profile is located in the lower part of the course of the Barrancas River (Figure 1). The Barrancas river catchment has 190 km^2 and its flow depends heavily on the seasonal precipitation regime, which determines sharp flow increases during summer, but remaining dry for the most part of the year. There is a total of four springs in the western flank of the Tusaquillas range where groundwater surfaces along with fractures in the igneous rocks, creating small wetlands spanning an approximate 0.8 km^2 each (Figure 1). Four fluvial terrace-levels were detected. The highest terrace (+9 m above the riverbed, Allounit A; Figure 2) is the most extensive. The other terraces, intermediate (+6 m; Allounit B; Figure 2) and low (+3 and +2 m; Allounits C and D, respectively; Figure 2) are odd erosion terraces associated with fast scouring by the fluvial system.

2.2 | The Barrancas Pueblo Profile

The Barrancas Pueblo profile (PBP) was obtained from a 4.10 m high exposed sedimentary sequence of an alluvial terrace. Forty-two samples were taken with a 10 cm interval for pollen, sedimentology,

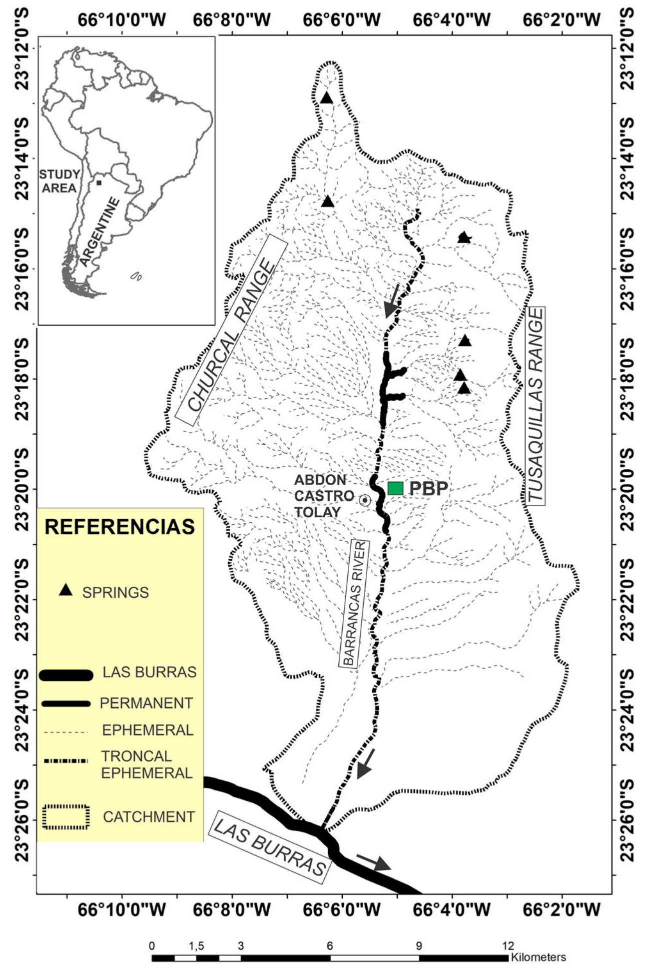

FIGURE 1 Location of PBP and hydrology of the Barrancas river basin. PBP, Barrancas Pueblo profile

diatom analyses, organic matter (OM), and carbonate (Ct) content measurements, and magnetic properties' analysis.

Up to now we have obtained three radiocarbon dates from peaty sediments in PBP: 1200 ± 60 BP (LP3451 2σ 934–1185 cal BP; midpoint 1060 cal BP), 1570 ± 60 BP (LP2910 2σ 1309–1535 cal BP; 1422 midpoint cal BP) and 2410 ± 80 BP (LP2907 2σ 2300–2720 cal BP; midpoint 2510 cal BP). These sediments are not affected by roots from live plants and there is no evidence of precipitated salts or carbonates. Moreover, there are no calcareous outcrops or thermal springs in the Barrancas basin that could cause reservoir effects or old carbon contamination.

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 PBP was studied following Miall (1982), (1996) and Friend (1983), describing the lithofacies grain size, sediments, soil structure and color. Those lithofacies were correlated with local sedimentary facies to interpret the general sedimentary environment.

The determination of organic matter (OM) and carbonate (Carb) content was conducted on the full sample set by loss-on-ignition (LOI), using a muffle furnace at 390°C for 16 hr (OM) and 950°C for 2 hr (Carb; Pirola, 2014). Samples were previously pulverized in an agate mortar and dried overnight at 95°C.

Magnetic properties were also measured on the full sample set. Sediments were air-dried and pulverized using an agate mortar. Initial mass magnetic susceptibility (χ) was measured with a Bartington MS2 instrument, whereas magnetic hysteresis cycles were obtained using a Molspin Ltd. vibrating sample magnetometer.

The pollen analysis was followed the standard procedures for Quaternary pollen analysis (Faegri & Iversen, 1989). Between 300 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 & 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 (Braun Wilke, Picchetti, & Villafañe, 1999; Cabrera, 1976). Pollen zones were determined by CONISS stratigraphically constrained Cluster Analysis (Grimm, 2004).

Diatom samples were treated following standard procedures (Battarbee, 1986), mounting the material in permanent slides with Naphrax®. Diatoms valves were identified and counted (300–400

