Paleohydrological Changes in Highland Desert Rivers and Human Occupation, 7000-3000 Cal. Yr B.P., South-Central Andes, Argentina

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This article focuses on local paleohydrological changes experienced by the Las Pitas and Miriguaca Rivers in the south-central Andes of Argentina and their impacts on hunter-gatherers as they transitioned to food-producing communities 7000–3000 cal. yr B.P. Paleoenvironmental reconstruction based on geomorphology, alluvial sedimentology, and diatom evidence indicates a dry phase of reduced streamflow between *ca.* 6700 and 4800 cal. yr B.P. for the Las Pitas River, and 6600 and 3000 cal. yr B.P. for the Miriguaca River. A phase of more humid environmental conditions commenced after *ca.* 4900 cal. yr B.P. along the Las Pitas River, and after 3000 cal. yr B.P. along the Miriguaca River. Differences in the chronology and magnitude of hydrological changes along both rivers are related to topographic and hydrological characteristics of their respective watersheds. Higher catchment elevation and enhanced orographic precipitation favored greater sensitivity for the Las Pitas River to short humid events during the middle-to-late Holocene. The archaeological evidence suggests that the paleohydrological changes within these catchments played a significant role in human occupational dynamics such that the Las Pitas River offered better environmental conditions for human occupation relative to the Miriguaca River as foragers increasingly relied on plant and animal domestication. © 2016 Wiley Periodicals, Inc.

INTRODUCTION

The middle-to-late Holocene (*ca.* 8000–3500 cal. yr B.P.) was a period of significant cultural dynamics as well as environmental and climatic changes in the highlands of the south-central Andes. This region, known locally as the *altiplano* or *puna*, with its salt flats, dried lakes, paleosols, glacial deposits, and archaeological sites, provides a number of crucial archives from which to tease out this complex interrelationship. Paleoenvironmental studies performed on several *puna* wetland areas have stimulated debate on climatic variability during this period. Some suggest that middle Holocene environmental conditions were dry, changing to more humid conditions—similar to those of modern times—toward the late Holocene (e.g., Veit, 1996; Grosjean et al., 1997, 2003, 2007;

Valero-Garcés et al., 2000; Abbott et al., 2003; Tapia et al., 2003; Morales, 2011; Tchilinguirian & Morales, 2013). Contrariwise, others have noted a predominance of humid environmental conditions during the middle Holocene before a drier spell during the late Holocene (e.g., Betancourt et al., 2000; Latorre et al., 2002). These disparities may relate to local geography (e.g., latitude, longitude and altitude), resolution scales, sensitivity of the analyzed proxy, chronological problems (e.g., ^{14}C reservoir effect; see Geyh et al., 1999), differential preservation, and, finally, environmental heterogeneity and its complexity in relation to climate (Garreaud & Aceituno, 2001; Grosjean et al., 2003). Consequently, the chronology, intensity, and duration of these environmental shifts in different parts of the Andean highlands of northern Chile, northern Argentina, southern Peru, and southern

Bolivia highlight a more complex paleoenvironmental picture, and therefore the need to generate regional and local environmental models (Grosjean, 2001; Yacobaccio & Morales, 2005; Nuñez, Cartajena, & Grosjean, 2013; Tchilinguirian & Morales, 2013).

Middle-to-late Holocene climate change influenced human settlement, adaptation, and culture change in the south-central Andes. Archaeological research on middle Holocene sites associated with *puna* wetlands indicates a series of highly complex social responses to existing environmental conditions. For instance, in the Salar de Atacama, the extreme aridity postulated for this area during the middle–to-late Holocene transition would have provoked a decline and/or *hiatus* in human occupation, a period traditionally referred to as the "archaeological silence" (Núñez, Cartajena, & Grosjean, 2013). However, patches/enclaves with more stable hydrological resources persisted during this time in places, such as the Puripica Gorge (Chile) or in Susques (Argentina). These areas served as ecological refugia exploited by hunter-gatherers, providing localized higher floral and faunal concentrations within the broader desert environment (Yacobaccio & Morales, 2005; Núñez, Cartajena, & Grosjean, 2013). In time, the intensive management of some of these enclaves engendered significant cultural change associated with increased social complexity, in effect laying the basis for the transition from hunter-gatherer to agropastoral societies in the late Holocene (Grosjean et al., 1997; Nuñez, Grosjean, & Cartajena, 2010). Thus, a thorough understanding concerning the development of these varied socioeconomic changes during the middle Holocene and transition to the late Holocene requires a detailed study of the cultural processes involved and the environmental history that underlies specific areas. Taking an interdisciplinary perspective, here we focus on a combination of paleoenvironmental and archaeological data to elucidate the impact of local environmental changes on hunter-gatherer procurement strategies and their transition to food-producing societies in Antofagasta de la Sierra (southern argentine *puna*), during *ca.* 7000–3000 cal. yr B.P.

To this end, we present a paleoenvironmental reconstruction of two rivers, Las Pitas and Miriguaca, and the surrounding area. Our reconstruction of streamflow history for these two rivers is based on cross-correlations between geomorphological, sedimentological, and diatomological proxy data. We focus on these two rivers given that there has been intense archaeological research in this area. This past research shows that archaeological sites dating to the period addressed here are mainly associated with the paleowetlands of these two rivers. Additionally, other archaeological data, such as rock art (Aschero, 2010) and lithic assemblages (Hocsman, 2014),

reveal cultural differences between the human occupations along these two rivers. We believe that a comparative analysis combining paleohydrology and archaeological evidence from these two river basins is relevant to our understanding the role of extreme, for example, arid and high altitude, environments in the process of sociocultural change.

GEOGRAPHICAL SETTING

The *puna* ecozone located in the Andean highlands stretches some 1800 km in length and varies 350–400 km in width. Antofagasta de la Sierra is located in the Catamarca Province, Argentina, at the southern end of these highlands at 25°50′–26°10′S and 67°30′–67°10′W, with elevations ranging 3000–4500 m above sea level (asl; Figure 1). In general, this area is characterized by strong solar radiation due to its high altitude, large diurnal temperature variations, rainfall seasonality, and low atmospheric pressure. Rainfall is restricted to austral summer, with annual values typically lower than 130 mm but with significant variation. Aridity and extreme temperature fluctuations are typical of high-altitude cold deserts (Garreaud & Aceituno, 2001).

Antofagasta de la Sierra is characterized by an endorheic drainage basin dominated by a Pliocene ignimbrite plateau, interrupted by igneous and metamorphic rock outcrops as well as by volcanoes and sedimentary rock sequences (González, 1992). There are also river terraces and plains in connection with the area's primary drainage: the Punilla River. The central basin of Antofagasta de la Sierra is bounded by higher elevations that include the Calalaste Mountains (5350 m asl) to the west and Galán Crater to the east (5900 m asl).

The adjacent Miriguaca and Las Pitas river basins share several geomorphological and geological characteristics. Both are tributaries of the Punilla River with catchments that reach to 5900 m asl along the border of Galán Crater, located in the Toconquis Mountains (Figure 1). The Miriguaca and Las Pitas river basins lack evidence of glacial action. However, the upper reaches of the basins contain certain periglacial features such as debris flow and solifluction lobes that cover the side slopes. Also, the flood plains of both rivers above 4800 m asl contain wetlands with soil mounds resulting from soil frost and riparian flora. Along the middle reaches of the two basins (4800–4000 m asl), the rivers have downcut into the ignimbrite plateau forming canyons 80–120 m deep with sheer vertical sides susceptible to rockslides. Finally, along the lower reaches (4000–3200 m asl), both rivers end in broad valleys inset 20–30 m into Pleistocene conglomerates that form a veneer over pediments. Five Late
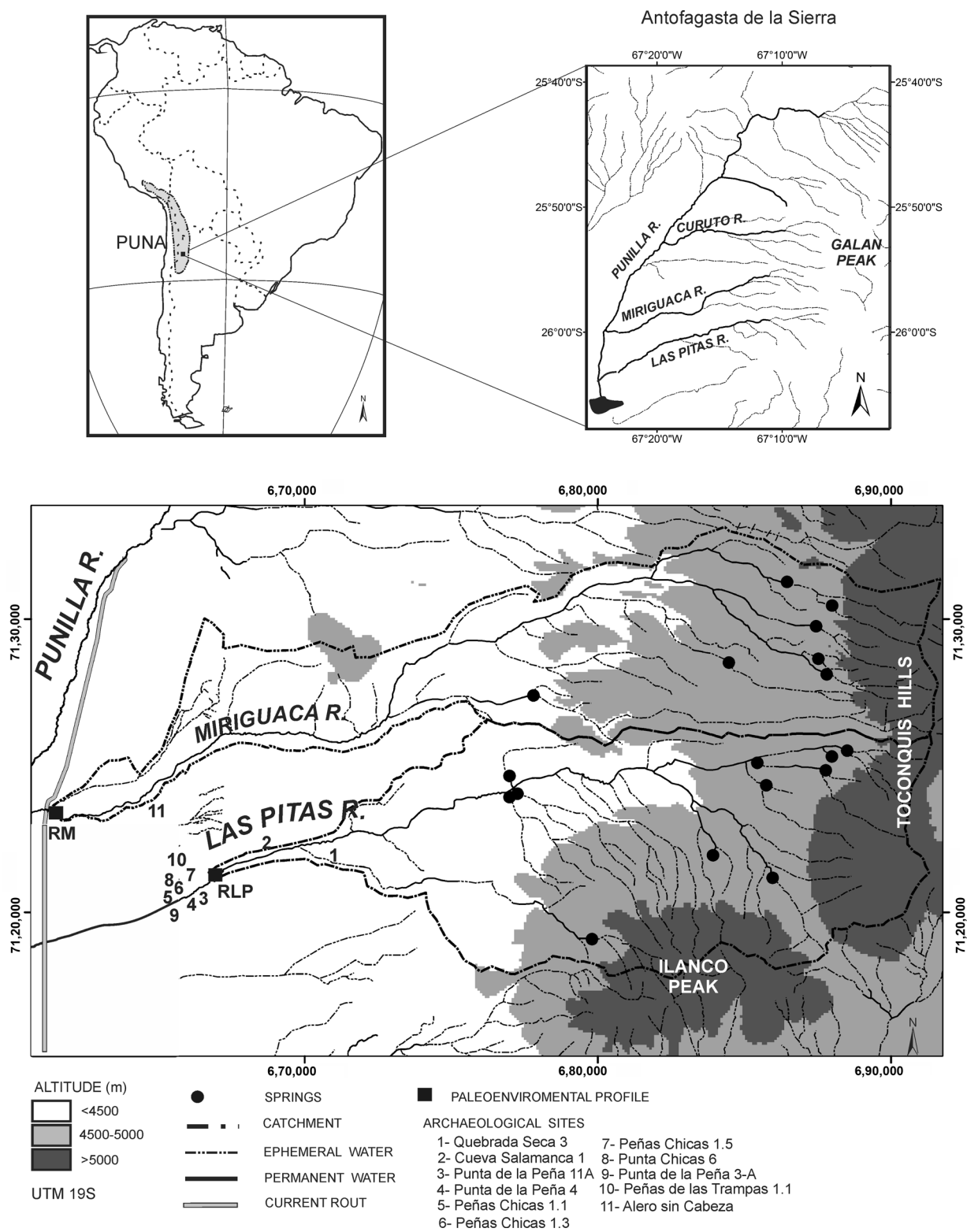
Figure 1 Geographical location of stratigraphic profiles and archaeological sites in study area.

