Climate of the Past

Hydroclimate variability in the low-elevation Atacama Desert over the last 2500 yr

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Abstract. Paleoclimate reconstructions reveal that Earth system has experienced sub-millennial scale climate changes over the past two millennia in response to internal/external forcing. Although sub-millennial hydroclimate fluctuations have been detected in the central Andes during this interval, the timing, magnitude, extent and direction of change of these events remain poorly defined. Here, we present a reconstruction of hydroclimate variations on the Pacific slope of the central Andes based on exceptionally well-preserved plant macrofossils and associated archaeological remains from a hyperarid drainage (Quebrada Maní, ~21° S, 1000 m a.s.l.) in the Atacama Desert. During the late Holocene, riparian ecosystems and farming social groups flourished in the hyperarid Atacama core as surface water availability increased throughout this presently sterile landscape. Twenty-six radiocarbon dates indicate that these events occurred between 1050–680, 1615–1350 and 2500–2040 cal yr BP. Regional comparisons with rodent middens and other records suggest that these events were synchronous with pluvial stages detected at higher-elevations in the central Andes over the last 2500 yr. These hydroclimate changes also coincide with periods of pronounced SST gradients in the Tropical Pacific (La Niña-like mode), conditions that are conducive to significantly increased rainfall in the central Andean highlands and flood events in the low-elevation watersheds at inter-annual timescales. Our findings indicate that the positive anomalies in the hyperarid Atacama over the past 2500 yr represent a regional response of the central Andean climate system to changes in the global hydrological cycle at centennial timescales. Furthermore, our results provide support for the role of tropical Pacific sea surface temperature gradient changes as the primary mechanism responsible for climate fluctuations in the central Andes. Finally, our results constitute independent evidence for comprehending the major trends in cultural evolution of prehistoric peoples that inhabited the region.

1 Introduction

Records of climate fluctuations over the last two millennia have increased significantly over the last few years as they offer the appropriate context to evaluate the relative role of natural versus anthropogenic factors in generating climate shifts at centennial time-scales. Paleoclimate evidence for the past centuries is now reaching a certain level of consensus regarding the temperature and/or hydroclimatic anomalies that were global in extent. In particular, during those intervals often included within broad definitions of the Roman Warm Period (RWP; 2200–1500 cal yr BP), Dark Ages Cool Period (DACP; 1500–1000 cal yr BP), Medieval Climate Anomaly (MCA; 1050–600 cal yr BP) and Little Ice Age (LIA; 600–100 cal yr BP) (Ljungqvist, 2010;

Pages-News, 2011; Graham et al., 2010; Wanner et al., 2008; De Jong et al., 2006; Mann et al., 2008).

Paleo-records from around the globe and model simulations suggest that these rapid climate changes involved reorganisations of major components of the Earth's climate system as these respond to internal/external climate forcings, such as the North Atlantic and Tropical Pacific (Helama et al., 2009; Reale and Shukla, 2000; Jones and Mann, 2004). Hence, large-scale temperature and/or hydroclimatic changes during the MCA have been associated with persistent shifts of the El Niño Southern Oscillation (ENSO) into a La Niña-like state in the tropical Pacific and the locking of the North Atlantic Oscillation (NAO) circulation into its positive mode (Mann et al., 2009; Graham et al., 2007, 2010; Pages-News, 2011; Seager et al., 2007; Trouet et al., 2009).

Although considerable efforts have been made to identify the spatial extent/expression, global impacts and underlying drivers, many aspects of southern hemisphere climate fluctuations over the past two millennia remain poorly defined. This is particularly true for the central Andes, which span from 10° to 30° S, where the causes, imprint, magnitude and timing of climate fluctuations during this period are hampered by the lack of sufficient data and imprecise chronologies. Exploring the past 2500 yr of climate variability in the central Andes could help elucidate shifts involved in the hemispheric circulation dynamics and associated patterns. Moreover, paleoclimate reconstructions from this area could provide insights into the centennial-scale climate variability at tropical and subtropical latitudes of South America. Potentially, these would encompass highly contrasting bioclimates that extend from the hyperarid to semi-arid environments of the western Andean slope to the forests and savannas of the eastern slope.

Here, we establish the hydroclimate conditions of the low-elevation northern Atacama Desert for the last 2500 yr to infer the timing, magnitude, extent and causes of sub-millennial or centennial-scale climate changes in the central Andes. Our reconstruction was compiled using the response of the hydrological, ecological and cultural systems within the endorheic basin of Pampa del Tamarugal (PdT) to changes in local hydroclimatic conditions over the last two and a half millennia. We compare our results to other regional reconstructions and conclude that tropical Pacific forcing is likely the most important driver of the climate of the Central Andes during the late Holocene.

2   The study site

The PdT basin (19°17′–21°45′ S) is located in the Central Valley (elevation range 1000–1600 m) within the hyperarid core of the northern Atacama Desert (Fig. 1). The subsurface sedimentary fill of the pediplain hosts the largest and economically most important aquifer system in northern Chile (JICA, 1995; Rojas and Dassargues, 2007). The

western basin margin is bounded by the Coastal Cordillera. The northern portion of the PdT basin (19°17′–21° S) extends along the foothills of the central Andes range. The southernmost portion of the PdT (21°–21°45′ S) is flanked to the east by the Sierra Moreno, a Paleozoic-Mesozoic range that is part of the Arequipa-Antofalla craton and rises up to 4000 m (Tomlinson et al., 2001; Ramos, 1988).

Rainfall is practically absent in the low-elevation desert (<1 mm yr^{-1} over the last century; DGA, 2007). PdT aquifer recharge takes place via surface-water infiltration at the apex of alluvial fans radiating out from perennial and ephemeral tributaries that head at >3500 m along the adjacent Andes and Sierra Moreno where summer rainfall is more frequent (Magaritz et al., 1989; JICA, 1995; Houston, 2002, 2006b). Only a few affluents retain enough surface flow to reach the northern PdT, and the dominant surface expression of water occurs along the western fringe where surface evaporation forces the outcropping of groundwater brines by capillarity (JICA, 1995).

We studied in situ organic-rich deposits, rodent-burrows and archaeological archives found at Quebrada Mani (QM) an unvegetated, uninhabited and ephemeral (dry) ravine that drains into the southernmost PdT basin ($\sim$21° S; Figs. 1, 2). All of these records are exceptionally preserved on the surface of two abandoned fluvial terraces (Fig. 3) that aggraded during the latest Pleistocene along the incised late Miocene fan deposit that forms the natural QM walls (T1). This fluvial fill occurred during major past changes in stream and groundwater discharge (Nester et al., 2007; Gayo et al., 2009) associated with a major pluvial that occurred throughout the central Andes during the last global deglaciation, now termed the "Central Andean Pluvial Event" or CAPE (17 500–14 200 and 13 800–9700 cal yr BP; Quade et al., 2008; Latorre et al., 2006; Placzek et al., 2009).