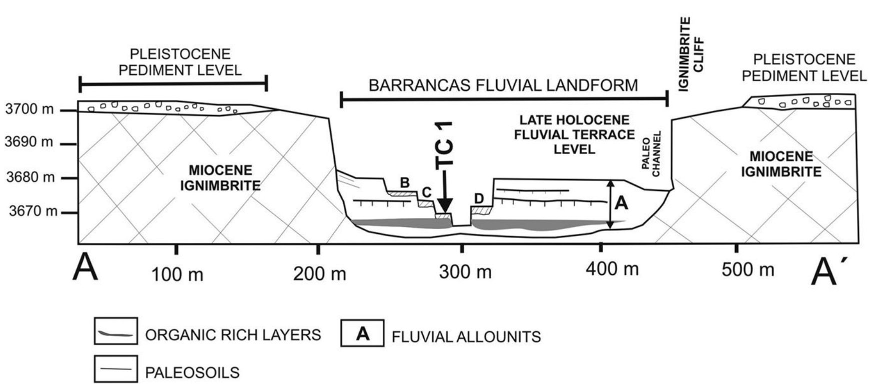

FIGURE 2 Geology of the Barrancas river basin and fluvial allounits

valves per slide) with OM (Reichert-Jung Polyvar, 1000×) and SEM (Zeiss Battarbee, 1986 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 obtained useing specific monographic works and several studies on diatom biodiversity in Argentinean Puna ecosystems (Grana et al., 2016; Krammer & Lange-Bertalot 1986, 1988, 1991a, 1991b; Maidana & Seeligman, 2006; Maidana, Seeligman, & Morales, 2009; Maidana, Seeligman, & Morales, 2011; Round, Crawford, & Mann, 1990; Rumrich, Lange-Bertalot, & Rumrich, 2000; Seeligman & Maidana, 2003; Seeligman, Maidana, & Morales, 2008). Ecological affinities of diatoms were obtained from Lowe (1974), De Wolf (1982), Vas and De Wolf (1993) and Van Dam, Mertens, and Sinkeldam (1994), and specific papers about several taxa (e.g., Levkov, Metzeltin, & Pavlov, 2013). As in previous works, (e.g., Morales, Bustos, & Maidana, 2015; Tchilinguirian & Morales, 2013) our general paleoenvironmental interpretations rest on a moisture index, based on a ratio of diatom life-form affinities (i.e., benthic + epiphitic + planktonic/aerophiles).

3 | RESULTS

3.1 | Geomorphology and stratigraphy

The stratigraphy of PBP was defined in relation to another stratigraphic sequence previously studied in the Barrancas basin with partially compatible chronology (i.e., PCC; Pirola et al., 2018). The correlation with PCC2, located 4 Km upstream from PBP, was based on the lateral continuity of erosive surfaces and distinctive lithological characteristics of paleosoils.

PBP presents four allounits: A3, A4, A5 and A6 (Figures 3 and 4). Allounit A3 is the base unit, consisting of an upward-fining succession of structured medium to coarse sands that give way to silts and clay-silts with organic matter and paleosol formation. Changes in lithofacies divide allounits A31, A32, and A33, whereas a local erosion surface defines allounit A34. Subunit A31 comprises medium to fine, upward fining sands with horizontal planar structures, evidence of bioturbation and gley colors (Shb and Slb lithofacies). The sedimentary environment corresponds to a medium to high-energy fluvial channel fill with an extremely shallow water table, as suggested by fine gravel (samples M7–M12) and medium sand (M1–M8) lenticular deposits. The gley colors of these sands and bioturbation indicate that it was a wet, vegetated environment. Subunits A32, A33, and A34 consists of fine sediments with evidence of pedogenesis. There are three lithofacies represented in these units. Paleosols (PS lithofacies) present dark-gray, very fine clay-rich sands with strong pedogenic features (e.g., strong regular blocky structures), root traces, and bioturbation. Organic matter (FOl) is another lithofacies present in these subunits; it occurs as finely laminated, almost black layers in the sedimentary sequence. Both paleosols and organic matter layers are deposited as continuous tabular bodies, exposed in the river margins up to 300 m upstream of the PBP sequence. Downstream, these deposits are covered by recent alluvial sediments. Less abundant are light-colored sand lithofacies (Sb or Slg) that form lenticular bodies 150–200 m long. They are composed primarily of granitic lithics, quartz, and K-feldspar from the granite outcrops located in the Tusaquillas range, which bounds the Barrancas basin to the east. These lithofacies correspond to temporary flows (alluvial fans) that cover the Barrancas alluvial plain (Figure 4).

Unit A4 is composed of fine massive bioturbated sediments with gley colors and discontinuous thin organic laminae. It represents a floodplain and an alluvial fill on which a paleosol developed. Sedimentation was slightly more stable than in unit A3. Unit A5 represents high-energy alluvial deposits, divided into two subunits, A51 and A52; the latter is not always visible in the exposed terrace profile. These units follow an intense erosion episode associated with an abrupt drop in the water table level. There is no visible organic matter deposition nor gley horizons indicative of reducing or permanent humid conditions. Mineralogical samples suggest lateral detrital input, with a high quartz content that indicates a granitic source area. These deposits are interpreted as the result of high energy, episodic sedimentation, associated with low frequency but very intense stormy events (Figure 4).

Unit A6 caps the PBP sequence. It consists of peaty deposits interbedded with fine granitic gravel from a lateral source area. It indicates a rise in water table levels that affected the only a few sections of Barrancas basin's mid-section.

3.2 | Geochemical and geophysical indicators

Organic matter (OM) presented a mean of 3.7% and SD of 3.0%; carbonate content showed similar values (mean, 3.8%; SD, 1.5%; Figure 5). Overall magnetic properties suggest that the prevailing magnetic fraction of PBP sediments is either magnetite or titano-magnetite (Figure 6).

OM and carbonate content and magnetic parameters of the PBP sequence present three distinct phases. A first phase, between

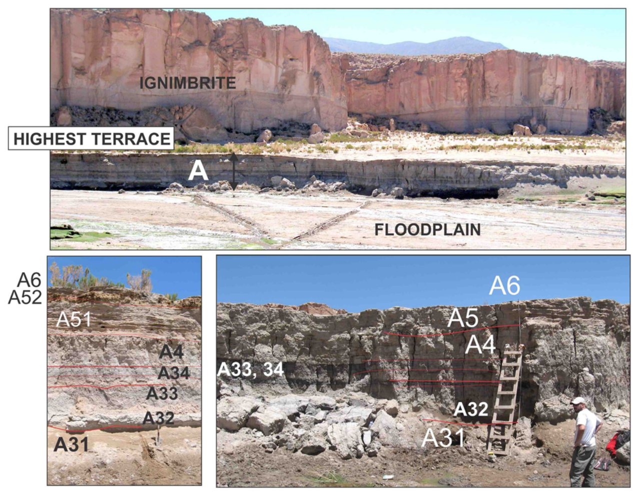

FIGURE 3 Eastern view of the PBP sampling site and fluvial terrace A (top); front view of the PBP sequence and lateral continuity of allounits (bottom). PBP, Barrancas Pueblo profile