Pleistocene to Holocene fluvial terraces are evident along both rivers, along with an active flood plain occupied by wetlands (*vegas*).

Despite the arid environment, both rivers are permanent due to greater precipitation in the higher parts of their basins. Orographic precipitation infiltrates into fractured volcanic rocks located above 4500 m asl and supports baseflow. The high elevation watershed for the Las Pitas River covers an area of *ca.* 100 km² and contains a greater number of springs compared to the Miriguaca River, whose high elevation watershed is restricted to *ca.* 60 km² (Figure 1). Variations in upland seasonal flooding is minimal, and water tables lie less than 0.5 m from the surface, allowing for the development of organic soils and riparian vegetation (cushion peat land) (Squeo et al, 2006). Streamflow slightly increases during the winter due to lower atmospheric temperatures and reduced evapotranspiration rates (Salminci, Tchilinguirian, & Lane, 2014). Seasonal streamflow variability increases in the lower basin, probably as a consequence of water loss due to infiltration and higher evapotranspiration rates compared to the higher basin. Furthermore, irrigation activities are another factor reducing streamflow in the lower basin (Tchilinguirian, 2009).

Previous paleoenvironmental analyses in the study area define the middle Holocene as a predominantly arid period followed by the more humid late Holocene. This reconstruction is based on multiproxy records, for example, geomorphology, sedimentology, diatom, and ostracod proxies, undertaken at the Laguna Colorada Salt Lake (26.03°S, 67.45°W), located 5 km west of the current study area, and at nearby marshes (Olivera, Tchilinguirian & de Aguirre, 2006; Tchilinguirian, 2009; De Micco, 2010; Grana, 2013; Tchilinguirian & Olivera, 2014). These paleoecological records provide a substantial starting point from which to understand spatial and temporal environmental changes along the Miriguaca and Las Pitas rivers during the Holocene.

ARCHAEOLOGY OF ANTOFAGASTA DE LA SIERRA

Antofagasta de la Sierra is a particularly rich area for sociocultural research into human adaptation to desert environments. Human occupation in the area began during the early Holocene (Figure 2) with hunter-gatherer settlement recorded in the lower stratigraphic level of the Peñas de las Trampas site that dates to *ca.* 10,190 cal. yr B.P. (Martinez, 2014). During the period between 8000–4000 cal. yr B.P., we have evidence in the Southern Andes highlands for sporadic occupation of hunter-gatherer sites. In some areas, such as northern Chile and

Argentina, the evidence suggests that certain areas that had been occupied during the early Holocene were abandoned (Núñez et al., 1999). However, the archaeology from Antofagasta de la Sierra shows greater habitation stability during this period (Mondini et al., 2013). In fact, between *ca.* 8500 and 6000 cal. yr B.P. there is evidence of considerable residential activity in areas above 3600 m asl that had high potential resource productivity (Mondini et al., 2013). These hunter-gatherer groups undertook mobility strategies that entailed regular visits to certain sites where they engaged in the intensive exploitation of guanaco (*Lama guanicoe*) and vicuña (*Vicugna vicugna*), thereby maximizing use of wild resources (Aschero and Martinez, 2001).

The archaeological evidence recovered from sites in the area dating 5500–3500 cal. yr B.P. reveals a process of intensification and increased social complexity, involving a local transition from a hunter-gatherer to food-producing way of life. This transition is characterized by a progressive reduction in residential mobility framed within increasing sedentism (Hocsman, 2002, 2006; Aschero & Hocsman, 2011). Crucially, important socioeconomic changes occur during this period such as the domestication of camelids as evidenced by osteometric changes (Aschero, Izeta, & Hocsman, 2014; Grant Lett-Brown, 2014; Urquiza & Aschero, 2014), and the use of a large variety of domesticated plants such as *Chenopodium* sp. aff. *quinoa*, *Oxalis tuberosa*, *Solanum tuberosum*, and *Zea mays* (Babot, 2011).

Aschero and Hoscman (2011) proposed that the commencement of productive strategies was not due to the influence of "nuclear areas," but rather to local factors within hunter-gatherer groups themselves. Their proposal for this new social dynamic is based on systematic research of 11 archaeological sites, supported by 26 radiocarbon dates, mostly from rock shelters. Of these sites, 10 are located in the Gorge of Las Pitas River (Quebrada Seca 3; Cueva Salamanca 1; Punta de la Peña 11A, 3A and 4; Peñas Chicas 1.1, 1.3 and 1.5; Puntas Chicas 6; Peñas de las Trampas 1.1); the remaining is located on the Miriguaca River (Alero sin cabeza; Figure 1).

This transitional process culminates *ca.* 2500 cal. yr B.P. when sedentism becomes reinforced through the founding of small permanent villages, such as the Casa Chavez Montículos site, inhabited by specialized agropastoralist groups (Olivera & Vigliani, 2000/2002; Grant Lett-Brown, 2014). Since *ca.* 1000 cal. yr B.P., the study area has witnessed increased sociopolitical complexity associated with large-scale agricultural production, significant population concentration in the central basin (La Alumbrera site), and an increased centralization and bureaucratization of power (Olivera & Vigliani, 2000/2002; Salminci, Tchilinguirian, & Lane, 2014).
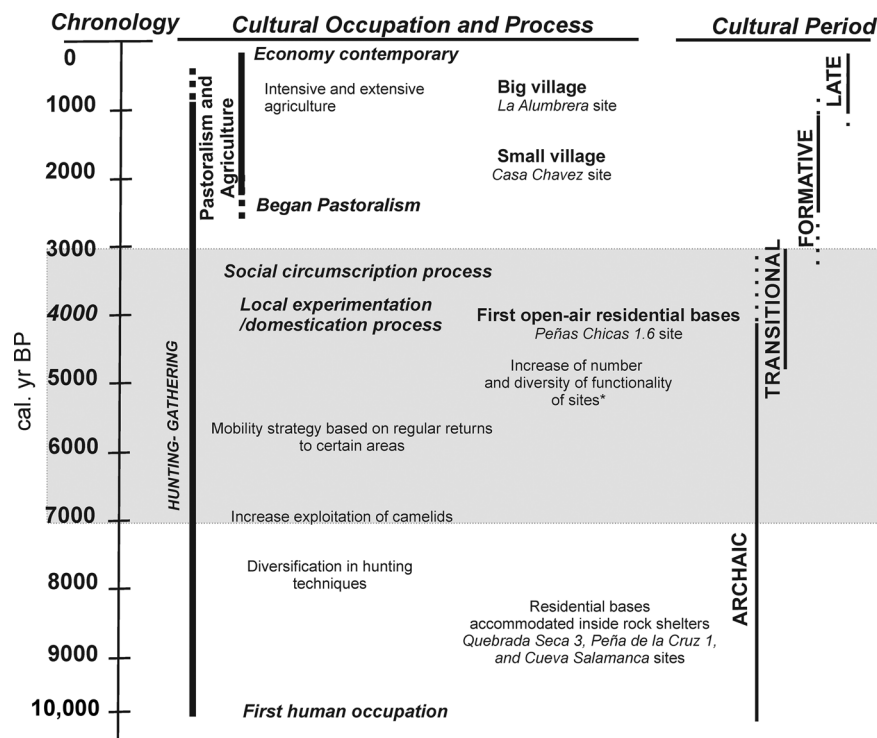
Figure 2 Chronological summary of the main cultural processes in Antofagasta de la Sierra. The gray bar indicates the period under study. Site information provided in Table II.

METHODS

Geomorphology and Sedimentology

The geomorphology of the Las Pitas and Miriguaca Rivers basins was studied using high-resolution satellite imagery with a 0.5 m spatial resolution provided by Google Earth™. Our study included the mapping of landforms with particular emphasis on the identification of wetlands and fluvial terraces. Watershed morphometry (slope, maximum height, and surface) was studied using digital topography models (SRTM).

Both rivers are *ca.* 35 km long and contain discontinuous exposures of alluvial deposits. We focused on two *ca.* 0.9 km long reaches, one along each river, that contain exposures of middle-to-late Holocene deposits. Other outcrops along both rivers are dominated by bedrock or Pleistocene and historical unconsolidated deposits. Detailed analysis and sampling were performed on 300 and 100-m long middle-to-late Holocene outcrops along the Las Pitas and Miriguaca Rivers, respectively. The Las Pitas River profile (RLP) is located in an ignimbrite canyon, 9.5 km upstream from the river's mouth; the Miriguaca River profile (RM) is located below an incised piedmont, 1.8 km upstream from the river's mouth (Figure 1). At both profiles, we describe the geometry of sediment bodies and identify lithofacies and lithofacies associations (FA). Distinctive lithofacies types were defined in terms of relative scales of strata thickness and internal bedding, yielding information on depositional features and formation processes at a relatively small-scale (Bridge, 1993). Lithofacies were classified on the basis of grain size, sedimentary structures, biological components, and geometry, following the procedures described by Friend (1983) and Miall (1982, 1996). Lateral and vertical changes as well as the distinctive spatial relations of the lithofacies (three-dimensional geometry) are the basis for FA definitions, thereby yielding more information about larger-scale aspects of the depositional environments.