The southernmost PdT is completely separated from the high Andean basins by the Sierra Moreno. Hence, local hydroclimatic and ecological patterns are strongly tied to summer rainfall variability along the central Andean highlands. Today, short-lived and occasional pulses in surface-water flooding and growth of isolated annuals (Gajardo, 1994) have been observed to occur along dry tributaries after unusually heavy summer storms in the Sierra Moreno and the central Andean headwaters (Houston, 2006b). Phreatophytes such as *Prosopis alba*, *Schinus molle* and *Caesalpina aphylla* can occasionally be found growing within the active drainages. Existing paleoclimate evidence from QM and other nearby inactive affluents show that positive headwater moisture anomalies promoted unprecedented shifts in the local hydrological and ecological systems on millennial time-scales. Indeed, increased rainfall during the CAPE led to increased perennial runoff and local water-tables, as well as enabling riparian ecosystems and human cultures to flourish in the presently sterile landscape of the PdT (Santoro et al., 2011; Nester et al., 2007; Gayo et al., 2009). Thus, these past traces of fossil ecosystems and human activities throughout inactive
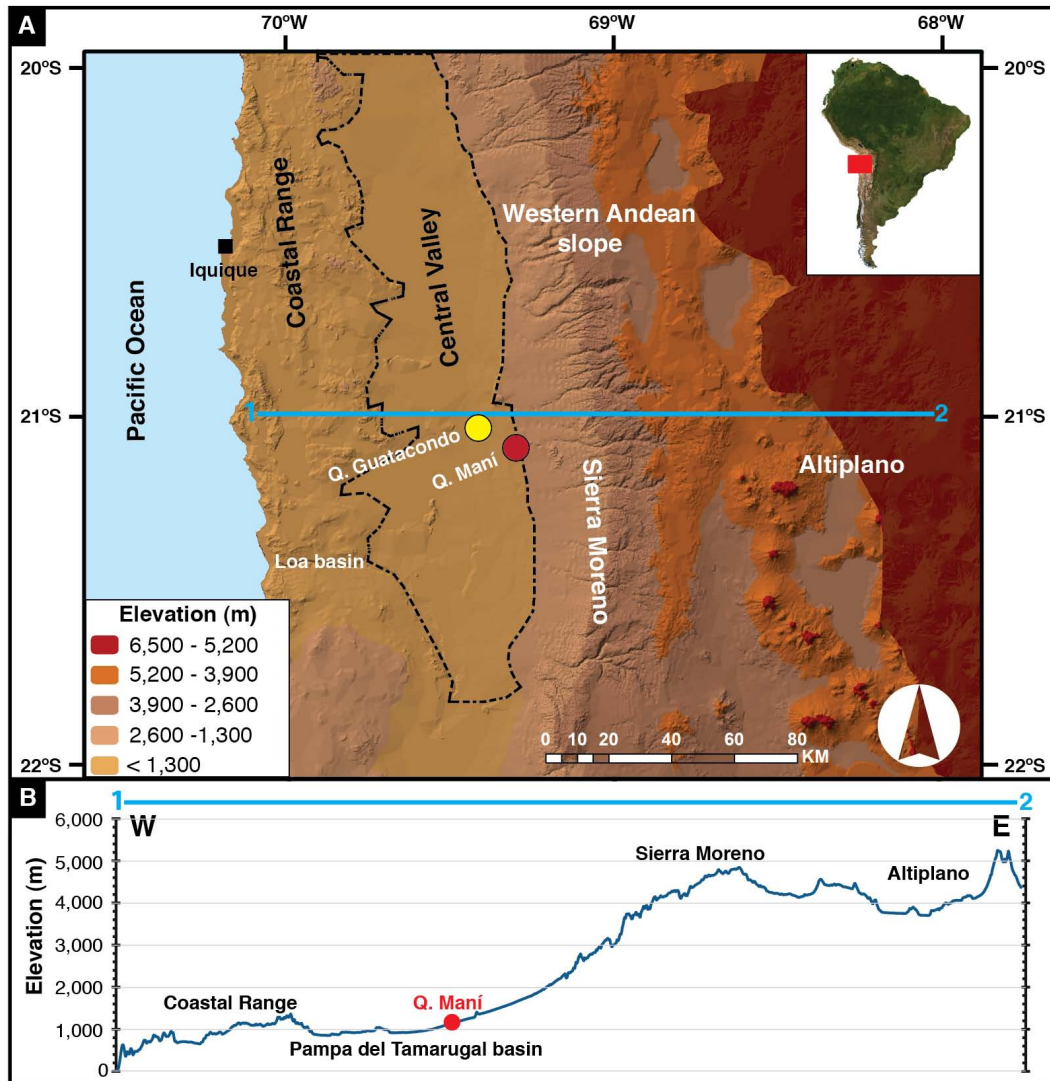
Fig. 1. (a) Study area indicating localities discussed in the text. Red dot: mean location for the 26 geohistorical archives recovered from QM and reported here. Yellow dot: Ramaditas archaeological site at Quebrada Guatacondo. Black dashed line: PdT basin boundaries. Horizontal white line: limit between the northern and southern PdT basin. **(b)** A topographic cross-section located along the transect labeled from 1 to 2 in **(a)**.

ravines of the PdT reflect local hydrological budgets above the modern mean triggered by increased rainfall amounts at higher-elevations. Paleoclimate reconstructions for the inactive canyons from the southern PdT basin thus represent established proxies for evaluating the hydrological response of the central Andes to global centennial-scale shifts in climate.