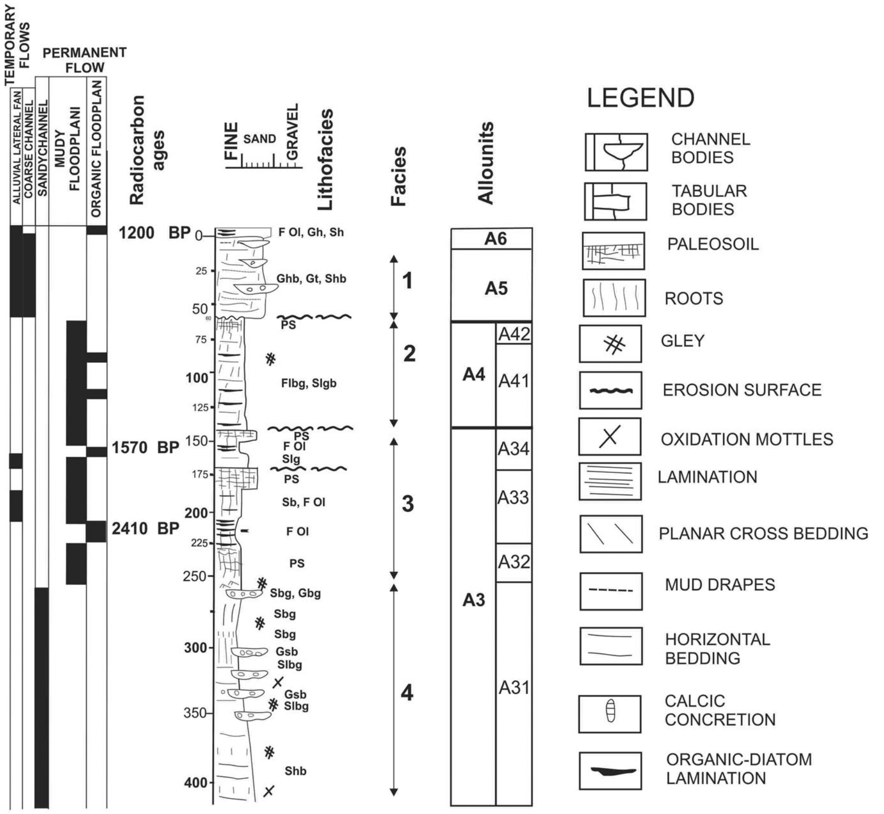

FIGURE 4 PBP lithofacies and overall stratigraphy. PBP, Barrancas Pueblo profile

samples M1 and M15 (410–260 cm), is defined by low OM and carbonate content. Following a peak of extensive parameters (mass magnetic susceptibility or χ, saturation magnetization or Ms, and saturation of remanence, Mrs) in sample M2 (400 cm), these parameters decrease until reaching stable, low values in sample M13 (290 cm). The opposite trend was found in the intensive parameters, coercive force (Hc) and coercivity of remanence (Hcr; Figure 5). This magnetic evidence suggests an upward-fining

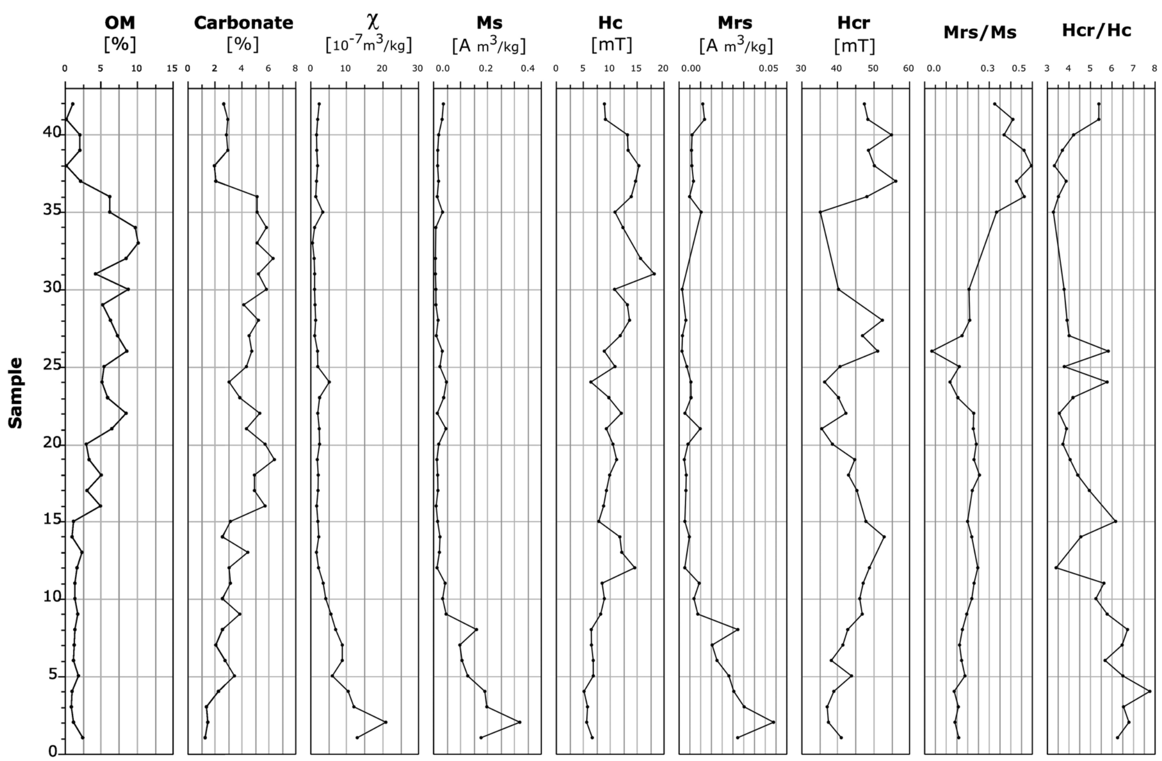

FIGURE 5 Organic matter (OM) and carbonate content and magnetic properties of the PBP sequence. PBP, Barrancas Pueblo profile

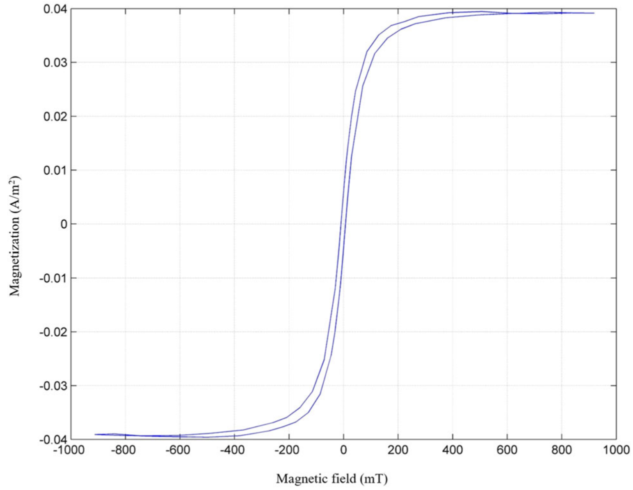

FIGURE 6 Most frequent type of hysteresis loop shape in PBP samples (in this example, M11). PBP, Barrancas Pueblo profile

sedimentary sequence for this phase, possibly related to a decrease in the overall energy of the fluvial system. The Day plot of Mrs/Ms versus Hcr/Hc (Figure 7, red dots) indicates that the dominant magnetic particle size in this section of the PBP sequence is single-domain with superparamagnetic particles (SD + SP). The source of SP particles may be linked to (a) volcanic glass inputs, (b) neoformation of SP magnetite associated to pedogenetic processes in subhumid to dry environments, and/or (c) diagenetic alteration due to water table oscillations (Orgeira, Egli, & Compagnucci, 2011). The occurrence of Fe-oxide mottles in this segment provides support for the latter hypothesis and geomorphological evidence suggests that pedogenesis was certainly a factor in the neoformation of SP particles in these samples.