Diatom data

Diatom analysis was conducted on samples obtained from Las Pitas River Profile (RLP; $n = 36$) and Miriguaca River Profile (RM; $n = 28$). Samples were pretreated following standard protocols of Battarbee (1986) and mounted on slides with Naphrax® (ni = 1.73). These were subsequently analyzed using a Polivar Reichardt Jung binocular microscope with Nomarsky Interference Contrast and 100× immersion plan-apochromatic objectives. Relative abundance was calculated counting between 300 and 500

Table I Radiocarbon ages from Las Pitas and Miriguaca River terrace exposures.

Lab Code	Profile, Sample (Depth in cm)	Measured ^{14}C Age B.P.	δ^{13}C $^0/_{00}$	Probability Range 2σ Calibrated (cal yr B.P.)	Median calibrated (cal. yr B.P.)
NSF-USA AA103378	Las Pitas River RLP (120)	3584 ± 38	−23.5	3959–3691	3801
NSF-USA AA103377	Las Pitas River RLP (172)	4365 ± 39	−23.9	5035–4823	4893
NSF-USA AA96539	Las Pitas River RLP (280)	5963 ± 52	−24.2	6890–6619	6733
CASI-UGA 8793	Miriguaca River RM2 (50)	1560 ± 40	−24.2	1446–1308	1399
NSF-USA AA85738	Miriguaca River RM1 (10)	2690 ± 39	−23.0	2852–2710	2759
CASI-UGA 8792	Miriguaca River RM1 (12)	3060 ± 40	−15.8	3350–3064	3199
NSF-USA AA85737	Miriguaca River RM1 (210)	5641 ± 45	−23.3	6466–6290	6369
CASI-UGA 8791	Miriguaca River RM1 (212)	5880 ± 40	−23.9	6736–6501	6625

valves, and the density of the total valves g^{-1} of dry sediment was estimated by the aliquot method (Battarbee, 1986). We follow Bradbury's (1988) proposal that diatom assemblage samples with less than 100,000 valves g^{-1} of dry sediment should not be considered reliable for paleoenvironmental inferences. Taxonomical identification was based on monographs by Rumrich, Lange-Bertalot, and Rumrich (2000), and other related articles.

Servant and Servant-Vilary (2003) indicated that the relationships between diatoms and habitat type provide a good indicator of changes in water depths for a number of rivers in the Bolivian *puna*. According to these authors, habitats are divided into two large groups. Group 1 is represented by facultative planktonic, benthic, and epiphytic species and indicates shallow aquatic habitats and high water tables associated with mesic conditions. Group 2, on the other hand, is mainly characterized by aerophilous species, and indicate the expansion of hydromorphic soils and humid meadows, that is, low water tables and less humid conditions. Information concerning ecological references are based on standard texts such as Lowe (1974); Van Dam, Mertenes, and Sinkeldam (1994), among others.

The relative abundance of significant species was plotted using Tilia-TGView Version 2.0.4 software (Grimm, 1992). Additionally, diatom stratigraphic biozones were determined with Optimal Partition using the Sum of Squares Criterion (OPTIMAL PARTn) calculated with ZONE v. 1.2 (Juggins, 1991). Finally, the statistical significance of the different zones was evaluated employing the Broken-stick model with the BSTICK v. 1.0 program, where the partitions with an observed variance reduction higher than the one for the null model were considered statistically discernible (Bennett, 1996).

Radiocarbon data

Chronological relationships between paleofluvial and cultural changes are based on radiocarbon ages, some previously obtained during earlier investigations in the region. Accelerator mass spectrometry (AMS) radiocarbon dating of eight fluvial sediment samples was performed on bulk organic matter from paleowetland sediments (Table I). The dated layers were mainly composed of complete and broken plant epidermis remains. This terrestrial plant material does not suffer from ^{14}C reservoir effect and is therefore highly effective for dating (Geyh et al., 1999; Valero-Garcés et al., 2000). All ages were calibrated to 2σ using the Oxcal v. 4.2.3 software (Bronk Ramsey & Lee, 2013) and the ShCal04 curve (McCormac et al., 2004). Midpoints were estimated by the mean value (μ) provided by the software, and the calibrated dates are presented as cal. yr B.P. rounded to the nearest decade.

Archaeological data

Archaeological data were compiled from available information contained in published literature from the study area. This was augmented with information on the inferred functionality of the archaeological sites for each chronological period (Table II). Functionality categories are numbered: (1) "residential base camp" (seasonal occupation site comprising sleep camps as well as a wide range of domestic activities); (2) "specific activities" (temporary occupation site used by a group or single, where they developed particular activities, such as hunting); (3) "activities associated to ritual events", such as human burials or intentional offerings; (4) no data available regarding functionality. It should be remembered that these categories are not mutually exclusive, as some sites were multifunctional.

RESULTS AND INTERPRETATIONS

Geomorphology

Fluvial terraces located along the lower reaches of the Las Pitas and Miriguaca Rivers are defined by elongated level

Table II Radiocarbon ages and functionality of archaeological sites from Antofagasta de la Sierra.

River	Archaeological Site-Dating Code	Laboratory Code	Material (Level)	Measured ^{14}C Age B.P.	Probability Range 2σ Calibrated (cal. yr B.P.)	Median Calibrated (cal. yr B.P.)	R	F	O	S	Reference
Las Pitas (≈ 3900 m asl)	Quebrada Seca 3–8	UGA 8357	Human bone (2b2)	4410 ± 60	5276 – 4827	4965	X	X			Hocsman (2002)
	Quebrada Seca 3–7	BETA 27801	Grasses (2b2)	4510 ± 100	5438 – 4844	5100	X	X			Hocsman (2002)
	Quebrada Seca 3–6	BETA 27802	Charcoal (2b3)	4770 ± 80	5610 – 5093	5441	X				Aschero et al. (2014)
	Quebrada Seca 3–5	AC 1115	Charcoal (2b2)	4930 ± 110	5894 – 5326	5614	X	X			Aschero et al. (2014)
	Quebrada Seca 3–4	BETA 59927	Charcoal (2b5)	5380 ± 70	6278 – 5940	6105	X				Aschero et al. (2014)
	Quebrada Seca 3–3	LP 270	Charcoal (2b5)	5400 ± 90	6294 – 5930	6120	X				Aschero and Hocsman (2011)
	Quebrada Seca 3–2	BETA 77745	Charcoal (2b10)	6080 ± 70	7156 – 6673	6880	X				Pintar (2014)
	Quebrada Seca 3–1	AC 1117	Charcoal (2b8)	6160 ± 100	7248 – 6743	6987	X				Pintar (2014)
Las Pitas (≈ 3600 m asl)	Punta de la Peña 11A-15	UGA 8355	Human bone (-)	3210 ± 50	3547 – 3220	3376		X			Aschero and Hocsman (2011)
	Peñas Chicas 1.3-14	LP 1421	Charcoal (3/4)	3490 ± 60	3867 – 3486	3699	X				Hocsman (2007)
	Peñas Chicas 1.1-13	LP 263	Charcoal (3)	3590 ± 55	3976 – 3644	3814	X				Aschero and Hocsman (2011)
	Peñas Chicas 1.1-12	LP 261	Charcoal (4)	3660 ± 60	4089 – 3720	3916	X				Aschero and Hocsman (2011)
	Punta de la Peña 11A-11	UGA 7977	Grasses (-)	3680 ± 150	4408 – 3584	3962		X			Aschero and Hocsman (2011)
	Peñas Chicas 1.3-10	UGA 15092	Charcoal (7)	3680 ± 50	4141 – 3733	3944	X				Aschero and Hocsman (2011)
	Punta de la Peña 4-9	UGA 9254	Charcoal (3x)	3820 ± 100	4420 – 3870	4145	X				Aschero and Hocsman (2011)
	Peñas Chicas 1.5-8	UGA 15097	Animal bone (-)	3830 ± 50	4402 – 3978	4151			X		Aschero and Hocsman (2011)
	Punta de la Peña 4-7	Beta77748	Wood (4a)	3870 ± 90	4508 – 3928	4212	X				Hocsman (2002)
	Punta de la Peña 4-6	Beta 77749	Wood (4b1)	4060 ± 90	4821 – 4236	4495	X				Aschero and Hocsman (2011)
	Punta de la Peña 4-5	UGA 7976	Charcoal and charred wood (5(6)2)	4100 ± 160	4963 – 4085	4534	X				Aschero and Hocsman (2011)
	Peñas de las Trampas 1.1-4	LP 1588	Grasses (2)	4210 ± 60	4842 – 4522	4683				X	Aschero and Hocsman (2011)
	Cueva Salamanca 1–3	Beta 311872	Charcoal (2-1a)	4460 ± 30	5268 – 4859	4989					Pintar (2014)
	Punta de la Peña 4-2	UGA 15094	Animal bone (6-3)	4560 ± 60	5432 – 4890	5149	X				Aschero and Hocsman (2011)
	Cueva Salamanca 1-1	LP 931	Charcoal (2(2a))	6250 ± 70	7264 – 6906	7090	X				Pintar (2014)
Miriguaca (≈ 3600 m asl)	Alero sin cabeza-3	LP 1846	Charcoal (-)	3390 ± 70	3818 – 3394	3573	X				Escola et al. (2013)
	Alero sin cabeza-2	LP1835	Charcoal (-)	3470 ± 60	3836 – 3483	3673	X				Escola et al. (2013)
	Alero sin cabeza-1	LP 1796	Charcoal (-)	3610 ± 70	4081 – 3641	3845	X				Escola et al. (2013)

Site functionality: R = residential bases; F = ritual activities, individual burial; O = ritual offering; S = specific activities.
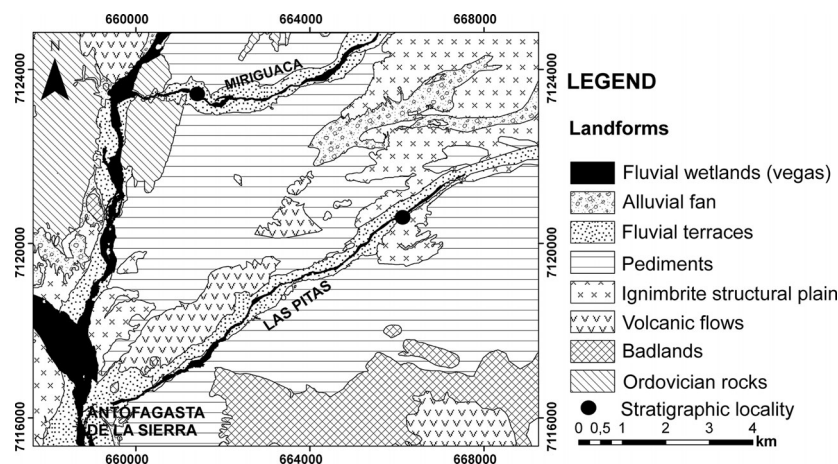
Figure 3 Geomorphological map. UTM Zone 19S, WGS 84.

surfaces flanking the borders of ignimbrite canyons and piedmonts (Figure 3). Eight terraces have been identified. Terraces I to V have a maximum height of *ca.* 20 m above the river channel and date to the Pleistocene. We interpret these as fill terraces (*sensu* Bull, 1991) formed by episodic downcutting and backfilling. Terrace VI contains alluvial gravels and sands with peats interbedded with diatomaceous silts. The peats date to between 6730 and 3500 cal. yr B.P. along the Las Pitas River, and *ca.* 6630 to 1400 cal. yr B.P. along the Miriguaca River (see below). Closer to the modern river channels are unpaired Terraces VI, VII, and VIII. Terraces VII and VIII are located 2 and 1 m above the channel, respectively, and composed of sands and gravel that post-date 1400 cal. yr B.P. The lower reaches of both rivers form valleys inset 20–30 m into the Pleistocene piedmont that is conformable with Pleistocene Terrace III farther upslope. The inset flood plains are occupied by marshes (Figures 3 and 4).