3 Materials and methods

Our reconstruction is based on radiocarbon dates and macrofossil analyses from eight in situ organic-rich deposits and from eighteen radiocarbon dated organic remains associated with archaeological artifacts (Table 1, Fig. 3). In situ organic-rich deposits yielded datable and taxonomically identifiable fossil-plant remains with no signs of tissue decay and damage (Figs. 4a, A1 and A2). Most of these are leaf-litter deposits preserved on the T2.5 surface (Fig. 3, Table 1). We also analysed two rodent burrows dug into a well-exposed late Pleistocene paleowetland deposit comprised of ~1.2 m thick fine-medium sands to fine silts (the deposit itself likely dates to ~11 700–7900 cal yr BP, unpublished data) on the T2.5 terrace (Figs. 3 and A3). These burrows contained hardened urine deposits with amalgamated feces, vertebrate remains and plant-macrofossils akin to rodent middens (QM-22A and QM-22C; Table 1; Fig. A3).
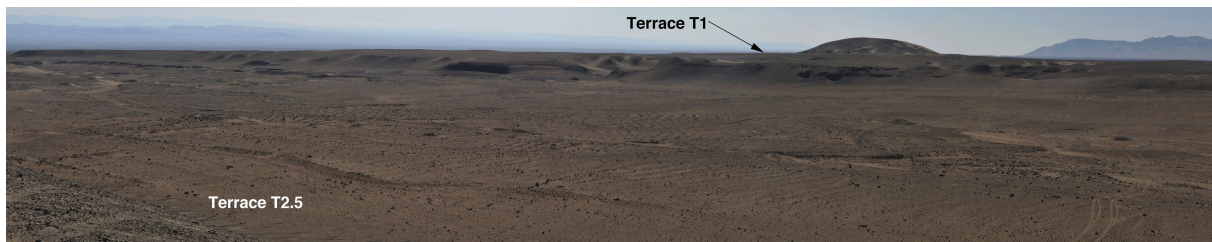
Fig. 2. A panoramic view taken looking northwest across the hyperarid Quebrada Mani (QM). Note the widespread extent of the stone-lined cultivation fields ("melgas" in spanish) on the T2.5 terrace. The valley is approximately 300 m wide and the T1 (late Miocene) terrace is visible in the near background. The low hill to the centre right is Cerro Challacollo (1503 m a.s.l.).
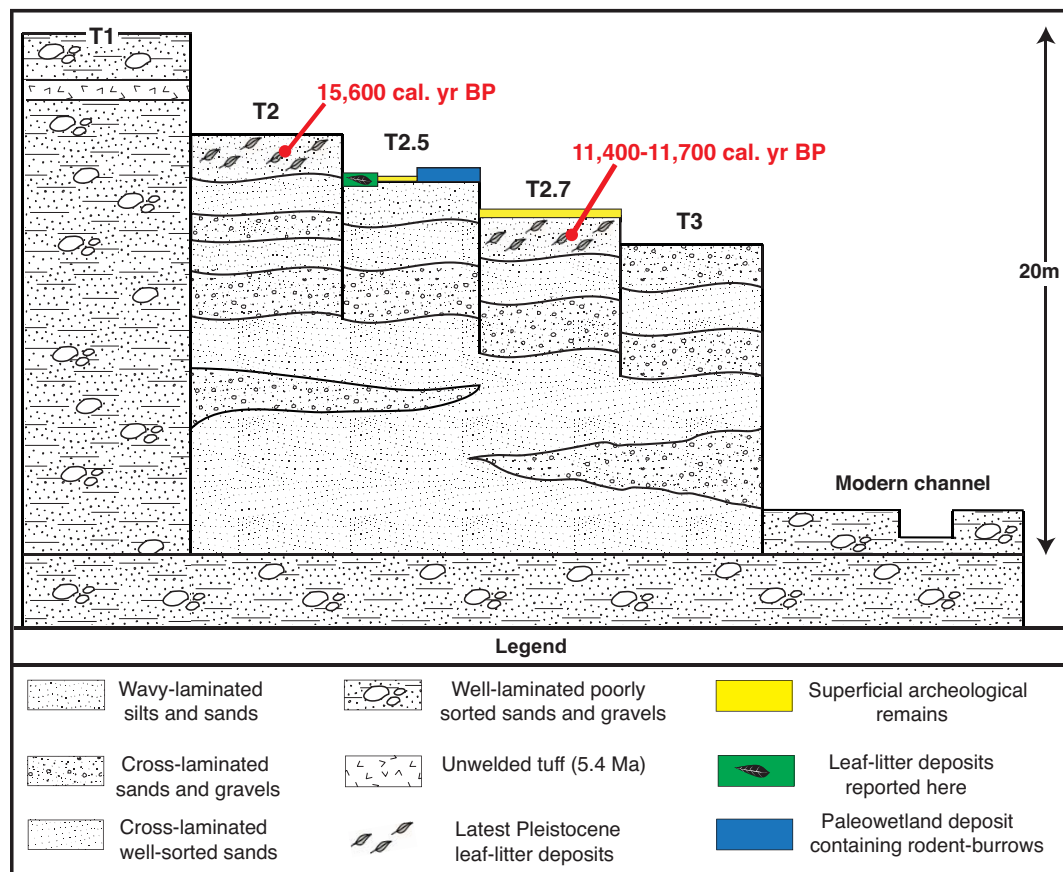

Fig. 3. A generalized stratigraphy of fluvial terraces found in Quebrada Maní (modified from Nester et al., 2007) showing the relationship between these units and the records reported here. Terraces are labelled in descending order (to the modern channel) as T1, T2, T2.5, T2.7, T3 and "modern". Fluvial terrace systems T2 and T3 dissect late Miocene alluvial fan deposits (T1) at ∼1200 m elevation, spreading beyond this point to form alluvial fans. The modern channel is inset by 1–3 m at 1250 m elevation and rests >5 m below T3 and continues as a confined channel for several kilometres downstream. Late Pleistocene leaf-litter deposits (ages shown in red numbers) and paleohydrological implications were reported in Nester et al. (2007).

Remains of past human activities abound upon the surface of QM T2.5 and T2.7 terraces (Figs. 2, 3), including malachite beads, lithic and shell artifacts, rock engravings (petroglyphs), bones, ceramics, agricultural infrastructure (including terraced crop fields, irrigation channels and dams) and collapsed structures. We strategically surveyed for organic remains found in association with these artifacts as these could offer datable materials unequivocally derived from when human activities took place at QM. Hence, we sampled underneath rocks placed along floodplain irrigation channels (Table 1, Fig. 4b) or lying on the ridges of stone-lined cultivation fields (locally termed "melgas"; Fig. 4c).

Table 1. AMS dates and depositional context for the 22 records used in this study. Calibrated ages in years BP and corresponding confidence intervals at 2σ level are illustrated graphically in Fig. 5a.

Sample ID	Laboratory code	Type of record	Dated Material	^{14}C yr BP	δ^{13}C (‰)	Cal yr BP	2σ cal yr BP
QM-14	UGAMS-4065	Leaf-litter mound	*Prosopis* sp. stems	790 ± 25	−22.9	680	−20/45
QM-16	UGAMS-4067	Leaf-litter mound	*Prosopis* sp. leaves	810 ± 25	−26.2	700	−35/30
QM-2A*	CAMS-129007	In situ cropped remains	*Zea mays* canes	870 ± 30	−10.4	735	−55/55
QM-26	UCIAMS-84337	Subsurface leaf-litter	*Prosopis* sp. leaves	935 ± 15	N.D.	790	−50/110
QM-2E1	CAMS-129008	Subsurface leaf-litter	*Prosopis* sp. stems	960 ± 30	−22.7	840	−90/75
QM-35C	UCIAMS-84341	Crop field onto T2.5 terrace	Plant remains	990 ± 15	N.D.	850	−50/65
QM-22A	UCIAMS-84334	Rodent burrow	Plant remains	985 ± 15	N.D.	850	−50/60
QM-22E	UCIAMS-84336	Cob inserted within QM-22C rodent burrow	*Zea mays* cob	985 ± 15	N.D.	850	−50/60
QM-30	UCIAMS-84339	Polygonal leaf-bed onto T2.7 terrace	*Prosopis* sp. leaves	995 ± 15	N.D.	850	−50/70
QM-18	UGAMS-4563	Leaf-litter mound	*Prosopis* sp. leaves	990 ± 25	−21.7	855	−60/65
QM-35A	UCIAMS-84739	Crop field onto T2.5 terrace	Plant remains	980 ± 20	N.D.	855	−60/60
QM-archeo1	UGAMS-4565	Archeological	*Prosopis* sp. seed	1000 ± 25	−18.8	855	−55/65
QM-24	UCIAMS-84356	Superficial material below a lithic shovel onto T2.5	*Prosopis* sp. leaves	975 ± 15	N.D.	860	−65/50
QM-22C	UCIAMS-84335	Rodent burrow	*Prosopis* sp. leaves	970 ± 15	N.D.	865	−75/45
QM-28	UCIAMS-84338	Polygonal leaf-bed onto T2.7 terrace	*Prosopis* sp. leaves	965 ± 15	N.D.	870	−95/35
QM-31	CAMS-129009	Leaf-litter mound	*Prosopis* sp. leaves	1110 ± 30	−24.3	960	−40/95
QM-40	UCIAMS-84355	Crop field onto T2.5 terrace	Plant remains	1205 ± 15	N.D.	1050	−70/120
QM-37C	UCIAMS-84343	Perched channel onto T2.5 terrace	Plant remains	1525 ± 15	N.D.	1355	−45/35
QM-37A	UCIAMS-84342	Perched channel onto T2.5 terrace	Plant remains	1535 ± 15	N.D.	1365	−50/35
QM-archeo 4C	UCIAMS-97258	Semicircular collapsed structure onto T2.5	Superficial charcoal	1575 ± 15	N.D.	1395	−50/120
QM-27	UCIAMS-84737	Crop field onto T2.7 terrace	Plant remains	1650 ± 20	N.D.	1470	−60/65
QM_archeo 4A	UCIAMS-97256	Semicircular collapsed structure onto T2.5	Superficial charcoal	1750 ± 15	N.D.	1595	−60/100
QM-archeo 4B	UCIAMS-97257	Semicircular collapsed structure onto T2.5	Subsurface charcoal	1765 ± 15	N.D.	1610	−65/80
QM-archeo 19	UCIAMS-97259	Test pit on a horseshoe-shaped dam located onto T2.5	Charcoal at 65 cm depth	2290 ± 15	N.D.	2230	−70/105
QM-38	UCIAMS-84742	Floodplain channel onto T2.7 terrace	*Prosopis* sp. leaves	2310 ± 20	N.D.	2230	−75/110
QM-39	UCIAMS-84344	Floodplain channel onto T2.5 terrace	Superficial charcoal	2240 ± 15	N.D.	2245	−125/65