From sample M15 to M36 (260–60 cm), extensive magnetic properties present very low values, whereas Hc and Hcr present higher but also very variable values. This suggests a reduction in the amount and grain size of the magnetic fraction, which may be related to higher organic and carbonate contents, which reach a maximum between 100 and 80 cm (Figure 5). A few samples within this segment fall with the SD + SP range in the Day plot (Figure 7, green dots). This data suggests neoformation of very fine magnetite particles due to pedogenetic processes in several levels along this section.

Finally, an increase in Hc and Hcr was found from samples M35 to M41 (70–10 cm). This may be due to differential magnetic mineralogy in this section, compared to the rest of the sequence, suggesting a change in sediment source area. This section also presents very low OM and carbonate content (Figure 5). Samples M41 and M42 underlie a paleosol level that was dated to 1200 yrs BP. These two samples present SP magnetite particles, as expected from lixiviation from this paleosol (Figure 7; yellow dots).

3.3 | Pollen

Fossil pollen studies were based on the analysis of 19 samples and a total of 19 taxa were identified at the family, genus and species levels (Figure 8). Overall, PBP pollen composition is dominated by the Poaceae family, except for M13 (290 cm), where Chenopodioideae constitute the most abundant taxum. The Asteraceae family does not exceed 20%, reaching a minimum in M20 (220 cm). The rest of the shrubs (*Fabaceae*, *Portulacaceae*, *Cactaceae*, *Solanaceae*, *Apiaceae*, *Cruciferaceae*, *t.Chuquiraga* and *Brassicaceae*) do not reach 10%, with the exception of Chenopodioideae that represent 40% of the assemblage in M13 (290 cm) and 30% in M15 (270 cm). Local humidity indicators are represented by *Cyperaceae*, *Ranunculaceae*, *Pteridophyta*, *Myriophillum sp*., and *Juncaceae*; they usually represent less than 10% of the sample, except in M41, M35, M36 (20, 60, and 70 cm) where the proportions of Pteridophyta and Cyperaceae increase, reaching a peak in M35 and M36. The presence of trees has also been detected, but they never exceed 5% of the pollen assemblage: *Alnus sp*., *Podocarpus sp*., and *Juglangs sp*.

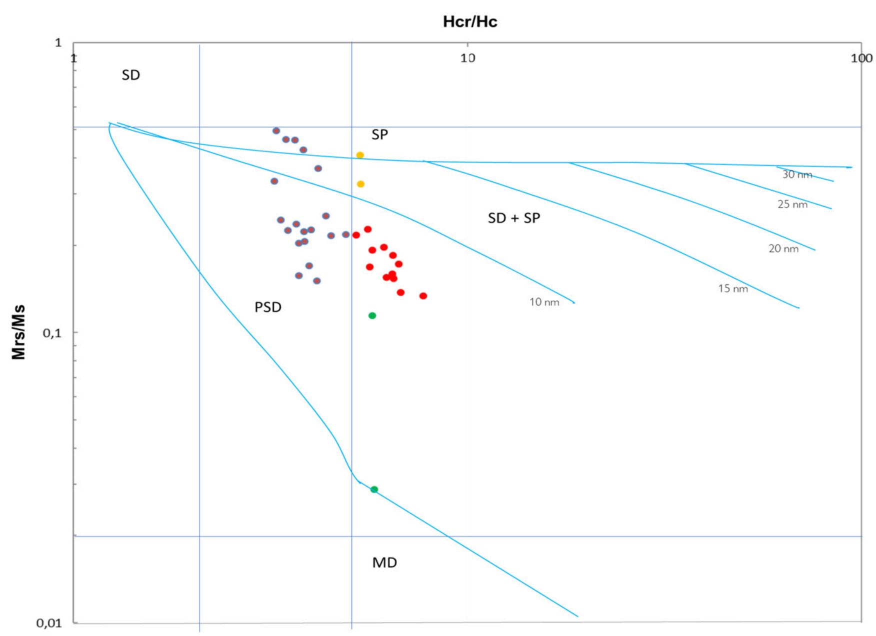

FIGURE 7 Day Plot (Mrs/Ms vs. Hcr/Hc) of PBP samples. Samples containing a SP fraction are represented in yellow (top 20 cm of the sequence); green (between 160 and 30 cm deep) and red (bottom 150 cm of the sequence). MD, multi domain; PBP, Barrancas Pueblo profile; PSD, pseudo single domain; SD, single domain; SP, superparamagnetic