Modern fluvial processes vary within and between the basins. In the higher (cryoandean belt) zone of both rivers (>4950 m asl), channels are indistinct and plant cover diminishes considerably with altitude. Between 4950–4000 m asl, streamflow is conducted in slightly meandering, 2 m wide and 1 m deep, channels that transport medium-sized gravels to coarse sands. Channels occupy 5–10% of the active flood plain or fluvial belt, while the remaining surface is covered by typical, intrazonal alto-Andean cushion peatland. These plants comprise compact, primarily circular cushions formed by closely packed shoots with short internodes, sometimes occupied by shallow pools. Associated with the peatland are organic and mineral soils affected by paludization, iron-reduction, and freeze-thaw processes.

Along the middle reaches of both rivers (4000–3350 m asl), channels occupy 70–80% of the fluvial belt. These channels are smaller than in the upper reaches of the

high basins, and the dominant grain sizes are coarse to very coarse sands, indicating a downstream reduction in grain size and stream competence. The cushion peat is degraded, or has flat and thin shapes associated with *Distichia muscoides*, surrounded by stands of tussock grass. Mineral sandy soils with Ag-C profiles and redox features are common. Evidence of freeze-thaw processes is absent, and soil humification is limited.

In the lower river basins, the channels cover 70–80% of the fluvial belt. The lower reach of the Las Pitas River has braided channels with coarse sandy and fine gravel. Today streamflow is ephemeral due to diversions for irrigation. The lower reach of the Miriguaca River, however, is permanent and has flood plain characteristics similar to its middle reach. Both rivers form a tributary alluvial fan covering a 1 km^2 area at their junctions with the Punilla River.

Depositional histories can vary between river reaches due to intrinsic geomorphic controls that generate equifinality problems (Knox, 1983; Schumm, 1991; Church, 2008; Harvey & Pederson, 2011). Both the Las Pitas and Miriguaca Rivers share some geomorphic attributes, for example, their flood plains have shallow hydrogeological basements (<10 m) and Quaternary gravel substrates. Likewise, the stream valleys have similar stream gradients and lithologies and lack visible evidence of neotectonics or dams caused by tributary Holocene debris flows. The main difference between these two river basins lie in the size of their high altitude catchment areas: the Las Pitas River has a high altitude catchment, that is, 20% larger and has more springs providing for greater baseflow (Figure 1). There are also local differences between the Las Pitas River and Miriguaca stratigraphic localities. Although both localities are downstream from major tributaries within their hydrological basins, the Las Pitas River locality is situated within a bedrock
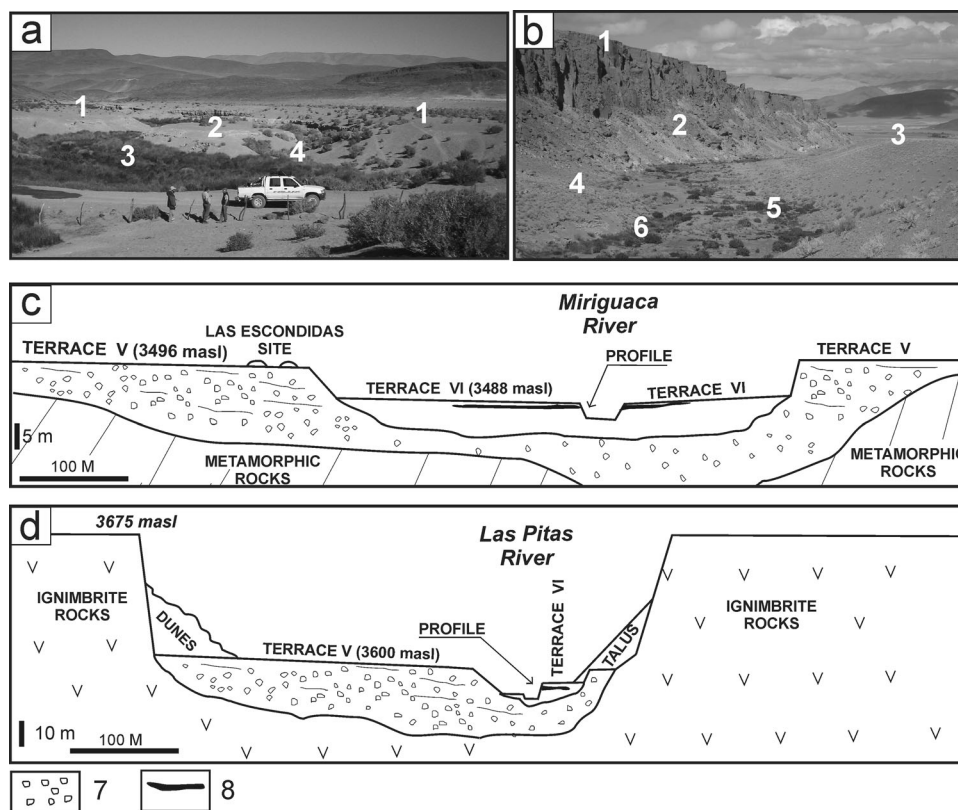
Figure 4 Landforms and cross-sections within study area. (a) Miriguaca Valley: (1) Terrace VI, (2) Terrace VII, (3) Flood plain with swamps, (4) paleochannel. (b) Las Pitas Canyon: (1) Ignimbrite cliff, (2) Block falls and colluvial sediments, (3) Terrace III, (4) Terrace VII, (5)Terrace VIII, (6) active channel. Geomorphological cross-section of Miriguaca (c) and Las Pitas (d) rivers: (7) Pleistocene coarse gravel deposits; (8) Paleopeat.

canyon with a more confined flood plain compared to the Miriguaca River locality, the latter located on the piedmont (Figures 3 and 4). Geomorphic differences between these two closely spaced rivers are likely to result in somewhat different fluvial responses to possible climatic forcing.

Sedimentology

We identify 20 lithofacies based on stratigraphy and sedimentology at the Las Pitas and Miriguaca stratigraphic localities (Table III) that are grouped into four primary lithofacies associations: FA1, composed of bedded alluvial gravel associated with braided channels; FA2, massive gravel related to gravity flows deposits; FA3, sand lenses and gravel channels covered by tabular layers of diatomaceous silt laminated with organic matter and soils associated with vegetated wetlands; and FA4, continuous tabular deposits of diatomaceous silt laminated with organic matter interpreted as alluvial plains of low depositional energy (Table IV).

Las Pitas River

The basal section of the Las Pitas River stratigraphic locality, dated to 5963 ± 50 ^{14}C yr B.P. (6730 cal. yr B.P.), is characterized by bedded gravels in a sand matrix with reddish (iron) mottles overlain by horizontally stratified sands (FA1). This facies is interpreted as high-energy braided channels devoid of paleomarshes. These gravels occur in tabular layers laterally extending > 200 m. These are overlain by layers of massive, matrix-supported gravels separated by an erosive discontinuity and are interpreted as debris flow deposits (FA2). Root traces suggest the existence of flood plain vegetation; however, it was probably not abundant enough to form organic peatlands. Interspersed within the debris flow deposits are thin and discontinuous lenses of stratified gravels and finer, laminated sediments with diatoms (FA3), indicating that there were at least two debris flow events. Cut-and-fill unconformities are common in the middle and upper sections, where the profile is dominated by a gravel-stratified facies with subordinate laminated organic and diatomaceous sediments (FA3). Diatom

Table III Summary of lithofacies described in this study.

Facies code (Miall 1996)	Description	Sedimentary structures	Interpretation
Gh	Gravel, clast supported	Horizontal bedding common clast imbrications	Channel fill, bar
Gmm	Gravel, matrix supported	Massive	Mud flows
Gcm	Gravel, clast supported	Massive	Debris flows
Gcmb	Gravel, clast supported	Massive, bioturbated	Mineral soil in debris flows
Sh	Sand, very fine to very coarse	Horizontal bedding	Channel fill, bar
Sb	Sand, very fine to very coarse	Massive, bioturbated	Mineral paleosols in overbank
Sm	Sand, very fine to very coarse	Massive	Sand flows form lateral valleys dunes
SO l	Sand, very fine to coarse with organic debris	Laminar	Overbank
SO m	Sand, very fine to coarse with organic debris	Massive	Overbank and backswamp
SO b	Sand, very fine to coarse with organic debris	Massive, bioturbated	Mineral soil in overbank
Fl	Mud, clay, organic	Planar laminations	Overbank and backswamp
Fm	Mud, clay	Massive, bioturbated	Overbank and backswamp
Cz	Muddy and very fine sand volcanic ash	Massive	Ash

layers are between 5 and 15 cm thick, forming lenses that laterally extend 10 and 50 m. These layers have been dated to between 4365 ± 40 ^{14}C yr B.P. and 3584 ± 40 ^{14}C yr B.P. (4890 and 3800 cal. yr B.P., respectively). In the upper section, a tabular and thicker (25 cm) diatom layer with laminated organic matter (FA4) laterally extends >200 m and dates 3800 cal. yr B.P. (Figure 5).