* Reported previously by Nester et al. (2007).

We also recovered remains of crop plants (e.g., maize) found either in rodent burrows or on the surface of cultivation fields (Table 1, Fig. A4). Exceptionally, we sampled *Prosopis* sp. leaves underneath a lithic shovel lying on the surface (Table 1). Superficial and subsurface charcoal samples were retrieved from a stone crop field ridge (Table 1) and underneath structural-stones that formed a semicircular collapsed structure of 4 m diameter associated with crop fields and irrigation channels (Table 1, Fig. A5). We also recovered charcoal at 65 cm of depth from a test pit excavated into a horseshoe-shaped dam structure built out of mud and stones that rises up to 1 m upon the T2.5 terrace (Table 1, Fig. A6). Other samples include semi-carbonized herbaceous remains contained in a mud section dug into a perched channel that runs parallel to the stream-bed in the contact between T2.5–T2.7 terraces and rises 82 cm above the T2.7 surface (Table 1, Fig. A7). These remains were sampled at 12 cm (QM-37A) and 26 cm (QM-37C) of depth along this section. Additionally, we recovered *Prosopis* sp. leaves from two superficial polygonal leaf-beds of 4 cm thick × 1 m length × 1.5 m width (Table 1, Fig. A8).

Organic deposits were hand-sorted for macrofossils under a dissecting binocular microscope (10–50 × magnification). Rodent burrow material was processed following procedures described in Latorre et al. (2002). Fossil plant remains were identified to the highest taxonomic level possible either by comparison with our reference collection of modern flora from northern Chile (housed at the Laboratorio

de Paleoecología, PUC) or by using published taxonomic keys (Muñoz-Pizarro, 1966; Nicora and Rúgolo de Agrasar, 1987). Molar teeth from a rodent cranium found within the QM-22C burrow were identified as well based on taxonomically relevant characteristics. This specimen was identified by directly comparing features of molars M1 and M2 with modern specimens.

Accelerator mass spectrometry (AMS) radiocarbon dating on short-lived plant tissue was preferred rather than associated woody materials to build our chronologies. Woody tissues resist degradation in hyperarid environments and represent minimum dates at best. All radiocarbon ages reported here were calibrated using CALIB 6.0 at 2-sigma (with the Southern Hemisphere Calibration calibration curve-SHCal04, Intercept Method; McCormac et al., 2004) and are given in calendar years before 1950 (cal yr BP).

Past hydroclimatic shifts at QM were inferred by considering the water requirements/adaptations and modern distribution ranges described for each taxa resolved taxonomically to family level or above that occurs within a plant-macrofossil assemblage (Table 2). This is because the existence of plant communities with distinct functional groups in the Atacama is determined by water availability (Arroyo et al., 1988), which in turn is tightly linked to the strong precipitation gradient (0 mm yr^{-1} at 1000 m a.s.l. to 120 mm yr^{-1} at 4000 m a.s.l.) that occurs on the western Andean slope (Houston and Hartley, 2003).
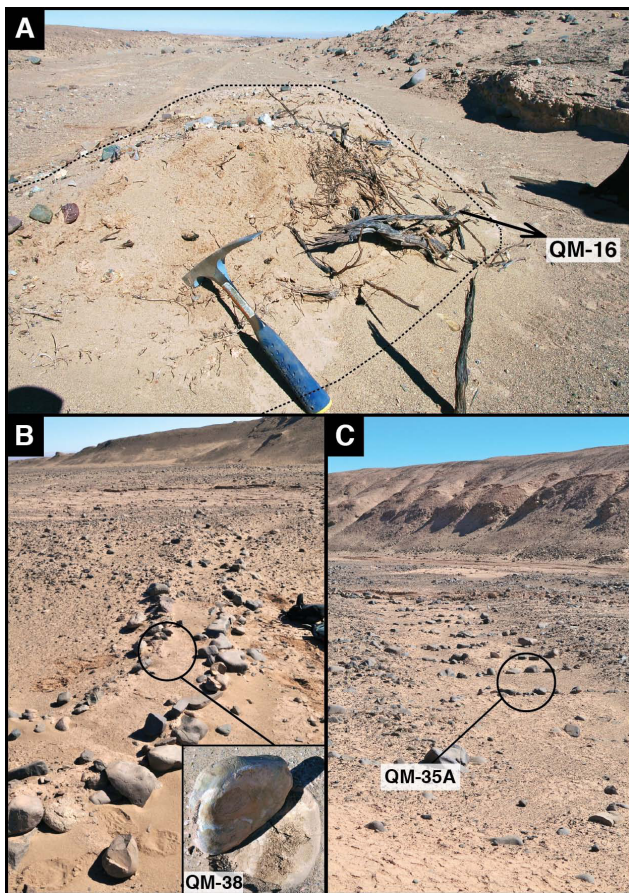
Fig. 4. (a) QM-16 in situ leaf-litter mound. Dashed line describes the deposit extension. **(b)** Floodplain irrigation channel. Details for *Prosopis* sp. leaves underneath a stone dam (QM-38 sample) are shown. **(c)** A "melga" (stone-lined crop field) built on the T2.5 terrace. Circle shows where the QM-35A sample was recovered.

Plant distributions were established by verifying the occurrence of taxa within five current well-defined plant formations developed from semiarid to hyperarid zones along the western central Andean slope between 16°–22° S (Table 2). Among these, hillslope ecosystems contain species occurring at elevations between 2600–3300 m and >3400 m (denoted Andean and Altiplano communities, respectively). These taxa survive on direct rainfall, experiencing annual rainfall amounts between 23–56 mm yr^{-1} (2600–3300 m) and >60 mm yr^{-1} at elevations above 3400 m (Houston and Hartley, 2003). The other three associations incorporate taxa adapted to extreme hyperaridity and survive either on fog (the coastal *Lomas* formations), groundwater outcropping (Pampa formations) or on perennial runoff (Riparian formations). Non-endemic taxa from the Atacama Desert were classified as exotic.

Functional groups for northern Atacama plants were defined based on published descriptions of life-forms (annuals vs. perennials) and water-use strategies (e.g., Mooney et al., 1980; Muñoz-Pizarro, 1966; Luebert and Pliscoff, 2006).