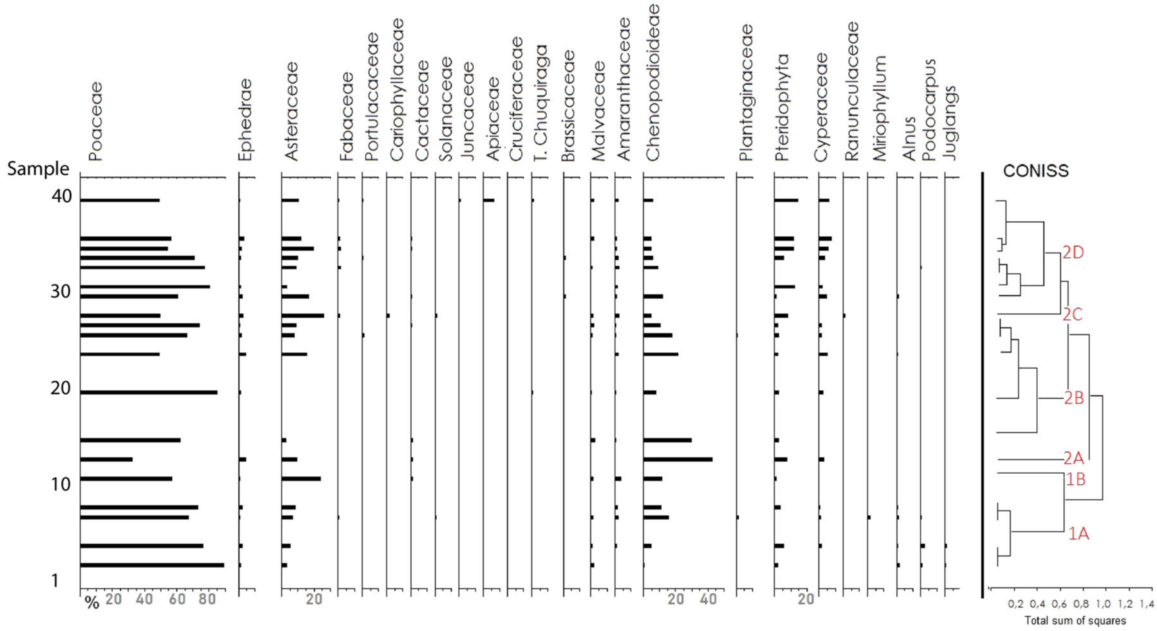

FIGURE 8 Most frequent pollen taxa in the PBP sequence. PBP, Barrancas Pueblo profile

Pollen concentration is generally low, but there is an important change towards the end of the sequence (M33) where pollen concentration increases dramatically; even though it decreases again at the top of PBP, these last 90 cm of the sequence present much higher pollen concentrations than the rest of the samples (Figure 9). While there is no evidence to suggest that pollen grains have been substantially chemically or mechanically modified (Havinga 1967; Pearsall, 1989; Lebreton, Messager, Marquer, & Renault-Miskovsky, 2010; Tipping, 2000; Tweddle & Edwards, 2010), changes in pollen concentration should not be directly interpreted in terms of pollen flux and vegetational cover in the Barrancas basin. There are diverse sedimentary environments represented in PBP that could differentially affect pollen deposition in the site.

Stratigraphically-constrained cluster analysis determined two main pollen zones and six subzones (Figures 8,9). Zone 1 (M2–M11; 400–310 cm) is subdivided into two subzones. subzone 1A (M2 to M8; 400 to 340 cm) presents high values of *Poaceae*, low percentages of Asteraceae and the presence of trees. The high percentage of herbaceous steppe elements would indicate enhanced humidity conditions at a regional scale. The presence of pollen types of *Alnus sp.* (a tree found in the tropical forest to the East) is indicative of an intensification of easterly winds. In subzone 1B (M11; 310 cm) *Poaceae* and local humidity indicators decrease, whereas *Asteraceae* and *Chenopodioideae* increase.

Zone 2 (M13–M40; 290–20 cm) is divided into four subzones. In subzone 2A (M13; 290 cm) there is a decrease in *Poceaeae* and low values of *Asteraceae*. Also, a maximum peak of *Chenopodioideae* is detected, with a slight increase in local humidity indicators. The continuity in the local humidity indicators coupled with an increase in *Chenopodioideae* suggests the onset of significant anthropic impact, within the framework of a mixed steppe with a lower contribution of herbaceous elements than in the previous period. subzone 2B (M15–M27; 270–150 cm) presents recurrent fluctuations in the values of *Poaceae* (between 60% and 80%) and *Asteraceae* (between 10% and 20%), and there *Chenopodioideae* proportions decrease. The indicators of local humidity (*Cyperaceae* and *Pteridophyta*) show predominantly low values, although they increase slightly towards the end of the subzone. The presence of *Alnus sp.* was also recorded in this subzone. In palaeoenvironmental terms, this assemblage is interpreted as representing an increase in the herbaceous steppe, albeit with high instability. Again, the presence of tropical forest tree pollen suggests the intensification of Easterly winds. subzone 2C (M28; 140 cm) is characterized by a maximum peak in the *Asteraceae* family. subzone 2D (M31-M40; 120–20 cm) presents an increase in local humidity indicators and shrub steppe percentages, although herbaceous steppe elements continue to dominate. It should also be noted that the sharp increase in pollen concentration observed in

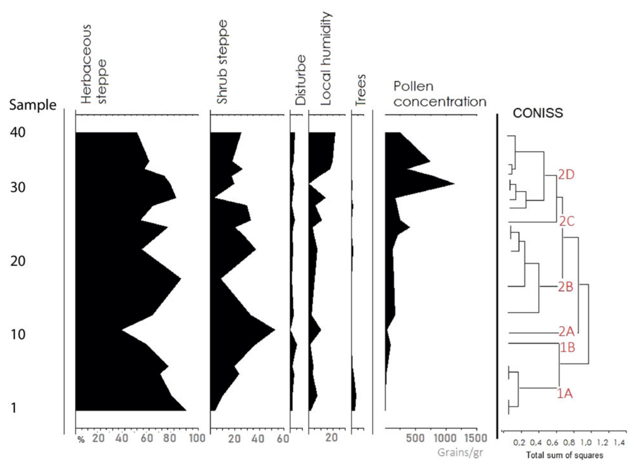

FIGURE 9 Pollen ecological spectra, zonation by constrained cluster analysis (CONISS) and pollen concentration

coincidence with this subzone is possibly due to the high pollen productivity of the species of the fertile plain (Figure 9).

3.4 | Diatoms

A total of 160 taxa were identified in the 23 fertile samples (more than 300,000 valves/gr) of the 42 samples analyzed. Sixty of these taxa were more than 5% in at least one sample, and some of them showed similar trends along the series forming assemblages (Figure 10). Three of the most conspicuous assemblages were (a) *Hantzschia amphioxys*, *Luticola andina*, and *Pinnularia borealis;* (b) *Denticula valida* and *Diadesmis gallica*: and (c) several species of genus *Nitzschia* conjoined with several of *Navicula.* The assemblages I and II are formed by well-known aerophilic species frequently found in samples recovered in the Puna. The latter group is constituted by typical benthic taxa. The cluster analyses (i.e., constrained single linkage by correlation) evidenced strong variability along the series, particularly starting at sample M30 (120 cm). This means that relevant species along the record are the same, but modifications in their frequency changed their dominance role along the record. Beyond this general variability, in the lower section of the record, four main diatom zones were identified: Zone A) from M6 (360 cm) to M8 (340 cm) dominated by the assemblage I; Zone B) is a transition zone represented by M19M20 (230–220 cm) codominated by the assemblages I and II; Zone C) from M21 (210 cm) to M26 (160 cm) also dominated by both assemblages (I and II) but with lower abundances of *D. valida;* and Zone D) from M27 (150 cm) to M29 (130 cm) that is dominated by the assemblage II but *D. valida* frequency slightly rise and *Frankophila similiodes* and *Nitzschia microcephala* became abundant. The assemblage III dominated the most part of the highly variable section above M30 (120 cm; Figure 10).