Miriguaca River

The lower part of Miriguaca River stratigraphic locality is exposed in a few places and contains two mineral paleosols of dark gray color interbedded with thin diatomite lenses and thin laminations of organic matter and fine gravels with strong stratification (FA3). These deposits date 5880 ± 40 and 5641 ± 45 ^{14}C yr B.P. (6630 and 6370 cal. yr B.P.) and are interpreted as a perennial high-energy fluvial environment with episodic mineral soil formation. Facies FA1, characterized by bedded gravels with thin lenses of white silt devoid of organic matter, appears above an erosive discontinuity that extends across the entire middle section of the profile, and in turn is overlain by debris flow deposits of Facies FA2. Within the debris flow deposits, a 10–20 cm thick, discontinuous lens of white fine, ashy sediment was identified and interpreted as fluvially redeposited volcanic ash. Fewer root traces occur within the ashy sediment, Facies FA1, and FA2 compared to the lower profile. The middle section is thus interpreted as an ephemeral fluvial environment dominated by episodic debris flow and high-energy floods (Figure 6). A discontinuity bounds the upper contact of these deposits and is overlain by a 1 m thick sequence of FA4 sediments that laterally extend > 200 m. These sediments include organic sands and diatomaceous

Table IV Description, dominant lithofacies, and depositional environment of the facies associations (FAs) preserved in Las Pitas and Miriguaca River terrace exposures.

| Facies Association	Dominant or Characteristic Lithofacies	Description	2D Strata Shape	Depositional Environment
FA1	Gh, Gt	Horizontally stratified, planar cross-bedded, though bedded medium to fine gravels and coarse to medium sands	Channel	Gravel braided channels
FA2	Gmm, Sm, Gcm	Poorly stratified gravels, matrix or clast-supported massive gravels	Channel	Debris flow and mud flows
FA3	Gh, Fl, Sh, Gt, Fm, SOl	Horizontally stratified, planar cross-bedded, thought bedded coarse sands, and stratified gravels lens (40–5% of the section) with diatomaceous muds and organic black sediments. Oxic red mottled sediments	Channel	Gravel channels with backswamps
FA4	Fl	Planar laminated organic black sediments interbedded light gray laminated diatomitic muds and silts. Thin wedge layer of light red fine sands	Sheet	Backswamp with peat in low-energy flood plain
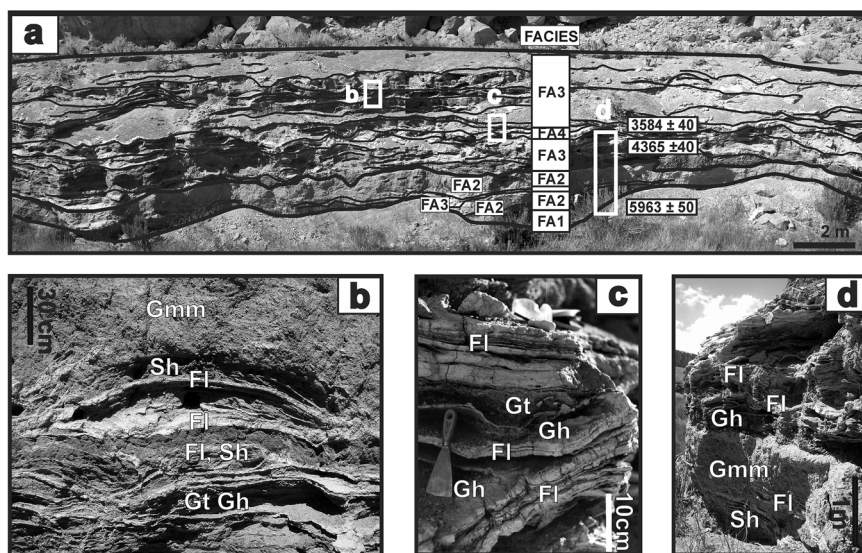
Figure 5 Stratigraphic exposure of terrace deposits at the Las Pitas section, facing north, showing fluvial sediments, paleowetland deposits, and facies. (a) General view of terrace deposits; (b) upper section with diatom mound deposits; (c) middle section of diatom and organic laminae facies (litho facies Fl); (d) lower section of debris flow sediments (lithofacies Gmm) and the beginning of diatom and organic swamp sediments (lithofacies Fl).

silts interbedded with organic matter. Organic sediment was dated to 3060 ± 40 ^{14}C yr B.P. (3200 cal. yr B.P.) and an overlying laminated silt to 2690 ± 40 ^{14}C yr B.P. (2760 cal. yr B.P.; Figure 6). The top of the stratigraphic sequence contains an erosional contact overlain by a 2 m thick succession of tabular bedded gravels that fine upward to finer grained deposits (Fl, Fm). This section corresponds to Facies FA3. Organic matter from the upper finer deposits dated 1560 ± 40 [14]C B.P. (1400 cal. yr B.P.; Tchilinguirian, 2009).
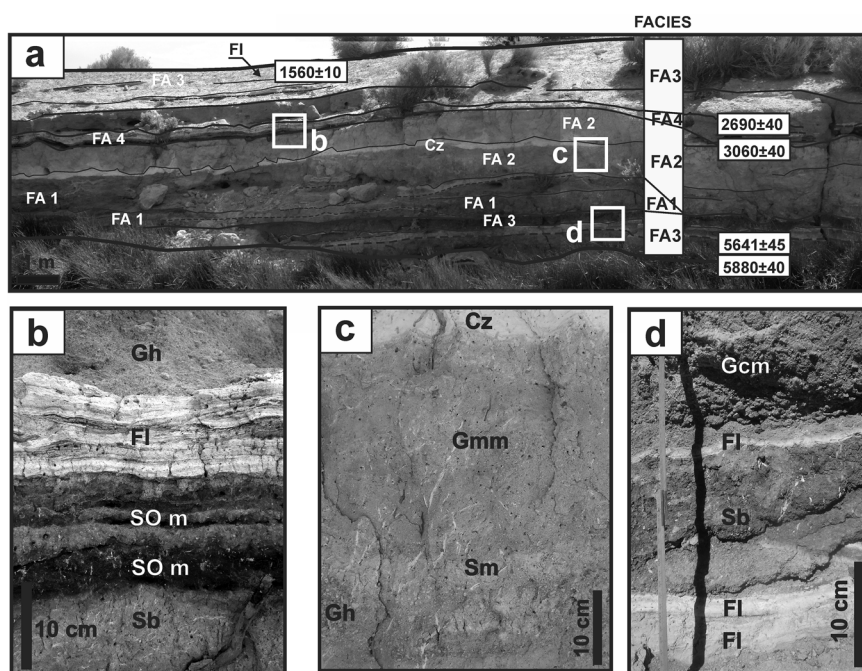

Figure 6 Stratigraphic exposure of terrace deposits at the Miriguaca section. (a) Main exposure facing south; (b) upper section with thinly laminated diatom and organic fine sediments (lithofacies Fl) and organic sandy sediments (lithofacies SO m), and coarser gravel deposits (lithofacies Gh); (c) middle section with debris flows sediments (lithofacies Gmm); (d) lower section with paleosols (lithofacies Sb).
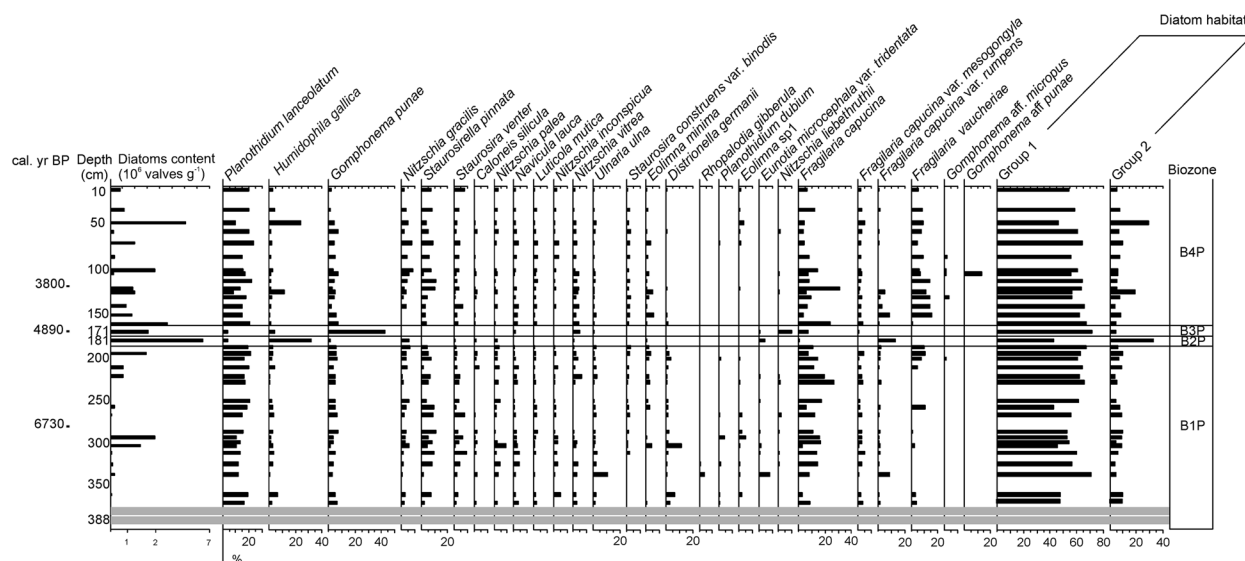
Figure 7 Diatom content and percent composition of dominant diatom assemblages from the Las Pitas River (profile RLP). The light gray bars indicate samples with densities < 100,000 valve gr^{-1} dry sediment. The solid lines mark the boundaries of the biozones.

Diatoms

Las Pitas River

A total of 34 samples from the Las Pitas River stratigraphic exposure contained sufficient quantities of diatoms for paleoenvironmental reconstruction. In these samples, 38 genera were identified, including 94 infragenera taxa. *Planothidium lanceolatum* and *Fragilaria capucina* complex (*sensu* Lange-Bertalot, 1980) are dominant throughout the stratigraphic sequence, followed by *Humidophila gallica* and *Gomphonema punae*, both frequent in Andean rivers (Seeligmann & Maidana, 2003).