Plants were categorised into the following four hygromorphisms, distinguishing the degree that these could vary according to environmental factors (facultative vs. obligate). Hygrophytes are plants growing in moist soils maintained by perennial bodies of water (such as those along ponds, in river floodplains and in wetlands). Phreatophytes are deep-rooted shrubs and trees that obtain water from a permanent groundwater supply. They often occur inside active washes in our study area. Mesoxerophyte plants are tolerant to prolonged droughts but cannot survive without two–three months of direct rainfall. Finally, xerophytes are plants that are tolerant to prolonged droughts, but survive by hydraulic-lift uptake and found in association with hygrophytes or phreatophytes.

4　Results and discussion

4.1　Chronology, paleoecology, archaeology and past hydroclimate conditions

Apart from the archaeological contexts previously described, we found that organic-rich deposits from QM occur in three different natural depositional contexts. The first of these are leaf-litter/wood mounds that emerge slightly above the T2.5 terrace (Fig. 4a). These are contained within fine sandy silts and represent fossilized understories of vegetation that likely were growing in situ upon the surface. The second type of deposits correspond to subsurface leaf-litter deposits found at <30 cm below the surface (Fig. A2). These deposits appear as concentrated plant material embedded within a wavy-laminated fine silt or sand matrix, possibly indicating an overbank depositional environment. Therefore, these represent in situ vegetation growing in areas with periodic ponding/flooding. Finally, the third type of deposit incorporates plant-macrofossils encased within rodent burrows dug into a pre-existent older surface. Since plant remains were incorporated into the midden for consumption and nest building from within the foraging range of the agent (usually <100 m for murid rodents), they can provide a discrete record for vegetation growing upon a limited area of the T2.5 terrace when they formed.

Twenty-six radiocarbon dates (Table 1) on samples from QM exhibit three clusters at 1050–680, 1615–1350 and 2245–2230 cal yr BP with important hiatuses at the intervals <680, 1350–1050 and 2230–1615 cal yr BP (Fig. 5a). We interpret this discrete clustering of ecological-archaeological activity as episodes of augmented productivity brought about by positive local hydrological budgets. That is, once surface water becomes available at QM, life invades this extreme hyperarid landscape creating a fertile oasis for economic human activities.

Major gaps in our chronology can be interpreted in two very different ways. They could reflect periods of lowered groundwater tables and/or decreased perennial runoff, which would lull plant productivity as local hydrological budgets

Table 2. List of taxa identified from macrofossil analyses on leaf-litter and rodent deposits from Quebrada Maní. (*) Indicates annual phenology. Functional group for each plant species: (Hy) Hygrophyte, (X) Xerophyte, (Ph) Phreatophyte and (Mx) Mesoxerophyte. Taxa distribution at major Northern Atacama Desert vegetational formations: (R) Riparian, (L) Lomas, (P) Pampa, (A) Andean, (AL) Altiplano and Exotic (Ex).

Species	Family	Functional group	Presence	Taxa distribution
Plant macrofossils				
Atriplex atacamensis	Chenopodiaceae	Facultative X (from X to Mx)	QM-16 QM-14	R, P, A, AL
Atriplex glaucescens	Chenopodiaceae	Facultative X (from X to Mx)	QM-14	R, A, AL
Atriplex sp.	Chenopodiaceae	Facultative X (from X to Mx)	QM-14	R, P, A, AL
Baccharis alnifolia	Asteraceae	Obligate Hy	QM-16 QM-14	R
Baccharis scandens	Asteraceae	Obligate Hy	QM-14	R
Chenopodium petiolare (*)	Chenopodiaceae	Facultative Hy (from Hy to X, Mx)	QM-14	R, L, A, AL
Cistanthe sp. (*)	Portulacaceae	Facultative Hy (from Hy to X, Mx)	QM-16 QM-14	R, L, A, AL
Cortaderia atacamensis	Poaceae	Obligate Hy	QM-16	R, A, AL
Cryptantha sp. (*)	Boraginaceae	Facultative Hy (from Hy to Mx)	QM-16	R, A, AL
Euphorbia amandi (*)	Euphorbiaceae	Obligate Mx	QM-14	AL
Junellia sp.	Verbenaceae	Obligate Mx	QM-14	A, AL
Muhlenbergia sp. (*)	Poaceae	Obligate Hy	QM-16	R
Nicotiana longibracteata	Solanaceae	Obligate Hy	QM-14	R
Polypogon interruptus	Poaceae	Obligate Hy	QM-16	R
Prosopis sp.	Mimosaceae	Obligate Ph	QM-2E, QM-3, QM-14, QM-16, QM-18, QM-22A, QM-22C	R, P
Solanaceae sp.	Solanaceae	No data	QM-14	No data
Solanaceae sp. 2	Solanaceae	No data	QM-14	No data
Tarasa operculata	Malvaceae	Facultative Hy (from Hy to Mx)	QM-14	R, A, AL
Tessaria absinthioides	Asteraceae	Obligate X	QM-16	R, L, P
Zea mays (*)	Poaceae	Irrigated	QM-22E	Ex
Animal macrofossils				
Auliscomys sp.	Cricetidae		QM-22C	AL

remained equal or below the modern. Hence, no macrofossils or artifacts would date to this period. Or they could arise from a sampling effort. Simply put, it is possible that more sampling could produce dates that "fill" in these gaps. Clearly, the absence of evidence (a "hiatus") may not constitute fail-safe evidence for absence. We extensively surveyed and dated all samples available in the field over the course of three field seasons in order to reduce this sampling bias. Yet because the contribution of these factors cannot be totally ruled out, we are cautious of any paleoenvironmental interpretations based on these hiatuses.