In paleoenvironmental terms, throughout the record we have observed an increase of the benthic species (or decrease of the aerophilic species), suggesting an increase of environmental humidity in the locality (Figure 11). The humidity index, that includes the other ecological affinities, is consistent with this trend. Although valve abundance does not show a clear pattern, three noticeable peaks in valve abundance (valves/g.) can be observed (M20, M27, and M33). These peaks could be explained by a) punctual nutrient input events that supported algal blooms or b) high mortality events due to sustained droughts. Due to the high pollen-grain counts and organic-matter content measured in these samples, we consider the former as the most likely explanation for these peaks in valve abundance.

4 | DISCUSSION

To test relationships between the environmental indicators, we constructed a correlation matrix using Spearman's rho, given that the variables exhibited nonnormal probability distributions.

High, positive correlations (Spearman's $\rho > 0.7$) were found between OM and carbonate content, OM content and diatom abundance, and OM and pollen abundance. This implies that OM content can be directly linked to increased terrestrial plant and algal productivity. Slightly weaker, positive correlations were found between hydrophytic pollen indicators—*Cyperaceae*, *Pteridophyta*, *Juncaceae*, and others—which are evidence of local humidity, and the diatom humidity index (HI); overall pollen abundance correlates positively to overall diatom abundance, the diatom HI, and carbonate

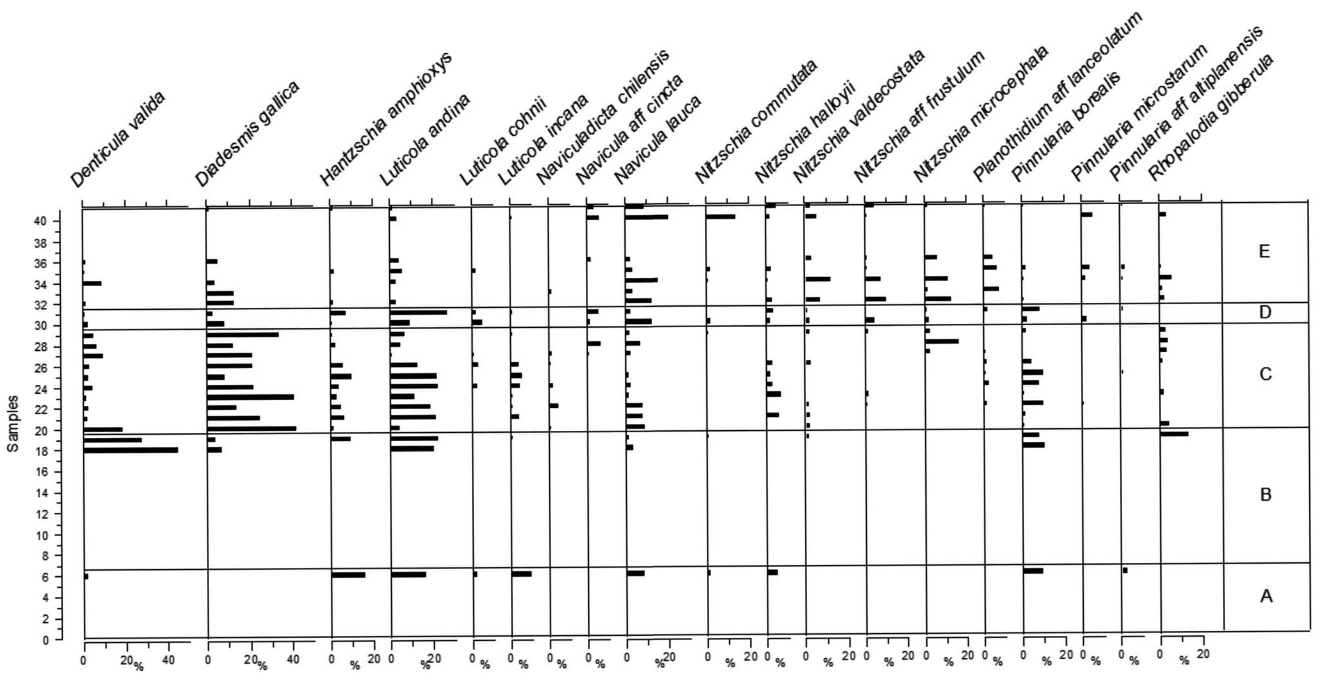

FIGURE 10 Most frequent (>5%) diatom taxa, diatoms concentrations, and floristic zonation of the PBP sequence. PBP, Barrancas Pueblo profile

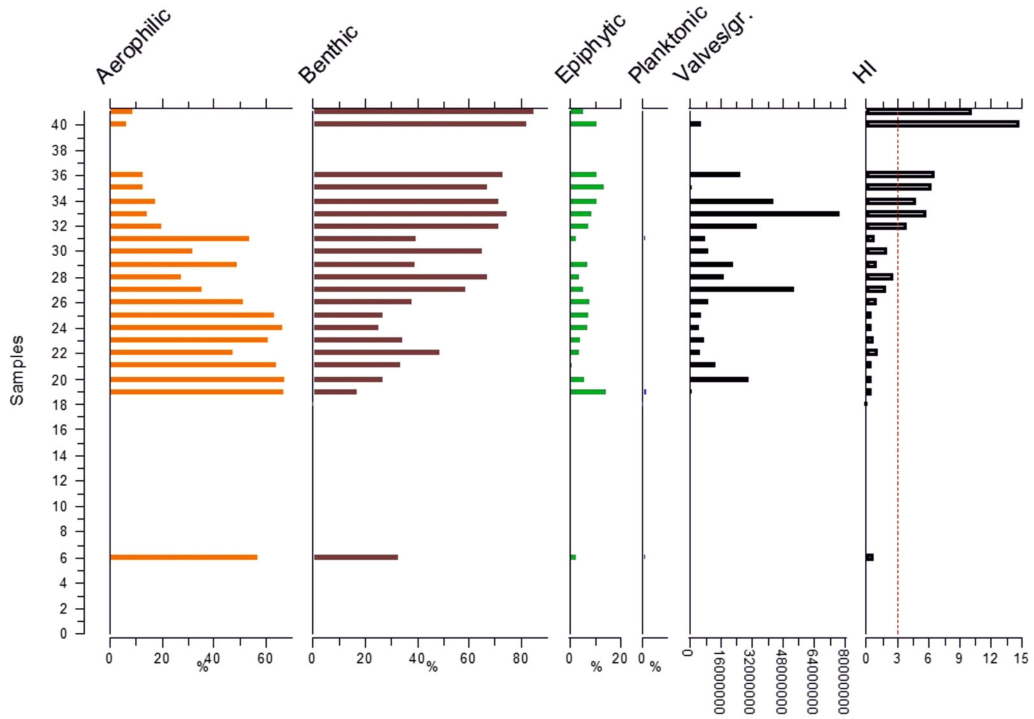

FIGURE 11 Diatom life-form affinity spectra, humidity index (HI), and diatom concentrations