Statistical analyses indicate four distinct biostratigraphic zones (Figure 7). Although the beginning of Biozone B1P (358–190 cm deep) has not been clearly identified, this biozone likely developed during the middle Holocene, *ca.* 6730 cal. yr B.P. Biozone B1P, is characterized by the dominance of the aforementioned species and a lesser presence of *Staurosirella pinnata* (10%), *Nitzschia gracilis* (8.3%), *Staurosira venter* (7.6%), and *Nitzschia palea* (3.3%). Most of these are species that prefer Group 1 habitats, in effect, moist river bank environments.
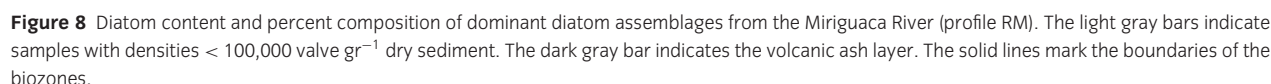
Higher in the profile, two Biozones, B2P (181 cm) and B3P (171 cm), are both defined by one sample each and significant changes in diatom assemblages when compared to the other biozones. Biozone B2P predates 4890 cal. yr B.P. and is characterized by a significant increase and dominance of aerophilous species such as *H. gallica* (31.7%). It implies a prevalence of Group 2 species and less humid conditions. At *ca.* 4890 cal. yr B.P., Biozone B3P develops, with a strong increase of *G. punae*

(42.3%) and an important peak in the relative frequency of *Nitzschia liebetruthii* (9.7%). *Gomphonema punae* is an endemic species in the Andes, although its autecology is still unknown. It could have been an epiphyte, a common characteristic of the *Gomphonemataceae* family, that adhered to a variety of algae, bryophytes, and vascular aquatic plants associated with periphyton (Round, Crawford, & Mann, 1990; Kociolek & Spaulding, 2003). These conditions identify Biozone B3P as a probable humid river margin environment with riparian vegetation.

After 3800 cal. yr B.P., the development of Biozone B4P (163–10 cm) is characterized by a diatom assemblage similar to Biozone B1P, except for the dominance of *Fragilaria vaucheriae* (between 15.2% and 5.5 %). This species is an efficient colonizer commonly found in the tychoplankton communities of rivers and lakes (Krammer & Lange-Bertalot, 1991). Consequently, an increase in Group 1 species is evident. On the other hand, a significant rise in diatoms contents is observed in the samples analyzed, suggesting higher paleoproductivity. Thus, it could be inferred that this biozone represents higher water tables that in turn allowed the development of a tycoplanctonic community.

Miriguaca River

Sediment samples collected at 154, 133, 125, 117, 86, 69, 60, 30, and 22 cm depth from the Miriguaca River stratigraphic exposure yielded densities lower than 100,000 valves g^{-1} of dry sediment, and thus provide less robust paleoenvironmental inferences. At a depth of 69 cm, a

Figure 8 Diatom content and percent composition of dominant diatom assemblages from the Miriguaca River (profile RM). The light gray bars indicate samples with densities < 100,000 valve gr^{-1} dry sediment. The dark gray bar indicates the volcanic ash layer. The solid lines mark the boundaries of the biozones.

stratum of volcanic ash, sterile in diatoms was visible. In the remaining samples, a total of 60 genera were identified, comprising 81 infrageneric taxa. Such samples were subdivided into three statistically discernible stratigraphic biozones (Figure 8).

Biozone B1M (212–173 cm deep) begins at *ca.* 6370 cal. yr B.P. and is characterized by a predominance of the aerophilic *H. gallica* (59%) with smaller percentages of typical fluvial species such as *P. lanceolatum* (13%), *Frankophila similoides* (9%), *Denticula elengans* (14%), and *Denticula valida* (8%). The fluctuation of species throughout Biozone B1M may represent river bank conditions with variations in humidity. Surfaces may have been shaded as large concentrations of *H. gallica* are found in high altitude environments where limited light intensity prevails (Morales, 2011).

Biozone B2M (167.5–22 cm deep) includes most of the stratigraphic exposure, including the volcanic ash layer, spanning a time of approximately 6300–3200 cal. yr B.P. This biozone is characterized by fluctuations in diatom abundances ranging from 100,000 valves g^{-1} of dry sediment to significantly lower densities, implying significant changes in available moisture through time. Diatom assemblages are characterized by a reduction in the abundance of *H. gallica,* with a strong decrease in Group 2 species. The lower part of this biozone is mainly conformed by *Pseudostaurosira brevistriata* (58%), *F. similoides* (27%), *Navicula lauca* (16%), and *Pseudostarosira catarctarum* (28%). Contrariwise, above the 45 cm level, *S. pinnata* (21%) and *S. venter* (14%) are recorded. All these species belong to Group 1 and grow in riparian habitats, but they appear discontinuously throughout the biozone.

Biozone B3M (9–5 cm below the surface), dated *ca.* 3200–2760 cal. yr B.P., contains *Anomoneis sphaerophora* var. 1 (20%) and *N. lauca* (12%) as the dominant species, together with benthic forms, such as *Nitzschia perminuta* (11.5%) and *N.* aff. *liebetruthii* (11.5%). It is interesting that *H. gallica* and *D. valida* reappear in this biozone, although in low percentages (8% and 4%, respectively) in comparison with Biozone B1M. Hence, despite the increase of aerophilous species (Group 2), the ones related to Group 1 habitats are dominant. It would therefore indicate a more humid environment than represented by Biozone B1M.

DISCUSSION

Middle-to-Late Holocene River Environments

Paleoecological and sedimentology data indicate that the paleoenvironmental changes recorded along the Las Pitas and Miriguaca Rivers may be divided into two distinct phases within the overall arid framework of the middle Holocene. These phases, however, present local chronological discrepancies and different magnitudes of environmental change along both rivers (Figure 9).

Paleoenvironmental phase I (PI), is defined by relatively less humid conditions compared to later phase II (PII). Phase I for the Las Pitas River dates *ca.* 6700–4800 cal. yr B.P., and *ca.* 6600–3000 cal. yr B.P. for the Miriguaca River (Figure 9). Prior to 6700 cal. yr B.P., streamflow conditions associated with high-energy braided channels would have been common to the Las Pitas River. Beginning at *ca.* 6700 cal. yr B.P., periodic
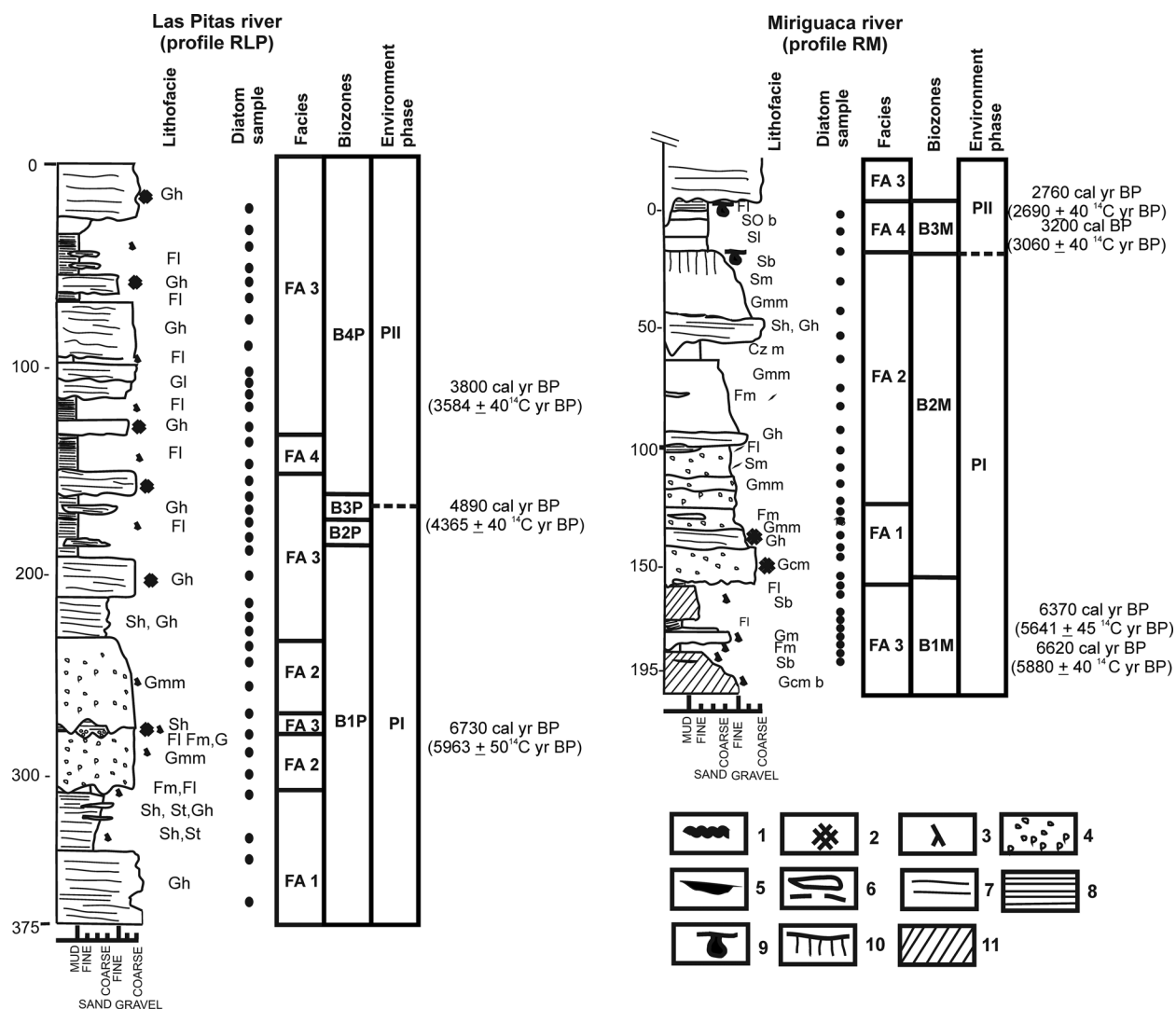
Figure 9 Model for the paleohydrological and paleoenvironmental evolution of the Las Pitas and Miriguaca Rivers. (1) Principal erosion surfaces, (2) Red iron-mottled sediments, (3) root features, (4) massive matrix-supported sediments, (5) organic-rich lens, (6) gravel lens, (7) horizontally stratified sediments, (8) thin laminar sediments, (9) faunal bioturbation, (10) weakly developed paleosol structure, (11) well-developed paleosol structure.

debris flows separated by episodes of marsh formation are recorded. Major sedimentary facies (FA1, FA2, and to a lesser degree FA3) and diatom evidence indicate a fluvial system with more stable paleohydrological conditions as compared to the Miriguaca River. Las Pitas streamflow during this phase is associated with thick gravel layers, suggesting a higher streamflow capacity than the Miriguaca River. On the other hand, the large dominance of adnate diatom taxa also depicts a riparian zone with strong abrasion events generated by rapid water velocities. These taxa produce and grow on large quantities of mucilage and are highly resistant to fluvial abrasion (Hill, 1996). Hence, their presence indicates stable streamflow,

where flooding events did not prevent the development of diatom communities along the river banks during this phase, except for two flood events recorded at the base of the profile (Figure 7).