A large cluster of seventeen dates between 1050 and 680 cal yr BP argues for a prominent increase in agricultural and biological activity at QM coeval with the MCA (Fig. 5). Nine ^{14}C-dates on leaf-litter deposits and rodent burrows indicate that between 960 and 680 cal yr BP, plants grew in situ upon the surface of T2.5 terrace (Table 1) and sustained rodent populations (Table 2). Similarly, radiocarbon dates from maize canes in life-position and organic materials in direct association with widespread farming vestiges suggest prolonged and intense agricultural activities within an extensive farming camp established along QM by 1050–730 cal yr BP
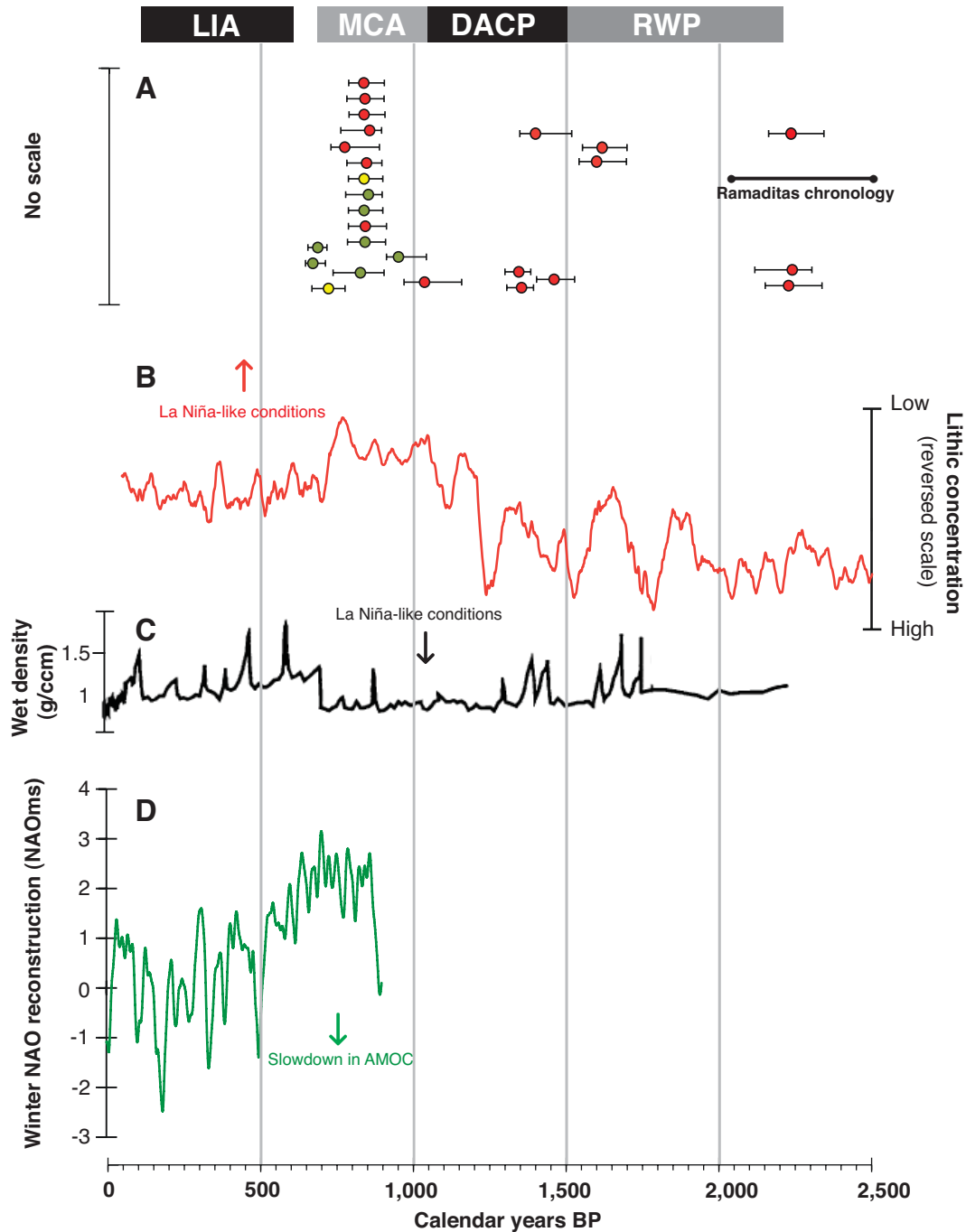
Fig. 5. Comparison of paleoclimate records: **(A)** all ^{14}C dates on paleoecological and archaeological samples from Quebrada Maní. Green circles: relict tree mounds and rodent burrows; red circles: organic materials associated with farming (irrigation) structures. Yellow circles: maize remains (in situ canes and corn cob found in a rodent burrow). Heavy horizontal dark line with circles indicates the chronology for Ramaditas archeological site (Rivera, 2005). **(B)** A 30-yr running average for lithic concentrations derived from sediment core SO147-106KL collected offshore central Perú; low lithic concentrations are interpreted as reduced precipitation runoffs associated to prevailing La Niña-like conditions (red arrow up) over the Tropical Pacific (Rein et al., 2005). **(C)** Wet sediment density from Laguna Aculeo (Jenny et al. 2002); reduced sediment density implies low frequency of flood sediment deposition as sustained La Niña-like conditions (black arrow down) promote reduced winter precipitation across central Chile. **(D)** Winter NAO reconstruction (further details on the estimation of NAOms, see Trouet et al., 2009); negative NAOms values are interpreted as a subdued Atlantic meridional overturning circulation (AMOC; green arrow down). Major global climate events over the last 2500 yr such as Little Ice Age (LIA), Medieval Climate Anomaly (MCA), Dark Ages Cool Period (DACP) and the Roman Warm Period (RWP) are indicated at top of figure.

(Table 1). A preliminary analysis on ceramic fragments associated with the farming vestiges preserved on the T2.5 terrace suggest affinities with the Charcollo-Pica pottery type from the Pica-Tarapacá complex. This cultural complex incorporates local farmer societies that inhabited perennial river canyons in the northern PdT basin between 1000 and 500 cal yr BP (Uribe et al., 2007).

Plant-macrofossil analyses from eight paleoecological samples indicate that the vegetation growing on the terrace surface between 960 and 680 cal yr BP had low taxonomic richness: some 20 taxa included in 10 Families (Table 2). Remains of perennial hygrophyte (obligate and facultative) and facultative-xerophytes abound in both tree-relict mounds and rodent-burrows (Table 2), along with abundant leaves indistinctly attributable to obligate-phreatophytes commonly found in the PdT (*Prosopis alba* or *P. tamarugo*). By analogy with the taxonomical composition and blend of modern functional groups present in northern Atacama ecosystems, we postulate that a riparian formation dominated by phreatophytes invaded QM between 960 and 680 cal yr BP. This assemblage is similar to those confined to perennial tributaries in the northern PdT and implies that surface water availability must have increased significantly during the MCA compared to what is now an inactive affluent.

Whether this increase was due to augmented water tables, increased perennial riverflow or anthropogenic channelling of resources from higher elevations for irrigation (a sophisticated irrigation system of channels and dams is clearly present at QM) or even a combination of all three factors needs to be assessed. Evidence for extensive water-dependent farming practices at QM (e.g., maize cultivation; Aubron and Brunschwig, 2008) support the notion that local exoreic hydrological patterns prevailed between 960 and 680 cal yr BP. Yet this could also explain the widespread presence of *Prosopis* sp. in our paleo-ecological archives as these trees could survive off the spillover/infiltration from crop irrigation. At present, all the *Prosopis* trees in the PdT basin grow in areas with shallow outcropping of groundwater, so it seems reasonable to suggest that local water-tables increased during the MCA within the QM drainage. In natural settings, this obligate-phreatophyte is indicative of phreatic levels down to ~13.3 m b.g.l. (metres below ground level), which represents the critical depth for vitality and potential-growth in *P. tamarugo*. QM today exhibits groundwater levels of >70 m b.g.l. (PRAMAR-DICTUC, 2007). These could rise quickly after flood events, however, but little information exists as to the magnitude of these changes. Observational data from two events of anomalous surface flow documented in PdT ephemeral watersheds during the summers of 1999–2000 and 2001 demonstrated that local phreatic levels were quickly recharged owing to infiltration from floodwaters into the underlying unsaturated aquifer (Houston, 2002, 2006b).

More importantly, artificial irrigation at QM must have been limited in extent. QM is an ephemeral canyon that rapidly grades into a narrow high energy box canyon above 1400 m a.s.l., with episodic large flooding events capable of destroying any but the most robust irrigation channels. Permanent river flow can be found in the tributaries of QM, but only above 3400 m where rainfall is high enough to sustain it. Even today, it would be a major enterprise to bring these resources >40 km down to the elevations of the extensive cultivation fields that flourished between 960 and 680 cal yr BP.