content. At the same time, aerophile diatom abundance, which is an indicator of subaerial exposure and, thus, of the depth of the water table, was inversely correlated to both local humidity pollen indicators and overall pollen abundance.

In turn, magnetic susceptibility was found to be highly and inversely correlated (Spearman's $\rho < -0.7$) to pollen abundance and, to a slightly lesser degree, to OM content, carbonate content, diatom abundance, and the diatom HI, and positively correlated to the abundance of aerophile diatoms. These relationships support the notion that, in this sedimentary sequence, magnetic susceptibility is tied to detrital input driven by aridization processes. Similarly, *Chenopodioideae* pollen content is inversely correlated to pollen indicators of local humidity and the diatom HI, and positively correlated to the abundance of aerophile diatoms. While some have argued that *Chenopodioideae* pollen abundance is a more robust indicator of human disturbance than of environmental change (Lupo et al. 2018), the correlations of this variable with others in our analysis underscore the value of *Chenopodioideae* pollen abundance as an indicator of aridity in our regional sedimentary sequences (Table 1).

Considering the correlations between variables and the sedimentological changes throughout the sequence, we can advance a summary description of the evolution of the Barrancas river basin since the onset of the late Holocene (pre-2400 BP) and until 1200 BP.

Allounit A31 (pre-2400 BP) represents a period of regular and relatively abundant precipitation, which supported moderate to high hydrological energy that hindered the development of a vegetated floodplain. At the end of this phase, the system's overall energy decreased, but with a higher incidence of torrential events that caused erosion of the river bed, manifested as an erosion unconformity in the stratigraphy.

Allounits A32 to A41 (from slightly before 2400 until some point between 1570 and 1200 BP) correspond to a stable, low hydrological energy phase, with shallow water tables that supported the vegetation of wide areas of the floodplain with hydrophitic species, creating *vega*-like environments and allowing paleosol formation. This phase presents relatively high OM content, pollen indicators of local humidity and benthic diatoms, particularly post-1500 BP. However, there are a few episodes of increased fluvial energy that caused erosive unconformities in the sedimentary sequence slightly before 1500 BP and slightly after, and before 1200 BP, indicating torrential events in a context of regional aridity. This is also supported by higher levels of shrub-steppe pollen indicators.

The last section of the sequence—slightly before 1200 BP and after the previously described events (Allounit A42)—represents the onset of the driest conditions in the basin because the beginning of late Holocene; MO levels drop, whereas shrub steppe pollen indicators increase. The final part of this section, Allounit A51, marks the interruption of the Barrancas river fluvial aggradation due to an increase in coarse detrital input from lateral river tributaries in a context of regional aridity that reduced water table levels. This changed in source area of the PBP sediments is also indicated by an increase in intensive magnetic parameters.

The results obtained in PBP illustrate particularly humid characteristics in a context of regional aridity, accompanied by increased variability between 2400 and 1500 BP (i.e., 2500–1400 cal BP). Evidence of this variability can be found both in soil formation processes associated to low-energy phases and in high-energy events

TABLE 1 Correlation matrix of paleoenvironmental indicators in the PBP sequence. Spearman's ρ are presented below shaded diagonal, p values above

	OM (%)	Carbo-nate (%)	X (10^{-7} m^2/ kg)	Polen abundance (grains/gr)	Grasses/ shrubs	*Chenopo-dioideae* (%)	Local humidity indicators (%)	Diatom abundance (v/gr)	Aero-philes (%)	Benthic (%)	Epiphitic (%)	Plank-tonic (%)	Diatom humidity index
OM (%)		0.000	0.000	0.000	0.875	0.476	0.616	0.000	0.504	0.257	0.984	0,037	0,504
Carbonate (%)	0.779		0.000	0.001	0.537	0.274	0.250	0.008	0.909	0.773	0.639	0,957	0,909
(10^{-7} m^2/kg)	−0.594	−0.637		0.000	0.786	0.657	0.576	0.000	0.020	0.004	0.494	0,397	0,020
Polen abundance (grains/gr)	0.793	0.704	−0.819		0.729	0.442	0.667	0.015	0.018	0.005	0.112	0,529	0,018
Grasses/ Shrubs	−0.039	0.151	−0.067	−0.088		0.631	0.200	0.181	0.103	0.306	0.459	0,777	0,103
Chenopodioideae (%)	−0.174	−0.265	0.109	−0.193	0.118		0.014	0.368	0.016	0.015	0.112	0,173	0,016
Local humidity indicators (%)	0.127	0.286	−0.141	0.113	−0.317	−0.566		0.306	0.025	0.090	0.090	0,371	0,025
Diatom abundance (v/gr)	0.697	0.539	−0.687	0.654	0.396	−0.272	−0.308		0.606	0.200	0.943	0,049	0,606
Aerophiles (%)	−0.147	0.025	0.482	−0.643	0.473	0.649	−0.615	−0.114		0.000	0.072	0,028	0,000
Benthic (%)	0.247	0.064	−0.579	0.731	−0.308	−0.658	0.489	0.278	−0.964		0.210	0,020	0,000
Epiphitic (%)	−0.004	0.103	−0.150	0.462	−0.225	−0.462	0.489	0.016	−0.382	0.272		0,401	0,072
Planktonic (%)	−0.437	−0.012	0.185	−0.192	0.087	0.402	−0.271	−0.414	0.459	−0.480	−0.184		0,028
Diatom humidity index	0.147	−0.025	−0.482	0.643	−0.473	−0.649	0.615	0.114	−1.000	0.964	0.382	−0,459	

represented by coarser-grained deposits and sedimentary unconformities. These unconformities are the result of erosion events that have deleted parts of the record whose extent can only be grossly estimated using overlaying dates, which creates significant biases that should not be ignored. However, the presence of variable sedimentary and erosion phases in PBP constitutes evidence on itself of increased variability during the late Holocene, in contrast with earlier, more continuous sedimentary records previously studied in this basin (i.e., TC1; Morales et al., 2018).