In contrast, the paleohydrological history of PI is more complex for the Miriguaca River. Initially, streamflow was shallow and ephemeral (FA1), with shaded margins (B1M) associated with paleosols and localized lenses of Facies FA3. Toward 6300 cal. yr B.P., debris flows were deposited (FA2) along the river bottom, generating inadequate conditions for the development of diatom communities due to hydrological and, thus, ecological instability (B2M).

A thick white and biologically sterile volcanic ash lens is interpreted as a volcanic air fall deposit. Above this lens are thick alluvial and mass wasting deposits containing re-transported ashes resting directly upon an erosive discontinuity. This sequence suggests a limited introduction of tephra into these deposits, probably due to limited fluvial transport and lack of surface stability and soil formation in the flood plain. Nearby, it has been observed that cycles of volcanic activity culminated with the dome collapse of Cerro Blanco (*ca.* 5480 ± 40 yr [14]C B.P.; Montero Lopez et al., 2010). However, as the ash lens in the study profile is redeposited, it does not allow precise age correlations. Regardless of the age of this deposit, both the ash and rapid alluvial-mass wasting deposition may have had a considerable impact on the aquatic community, ecologically and hydrologically modifying this part of the river and transforming it into an unstable wetland. This situation could explain the low diatom abundance in the middle part of the profile and in the recorded sedimentological facies.

Both rivers contain evidence for more humid environmental conditions during PII. Diatom analysis indicates an increase in water table levels associated with more sustained baseflow, resulting in more extensive wetland formation (Figure 9). The beginning of this more humid phase is diachronic. Along the Las Pitas River, it starts after *ca.* 4890 cal. yr B.P. with the deposition of extensive lenses associated with Facies FA3. As opposed to the previous phase, PII is represented by laminated deposits with abundant diatoms and organic matter that alternate with bar and swale stratified gravels. These gravels are thicker and more laterally extensive than in the previous PI. Common red iron mottles in alluvial sands and gravels indicate a shallow phreatic table favoring localized pools (2–10 m^2) with greater organic and diatom sedimentation. Diatoms assemblages indicate areas marginal to the channel that are susceptible to frequent inundation (B2P). Toward *ca.* 4800 cal. yr B.P., deposits suggest greater surface stability, possibly vegetated (B3P), and later dominated by tychoplanktonic species, indicating rising water table levels and more humidity (B4P) until *ca.* 3800 cal. yr B.P. Diatom composition coincides with facies interpreted as high-energy channels across the flood plain, but with areas of high biological productivity (FA4 and FA3). Increases in effective moisture are also recorded between *ca.* 4270 cal. yr B.P. and 4100 cal. yr B.P. at Laguna Colorada, representing short pulses of moisture during an otherwise arid period in Antofagasta de la Sierra (Tchilinguirian, 2009; Grana, 2013). Finally, after 3600 cal. yr B.P., the Las Pitas River downcuts and creates a 5 m deep incised channel, resulting in a drop of the local base level (Tchilinguirian, 2009).

Evidence for PII begins later for the Miriguaca River, starting *ca.* 3000 cal. yr B.P. and continuing until 1600 cal. yr B.P. This is indicated by the dominance of Facies FA4 and FA3, which contain organic soils and reflect a shallow phreatic table and highly productive pools within the flood plain. Additionally, diatom analyses indicate the existence of puddle marshes (BM3). Thus, PII along the Miriguaca River can be correlated with increases in humidity *ca.* 3000 cal. yr B.P. that were registered regionally within the Antofagasta de la Sierra (Laguna Colorada, Mojones River, Curuto River) and farther north on the *puna* (Salar de Atacama, Negro Francisco lake, Titicaca lake) (Grosjean et al., 1997, 2007; Tapia et al., 2003).

In sum, the evidence presented here indicates that the Las Pitas River was a permanent watercourse throughout the middle-to-late Holocene, although with diminished discharge and more limited formation of organic and puddle marshes during PI. The following phase (PII) is characterized by greater discharge and marsh formation. Meanwhile, the Miriguaca River had a more stable baseflow only after 3000 cal. yr B.P. (PII); between 6600 and 3000 cal. yr B.P., streamflow was more irregular.

The diatom and alluvial stratigraphic evidence allow us to infer hydrological changes within the catchments of the Las Pitas and Miriguaca Rivers. The quantity, energy, and seasonality of runoff depend on the dimensions, altitude, soils, vegetation, and geology of the catchment areas as well as local geomorphic controls (Schumm, 1991). The geology, vegetation, climate, and soils of the two adjacent hydrological basins are similar, differing primarily in the greater catchment area, elevation, and number of springs in the Las Pitas watershed. The lower reaches of the Las Pitas and Miraguaca rivers both contain shallow alluvial fill over bedrock. However, the Las Pitas River is more entrenched and confined (Figure 4d). The two rivers' hydrological response to climate change may differ due to a combination of local geomorphological controls and contrasting size and morphometry of their watersheds. The higher altitude Las Pitas catchment area, exceeding 4500 m asl along its eastern perimeter, experiences greater orographic rainfall. Thus, the effects of increased moisture during the local humid events of PI were likely greater for the Las Pitas River than for the Miriguaca River. Upland precipitation supplies the high mountain aquifers that discharge into lower elevation springs and subsequently into wetlands, favoring elevated water tables. The confined nature of the Las Pitas flood plain reduces the effect of evapotranspiration facilitating a more stable baseflow. Consequently, the development of more stable wetlands (cushion peats) mitigated the overall aridity of the region. For the Miriguaca River, however, and its lower elevation upper basin, the

hydrological input was smaller resulting in shallower and/or more unstable water tables. Also, the open and wide flood plain of the lower Miriguaca River permits a more spatially dynamic and exposed alluvial reach, facilitating greater evaporation losses compared to the confined canyon of Las Pitas. Consequently, the lower Miriguaca River contained poorly developed wetlands during PI, marked by ephemeral streamflow.

Minor humid-arid cycles between *ca.* 8000 and 3600 cal. yr B.P. have been identified elsewhere in the region (Grosjean et al., 1997, 2007; Morales, 2011; Tchilinguirian et al, 2014). Veit (1996) argues that wet periods during the middle Holocene, while recharging local aquifers, were not sufficient to generate the geo-ecological conditions needed to produce extensive and long-lasting marshes. In effect, these wet cycles had restricted local consequences. Thus, increasing aridity during the late Holocene gave rise to diminished base-flow and greater seasonal discharge variability for the Miriguaca River. In contrast, short episodes of increased moisture during the middle Holocene generated a greater hydrological response for the Las Pitas River: more sustained baseflow, reduced discharge variability, and enhanced peat formation.

Environmental Fluctuations and Human Occupations

Paleohydrological changes between *ca.* 7000 and 3000 cal. yr B.P. in the Antofagasta de la Sierra seem to have triggered different local environmental responses that favored the development of a hunter-gatherer landscape (Aschero & Hocsman, 2011; Mondini et al., 2013). Paleoenvironmental evidence indicates that changes in effective moisture were not spatially homogenous, resulting in locally variable expansion and development of wetlands within and between hydrological basins. This situation likely played a key role in middle-to-late Holocene human occupations of this region (Figure 10).

Archaeological sites identified so far that date *ca.* 7000–6800 cal. yr B.P. are located in the high and middle reaches of the Las Pitas River (3900–3600 m asl): Cueva Salamanca 1 and Quebrada Seca 3, respectively. These sites are defined as hunter-gatherer residential bases located near wetlands and within rock shelters with favorable protection/hiding conditions within the Las Pitas ignimbrite canyon. However, no sites date to the period between *ca.* 6700 and 6300 cal. yr B.P. (Figure 10), although some settlements such as Quebrada Seca 3 (e.g., levels 2b6 and 2b7) could not be properly dated (Aschero, 1988). This apparent absence has been interpreted as a reduction in occupational intensity relative to earlier periods along the river (Pintar, 2014). Be-

tween *ca.* 6100 and 5400 cal. yr B.P., settlements in the higher parts of the Las Pitas watershed (e.g., Quebrada Seca 3) present structured spaces with evidence of space preparation and maintenance activities (Aschero, Elkin, & Pintar, 1991). This has been interpreted as a mobility strategy based on regular returns to certain places, possibly associated to well-established seasonal rounds/circuits (Aschero & Hocsman, 2011). Paleoenvironmental data from Las Pitas indicate that during this period the river's hydrological behavior was characterized by shallow perennial flow and limited development of organic and stagnant marshes within an otherwise regional arid context (PI). In addition to water availability, other factors may have favored settlement in the area, such as a preference for shrub land.

Archaeological evidence suggests a change in human activities at the Quebrada Seca 3 site between *ca.* 5600 and 4900 cal. yr B.P. During this period, we see evidence for multiple intra-site space—residential base activities as well as symbolic and ritual practices (Figure 10). At approximately 4900 cal. yr B.P., the site seems to have been abandoned and living areas were covered by sediments (Aschero, 1988). Toward the end of this period as Quebrada Seca 3 is abandoned, there is evidence of new settlements along the middle reaches of the Las Pitas River, namely Cueva Salamanca 1 and Punta de la Peña 4. These two sites also present evidence of settlement dating back to 7000 cal. yr B.P. and 10,000 cal. yr B.P., respectively (Hocsman, 2002; Mondini et al., 2013; Pintar, 2014). We believe that local hunter-gatherers organized their settlement-subsistence and mobility systems within the rich mosaic of this environmental framework.