Nevertheless, there is a clear human factor behind the presence of *Prosopis* in our deposits. These trees have been planted and exploited for centuries by local populations for shade, food resources, fuel and building materials (Habit et al., 1981; Núñez and Santoro, 2011). The gathering and consumption of *Prosopis* trees and maize are considered common practices of the Pica-Tarapacá cultural-complex (Marquet et al., 1998; Uribe, 2006). In fact, we found unambiguous evidence for broad usage of *Prosopis* by QM inhabitants during the MCA. Over 44 % of farming vestiges dated between 1050 and 730 cal yr BP yielded short-lived *Prosopis* tissues (Table 2). Remains of *Prosopis* tree stumps and buried wooden posts can be found throughout the irrigation channel complex at QM. Therefore, their presence in QM during the MCA may be related to the presence of a farming society that significantly transformed the watershed landscape. Based on the above, we argue that this was the result of increased and persistent surface runoff that sustained these agriculture practices for hundreds of years at a time.

In contrast, the presence of hillslope mesoxerophytes and the sigmodontine rodent *Auliscomys* sp. (Table 2) in our samples could be interpreted as a rise in local rainfall during the MCA at QM. Outstanding local preservation of desert pavements and exposure ages on boulders preserved ~150 km north of QM indicate, however, that the PdT has remained hyperarid (with occasional increases in runoff) over the last 14.6 million years (Evenstar et al., 2009). Again, we suspect that the hillslope taxa present in our record are linked to human activities for two reasons. Firstly, modern Andean human communities forage for and use *Euphorbia amandi* and *Junellia* sp. (Villagrán et al., 1999, 2003), so these species could have been introduced deliberately for these purposes by QM inhabitants. Secondly, sigmodontines frequently invade grain-crops (Nowak, 1999). Therefore, the presence of *Auliscomys* sp. can be explained by passive human transport as corn production thrived locally. In fact, one of our rodent burrows contained both a well-preserved maize cob and *Auliscomys* sp. remains, all dated to 850 cal yr BP and surrounded by abandoned cultivation fields.

Evidence for earlier human occupation at QM comes from nine ^{14}C dates taken on buried charcoal and plant fragments from a section dug into a perched irrigation channel and other archaeological remains, including a dam and other structures found near the apex of the QM fan (see Sect. 3, Materials and methods). These dates reveal two distinct periods of increased activities dated at ~2200 and 1615–1350 cal yr BP (Table 1) that coincide with the RWP onset and RWP-DACP

transition (Fig. 5a). As stated above, this evidence represents agricultural practices that rely on the capture and distribution of freshwater flow (Aubron and Brunschwig, 2008). Hence, we propose that these older events were mediated by augmented surface-water availability along the QM drainage.

Archaeological irrigation features in the QM drainage dated to ~2240 cal yr BP are contemporaneous with the Ramaditas site, an extensive farming/village complex dated to 2560–2040 cal yr BP (Fig. 5a; Rivera, 2005) along Quebrada Guatacondo, an ephemeral drainage located ~19 km northwest of our site (Fig. 1). Akin to QM, the colonization and exploitation of Q. Guatacondo has been interpreted as the result of steady, reliable and low intensity increased runoff when compared to today (Bryson, 2005). This implies that the amplified hydrological budgets witnessed at QM, at least for the onset of the RWP, involved other inactive tributaries from the southernmost PdT basin with similar direction and magnitude. By combining data from both archaeological sites we can obtain a constrained chronology for such hydroclimate conditions. In fact, continuous occupation of Ramaditas between 2500 and 2040 cal yr BP argue for a ~500 yr-period of increased surface water availability as well a shorter duration for the ensuing radiocarbon gap, which spans from 2040 to 1615 cal yr BP (Fig. 5a). The postulated duration of the positive hydroclimate anomalies documented here is certainly testable by future studies that incorporate further archaeological and paleoecological archives retrieved from the southernmost PdT basin.

4.2 Regional paleoclimate of the last 2500 yr

We argue that the unprecedented positive hydrological anomalies inferred for the southernmost PdT basin were attributed to increased moisture availability at higher elevations in the Sierra Moreno over the past 2300 yr (Fig. 5a). This could have come about either by direct increases in rainfall or glacial-melt output and/or reduced evaporation rates (an air-temperature function). All constitute alternative explanations for the persistence of perennial riverflow throughout much of the duration of the MCA and at the onset of the RWP and the RWP-DACP transition.

The relative contribution of glacial meltwater in generating increased surface water availability over the last two and a half millennia can only remain speculative until the recent glacial history of Sierra Moreno (with peaks topping 4000 m a.s.l.) is established. In contrast, the contribution of reduced evaporation by decreased temperatures can be dismissed because global and regional reconstructions suggest that the RWP onset and MCA were periods of exceptional warmth (Neukom et al., 2010; Ljungqvist, 2010; Mann et al., 2008). More importantly, observational data suggest that evaporation rates over the central Andes are primarily controlled by moisture availability owing to the effects of cloudiness on net radiation (Vuille et al., 2000; Houston, 2006a). Hence, the simplest explanation is that the events of

increased surface water availability detected in QM at 2500–2040; 1615–1350; and 1050–680 cal yr BP can be interpreted as the result of protracted pluvial events in the Sierra Moreno and central Andes during the RWP onset, RWP-DACP transition and MCA.

Many paleoclimate reconstructions from the central Andes, however, do not agree or are inconclusive regarding our chronology of hydroclimate changes. For example, limnogeological records from the Altiplano indicate that present-day conditions have remained stable over the last 3000 yr (e.g., Baker et al., 2005) or that the centennial-scale variability over the last two millennia was marked predominantly by negative precipitation anomalies (e.g., Grosjean et al., 2001). Peaks in inorganic concentrations and Cyperaceae pollen analysed in a core retrieved from the Marcacocha basin (13° S; 3355 m a.s.l.) have been interpreted as evidence for negative rainfall anomalies at 2450; 1850; and 1400 cal yr BP and during the entire interval encompassing the MCA and the LIA, ~1050–150 cal yr BP (Chepstow-Lusty et al., 2003). Similar conclusions were reached for the Titicaca basin record (16° S, ~3810 m a.s.l.) which shows three dry events at 2400–2200; 1900–1700 and 900–600 cal yr BP, the latter followed by a period of increased moisture throughout the LIA (Abbott et al., 1997, 2003; Mourguiart et al., 1998). Contrasting hydroclimate conditions have been also inferred from a calcite record recovered from varves at lake Pumacocha (10° S, 4300 m a.s.l.) during the MCA and LIA intervals (Bird et al., 2011). Modern inter-annual precipitation variability at Pumacocha is under the same climate regime as the QM headwaters (Garreaud et al., 2009), yet increased $\delta^{18}O_{calcite}$ in the lacustrine sediments suggest that the Peruvian Altiplano experienced dry conditions during the MCA (1050–850 cal yr BP; Bird et al., 2011). In contrast, negative values in $\delta^{18}O_{calcite}$ by 650–130 cal yr BP argue for maximum precipitation throughout the LIA (Bird et al., 2011).

Archaeological evidence from the Titicaca area and its Katari tributary also point to opposite hydrological and cultural patterns between the Altiplano and the QM drainage during the MCA. Binford et al. (1997) show that reduced stream flow and phreatic levels at Katari were caused by a conspicuous drought that in combination with anthropogenic factors provoked the collapse of the Tiwanaku States between 800–750 cal yr BP. It is interesting to note that these were also farming societies that inhabited and exploited an artificial regional hydrological productive system in the Titicaca basin from 2300 cal yr BP (deMenocal, 2001; Kolata, 1993, 1991).