The moisture variability in the Puna has been traditionally associated with variability in SASM intensity. Lake Pumacocha and Huagapo cave records indicate high variability in monsoon intensity in decadal and centennial time scales post-3000 cal BP, and an increase in the amplitude of short-term variability after 2200 cal BP (Bird, Abott, Rodbell, Vuille, 2011; Kanner et al., 2013). However, these regional trends also indicate more humid conditions during this time span. Barrancas area, on the other hand, shows a decoupled signal of moisture with both areas. Regional moisture conditions seem to end before at ca. 2500 cal BP in Barrancas basin. A possible explanation for this different sign between SASM intensity and regional moisture in the Dry Puna of Argentina could be that it is rather an issue of *transport*. It is possible that the observed moisture variability during this period over the Altiplano could be related to changes in the intensity of moisture transport from the East, rather than to the intensity of convection, and therefore overall precipitation amount, over the Amazon. In this regard, Garreaud, Vuille, and Clement (2003) have stated that moisture availability in the Altiplano is not directly controlled by moisture changes in the source area; instead, they argue that factors affecting moisture transport are the main drivers of moisture availability in this region.

The evidence presented here is relevant for the modeling of the environmental scenario in which human occupations in the locality took place. An increase in local humidity in a regionally arid landscape, combined with enhanced short-term climate variability, might have provided both an incentive and the conditions of possibility for the aggregation of human groups in particular areas of the Puna; a process that has already been observed in the hyperarid mid-Holocene. This nucleation of human populations would have driven a process of economic intensification, implying significant changes in the technological organization to increase resource productivity and stability in the face of environmental fluctuations (Morales et al., 2009). In this respect, it is worth noting that ceramic technology and evidence of a significant herding component in the economy appear almost synchronically in the highlands of northwestern Argentina, ca. 3000 BP (e.g., García, 1988/9; Fernández, 1988/9; Yacobaccio et al., 1997-1998–1998). The adoption of ceramics allows human groups to store foodstuffs for future consumption and facilitates resource intensification by improving nutrient extraction through new cooking techniques (Rice, 1999). A pastoralist economy, on the other hand, implies a form of "live storage" that helps human groups cope with periods of resource-patch deterioration—that is reduced water and/or pasture availability—and decreases in wild animal protein return rates (Göbel, 1994; Olivera, 1997). The highest intensity of occupation recorded in

Barrancas occurs in this period, both in rockshelters and open-air sites. The Morro Blanco rockshelter presents occupational characteristics indicative of its use as a "rest stop" within a pastoral mobility complex. The open-air site Punta Motaite is associated to engraved and painted rock art motifs included camelids with ropes around their necks, anthropomorphic figures among camelids, and human characters wearing complex attire. These motifs denote a strong, close relationship between people and camelids (Yacobaccio et al., 2016).

There is a long history of research focusing on strategies available to hunter-gatherers and pastoralist societies to cope with the risk generated by unpredictable fluctuations in critical resources (e.g., Cashdan, 1990; Halstead & O'Shea, 1989). Diversification of the resource base is one of these strategies that allow managing risk, allowing human groups to supplement or replace a failing resource with another. Diversification is not purposefully undertaken to reduce risk, but it is the natural outcome of a situation where there is a drop in the availability of high ranking resources (Kelly, 1995). Intensification and specialization in certain resources is another way in which human groups can increase the stability and/or productivity of their resource base.

Under the observed highly fluctuating and frequently arid conditions at the regional level, the human groups that inhabited the Argentinean Dry Puna during the late Holocene probable faced mobility restrictions that precluded a strategy exclusively based on mobility as a way to cope with increased environmental risk. Therefore, these societies opted for other strategies that included specialized herding techniques, the development of irrigation structures (in areas amenable to farming), diversification of production activities, -for example, incorporating cultivars, increased logistic mobility to access diverse pasture localities, increased storage practices, and possibly the intensification of social mechanisms of cooperation, such as the formalization and enhancement of regional exchange networks.

5 | CONCLUSIONS

The PBP paleoenvironmental record suggests ongoing local moisture availability for most of the late Holocene, as evidenced by the high frequency of bioturbated sediments, organic matter lenses, and paleosol formation events. Slightly before 2400 to 1500–1300/1200 BP there was a stable, low hydrological energy phase, with shallow water tables that supported the vegetation of wide areas of the floodplain. These conditions imply high availability of pastures and water for both animal and human consumption. At a broader, regional scale, the Barrancas basin could have functioned as a highly productive, dependable resource patch within the desert landscape of the lower Pastos Chicos river basin and Salinas Grandes.

However, throughout most of the studied period but particularly between 1500 and 1200 BP, there were high flow episodes that caused erosive unconformities in the sedimentary sequence, indicating stormy events in a context of regional aridity. Finally, after 1200 BP, the interruption of the Barrancas river fluvial aggradation suggests a context of regional aridity that reduced water table levels, representing the driest conditions in the basin since the beginning of the late Holocene. High environmental variability post-3000 BP could have put a premium on strategies to reduce the risk associated with the unpredictability of resource availability. Such strategies included economic specialization and intensification, as well as storage practices designed to control and mitigate resource variability and broaden the resource base (Escola, 2002), for instance, the use of ceramic technology and the maintenance of camelid herds as a form of "live storage". Moreover, in the context of a long-term trend of reduced residential mobility and intensification in camelid use fostered by mid-Holocene habitat fragmentation (Yacobaccio, Morales, & Hoguin, 2017), pastoralism provided an effective mechanism to articulate and increase access to diverse environments and patched resources. The consolidation of the Andean pastoralist way of life could be thus interpreted as the natural corollary of this comprehensive risk-aversion strategy.

Finally, we have observed a decoupling of local and regional signals of humidity and aridity -for example, as indicated by regional SASM intensity records- that could be explained by factors affecting southward moisture transport along the eastern flank of the Andes, rather than to differences in moisture levels in the SASM core region. Mismatched regional and local signals notwithstanding, we consider that *variability* is the key feature driving cultural responses at the period studied, which implies that issues related to *frequency*, *intensity* and *periodicity* may have a had a stronger influence on human societies than the specific *sign* (e.g., wet/dry) of climate change.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest.

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