Toward *ca.* 4600 cal. yr B.P., a new change in settlement patterns is noted for the Las Pitas River, coinciding with the more humid PII environmental phase. This change occurs at a time of increased spatial variability in moisture in a regional context during which the environmental conditions along the Miriguaca River remain typical of PI (Figures 9 and 10). It is possible that greater effective moisture along the Las Pitas River provided for a more intensive and expansive use of the hydrological basin (Figure 10). Not only are a larger number of possibly contemporaneous sites recorded for this period, but they are also associated to specific in-site activities, such as residential bases, ritual practices including the intentional disposition of objects/burials, and sites for other activities. This greater number and diversity of sites include Punta de la Peña 4, Punta de la Peña 11.A; Peñas Chicas 1.1, Peñas Chicas 1.3, Peñas Chicas 1.5; Peñas de las Trampas 1.1 (Hocsman, 2006; Aschero & Hocsman, 2011). Moreover, the first evidence for an open-air residential settlement for this period can be seen in the Peñas
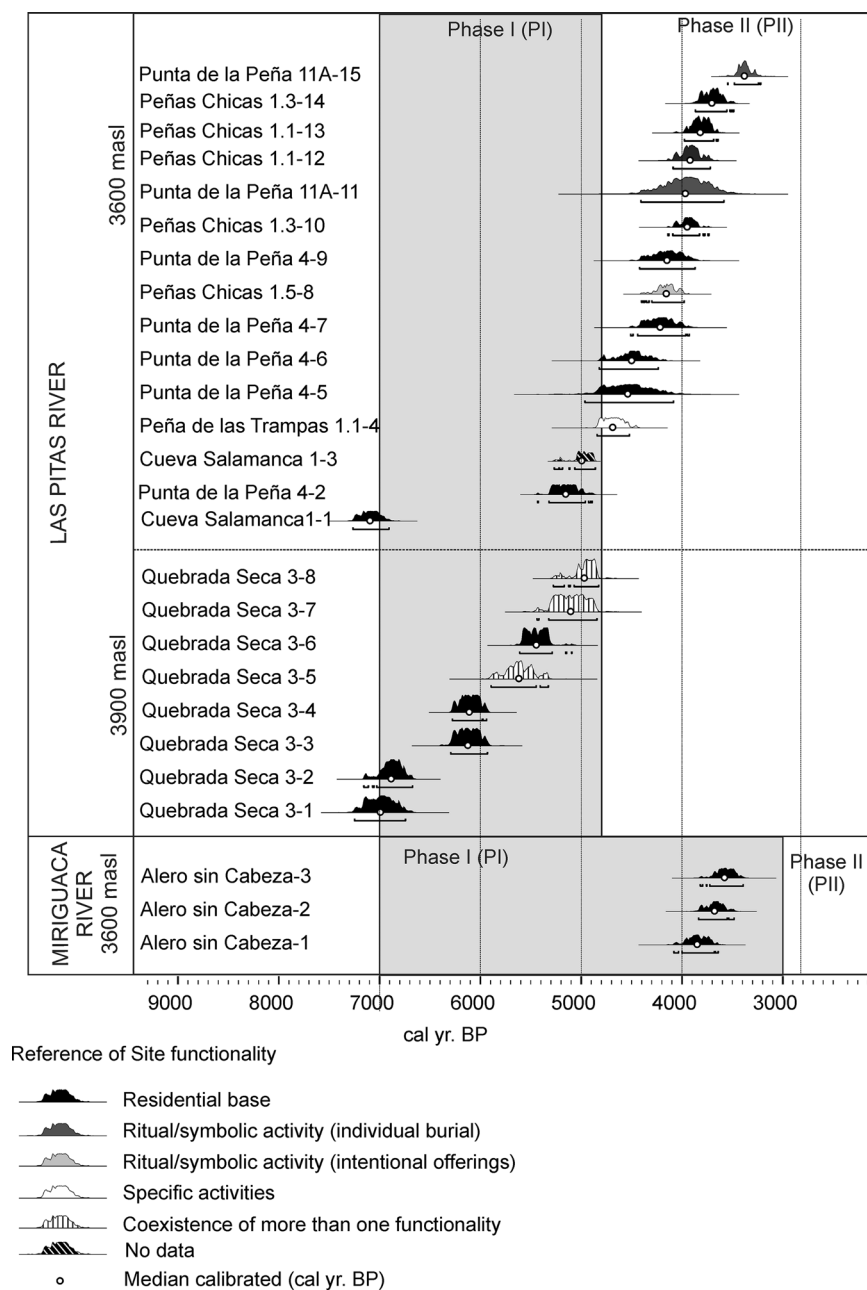
Figure 10 Local paleohydrological changes and human occupation along the Las Pitas and Miriguaca Rivers. Paleoenvironmental phase I (PI) is defined by relatively dry conditions; paleoenvironmental phase II (PII) is defined by moister conditions.

Chicas 1.6 site located along the Las Pitas River dating to *ca.* 3900 cal. yr B.P. (Aschero & Hocsman, 2011).

In contrast, surveys conducted in the Miriguaca River basin have not reported the presence of early hunter-gatherer occupations to date (Escola et al., 2013; Escola et al., 2015). The earliest evidence for human occupation in this basin post-dates 3800 cal. yr B.P. and occurs at the site of Alero sin Cabeza, a residential base

located in a rock shelter and defined by semipermanent occupations with strategies of space use similar to that of Las Pitas River (Escola, Aguirre, & Hocsman, 2013; Escola et al., 2013). Alero sin Cabeza dates to the end of PI for the Miriguaca River where ecological conditions were characterized by discontinuous riparian zone development (Figures 8 and 9). More humid conditions and perennial streamflow occur later, *ca.* 3000–2700 cal. yr

B.P., that may have facilitated more intensive use of the flood plain, including food production after *ca.* 2000 cal. yr B.P. (Escola et al., 2013; Escola et al., 2015). It should be noted that hydrological fluctuations for this river during PI would have influenced occupations prior to 3800 cal. yr B.P.

Apart from differences in use of space across both river basins, a social circumscription process has been postulated for the region during the period between 3800 and 3000 cal. yr B.P., associated with a more strict demarcation of territories (Aschero, 2010). This circumscription coincided with the prevailing, extremely arid conditions predominant at the regional (*puna*) level. These conditions would have created environmental barriers to hunter-gatherer mobility (Hocsman, 2006; Aschero & Hocsman, 2011). Furthermore, during this period, pre-existing local environmental factors, such as the differential availability of wetlands between river basins, would also have played an important role in human settlement within Antofagasta de la Sierra. For example, the Las Pitas River had different reaches with favorable environmental conditions for food procurement. This ecological situation supports our proposal that the river reaches with more wetlands may have been favored by hunter-gatherers, an interpretation that is supported by the human occupation strategies recorded in archaeological sites along the river during this period.

The reduction of residential mobility develops as part of an overall process of sedentism (Aschero & Hocsman, 2011). However, the increasing settlement stability in the landscape within our study area did not necessarily lead to a reduction or cessation of regional/macroregional mobility, given recurrent evidence for movement of exotic materials and certain raw materials from distant regions throughout the archaeological record of these sites (Hoscman, 2006; Escola, Aguirre & Hocsman, 2013).

In the Las Pitas River there were long-lived settlements possibly associated with quinoa (aff. *C. quinoa*) cultivation. Archaeological evidence for harvesting of this domesticated pseudocereal occurs at Peñas Chicas 1.3 (Babot, 2011). The presence of stalks of this crop in the residential base may be interpreted as a local experimentation/domestication process or alternatively, as the incorporation of an already consolidated practice (Aguirre, 2007; Aschero & Hocsman, 2011; Babot, 2011). Several microthermal cultigens such as tubers (Babot, 2011) are also present. Probably, more humid conditions with a sustained baseflow and peat formation associated with PII for the Las Pitas River would have generated the appropriate background to conduct initial experiments or introduce cultigens into the study area at this early period. Consequently, it is possible that it represents the beginning of local horticultural practices by hunter-gatherers

in their process toward full food production (Aschero & Hocsman, 2011).

Modifications in the relationship between hunter-gatherers and faunal resources through time have also been noted in the area. This is evident for both the Las Pitas River at *ca.* 4200 cal. yr B.P. and the Miriguaca River at *ca.* 3800 cal. yr B.P., where osteometric changes indicate the presence of a transitional morphotype between wild guanacos and herded llamas (Aschero, Izeta, & Hocsman, 2014; Grant Lett-Brown, 2014). Such changes would have resulted from the implementation of a new strategy for protecting the herd, leading to a gradual domestication process (Grant Lett-Brown, 2014). Pastoralism would have developed in areas with hydrological resources, including wetlands within a regional context of generalized aridity. Consequently, hunter-gatherers' close interrelation with the environment is not only defined in terms of their search for, and exploitation of, available wetlands. Rather they should also be seen as active agents in their environment, generating changes and impacting their surroundings at the same time, for instance through the domestication of plants and animals (Grana, 2013). All in all, there would have been a permanent interrelationship between hunter-gatherer societies and the environment, generating important changes in socioeconomic dynamics and the emergence of agropastoral societies.

CONCLUSIONS

Our research supports the hypothesis that human settlement in the *puna* was closely related to environmental and hydrological changes during the middle-to-late Holocene. Through analysis of Las Pitas and Miriguaca alluvial stratigraphy including diatom assemblages, we infer that landscape elements such as topography, hydrogeology, and geomorphology have conditioned the effects of broad-scale climate change on local environments, minimizing the impact of aridity during the middle Holocene. For example, the high altitude catchment of the Las Pitas River basin collected more water from seasonal orographic precipitation during middle-to-late Holocene minor humid pulses, resulting in more springs and larger wetlands than along the Miriguaca River. The higher elevation catchment facilitated the development of a more stable flow regime, indicated by the presence of more FA3 and FA4 sedimentary facies along the lower Las Pitas River.

Differences in the paleohydrological behavior of these rivers in relation to the occupations and functionality of local archaeological sites suggest that the Las Pitas and Miriguaca hydrological basins played different roles in

the hunter-gatherer occupation of the area. Hydrological differences produced differential concentrations of resources between the basins related to primary productivity and water availability, both during the arid conditions of phase I and in the diachronic development of the more humid phase II. This likely led to a territorial demarcation at the familial group or lineage level in and between rivers, as evidenced in the access to specific lithic resources and in the characteristics of both art and projectile point design that follow distinctive styles/features specific to certain areas along both rivers (Aschero & Hocsman, 2011).

The differential availability of water associated with Andean wetlands within our study area favored the systematic occupation of certain spaces. In the long-term, these spaces may have functioned as a catalyst for land-use intensification processes, stimulating sedentism. Hence, hydrological variability facilitated the development of new sociocultural contexts, in this case animal/plant domestication and the development of increasing social complexity. This social complexity set the basis for later agropastoral societies in this area of the southeastern Atacama *puna*. These results highlight the importance of interdisciplinary studies in defining environmental changes at local/regional scales (*sensu* Dincauze, 2000) that in turn help us to better understand the complex interrelation between environment and humans in desert areas.

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