That paleoclimate records along the western Andean slope evince pluvial phases at times associated with prevailing drier conditions over the Altiplano is hardly new. Indeed, several authors have highlighted the discrepancies between the timing and direction of hydroclimatic changes on the Altiplano versus the western Andean flank over the last 21 000 yr (Rech et al., 2002, 2003; Betancourt et al., 2000;

Latorre et al., 2002; Grosjean, 2001, 2003; Quade et al., 2001). Different sensitivities to climate change, lags in groundwater and lacustrine records, and sub-regional variations have all been suggested as possible explanations for these discrepancies (Betancourt et al., 2000; Latorre et al., 2005).

Our chronology of positive hydrological anomalies over the southernmost PdT basin and Sierra Moreno is practically synchronous with evidence for wetter interludes detected in other records from the upper margin of the Atacama Desert (>2000 m of elevation) during the MCA and by the RWP onset and RWP-DACP transition. Raised shorelines from the Aricota basin (17°22′ S, 2800 m a.s.l.) indicate a moderate lake highstand from 1610 to ∼1300 cal yr BP brought about by increased moisture budgets in the Peruvian Andes (Placzek et al., 2001). Similarly, the extent and vertical thickness of paleowetland deposits dated at 2600–1300 (Unit D1) and 800–400 cal yr BP (Unit D2) imply elevated water tables within incised canyons and springs across the northern and central Atacama (18°–23° S; Rech, 2001, 2003, 2002). Prevailing wetter conditions at 2300–2000; 1400–1200 and 1020–600 cal yr BP have also been inferred from rodent-middens collected between 18° and 25°30′ S along the western Andean flank (Latorre et al., 2002, 2006, 2003; Holmgren et al., 2008; Maldonado et al., 2005). Rainfall anomalies calculated using the modern relationship between rodent fecal pellet diameters (a proxy for body size) and mean annual rainfall argue for a three-fold increment in rainfall in the Calama and Salar de Atacama basins (∼24° S) during the MCA (Latorre et al., 2010). The presence of steppe grasses (today confined to elevations >3900 m a.s.l.) in rodent middens from the Calama basin's perennial Río Salado (∼22° S, 3100 m a.s.l.) suggest a large rainfall increase at 800 cal yr BP, which rapidly decreased to modern values by 700 cal yr BP as indicated by the presence of local taxa (Latorre et al., 2006).

4.3 What has driven the long-term hydrological and ecological dynamics of the PdT over the last 2500 years?

Today, most of the tropical rainfall that reaches down to ∼2000 m a.s.l. along the western Andean flank occurs during the austral summer as moisture sourced from the South American Summer Monsoon (SASM) (Zhou and Lau, 1998) spills over the Andean crest. This seasonal circulation pattern is controlled by the position and strength of the Bolivian High (Garreaud et al., 2003). Intensification and southward displacement of the Bolivian High enhances easterly flow and increases moisture influx from the Amazon basin and Gran Chaco into the Altiplano and along the western slope of the Andes (Garreaud et al., 2003; Vuille and Keimig, 2004).

At orbital and millennial time-scales, past hydrological change on the Altiplano and western Andean slope over the last 180 ka has been linked to mechanisms that affect either SASM moisture availability or the westward transport of moist air masses from eastern South America. The first of these hypotheses stresses the role of North Atlantic SSTs and concomitant effects on moisture availability in the Amazon basin and westward advection of SASM-derived moisture across the Altiplano and onto the Pacific slope of the Andes. Wet phases are usually interpreted as a propagation of the slowdown in the Atlantic Meridional Overturning Circulation (AMOC), resulting from strengthened northeast tradewinds and a southward displaced Intertropical Convergence Zone (ITCZ) during cold events in the North Atlantic (Ekdahl et al., 2008; Baker et al., 2001a, b; Fritz et al., 2004).

A different hypothesis links past positive hydroclimatic anomalies to ENSO-like variability, in particular to tropical Pacific SST-gradients (Latorre et al., 2006; Quade et al., 2008; Placzek et al., 2009). This causal mechanism is based on the modern control that Pacific SST gradients exert on the inter-annual and inter-decadal rainfall variability over the central Andes by modulating upper level circulation (Vuille et al., 2000; Garreaud et al., 2003; Vuille and Keimig, 2004). Enhanced SST gradients during la Niña years lead to increased influx of humidity through the strengthening and southward displacement of the Bolivian High and a subdued zonal upper level westerly circulation (Garreaud et al., 2003; Vuille and Keimig, 2004). Opposite atmospheric conditions during El Niño years lead to extended summer drought throughout the Altiplano (Aceituno et al., 2009).

Modern hydrological observations support the role for ENSO variability in driving hydrological shifts in the southernmost PdT. Houston (2006c) has pointed out that ENSO activity is the primary factor behind modern inter-annual variations for the hydrological patterns in the hyperarid Atacama. During La Niña years, increased summer rainfall in the high-elevation headwaters promote surface floods along ephemeral streams from the southern basin and increase runoff in perennial streams located at the northern PdT basin (Houston, 2006b, c, 2001, 2002).

Model simulations and diverse proxy records from widely distributed regions around the world indicate that during the MCA the tropical Pacific was locked into La Niña-like mode and warmer SSTs prevailed in the North Atlantic as well as an enhanced AMOC (Fig. 5b–d; Graham et al., 2007, 2010; Trouet et al., 2009; Makou et al., 2010; Pages-News, 2011; Cobb et al., 2003; Richter et al., 2009; Norgaard-Pedersen and Mikkelsen, 2009; Jenny et al., 2002). This would explain in part why we observe such a large positive hydroclimatic anomaly in the southernmost PdT basin during a large fraction of the MCA. The implication is that the persistence of perennial riverflow in the PdT is chiefly a response to centennial scale modulations of the tropical Pacific SST gradient through its influence on upper circulation and moisture transport across the Altiplano (i.e., Garreaud et al., 2003).

This is harder to judge, however, for the earlier hydroclimatic anomalies in the southernmost PDT basin observed between 2500–2040 cal yr BP (RWP onset) and

1615–1350 cal yr BP (RWP-DACP transition). Increased lithic concentrations in a sediment core offshore central Perú (Fig. 5b; Rein et al., 2005) argue for prevailing El Niño-like conditions in the equatorial Eastern Pacific between 2500 and ~1250 cal yr BP (Fig. 5b). In turn, this would imply that these older hydroclimate anomalies occurred during increased El Niño activity, an explanation that is unsupported by what we know regarding how the modern climate system works. In contrast to the lithic concentration record, however, rainfall histories from other regions sensitive to positive ENSO events (El Niño; Aceituno et al., 2009) such as central Chile (Laguna Aculeo, Fig. 5c; Jenny et al., 2002) point to significantly drier conditions during both intervals. Indeed, Laguna Aculeo experienced low debris-flow activity due to reduced local rainfall that have been linked to prolonged La Niña-like conditions at ~2200–1750 and ~1600–1450 cal yr BP (Fig. 5c).

As observed for the MCA, warmer SSTs in the North Atlantic by the onset of the RWP and RWP-DACP also occurred during the earlier positive hydroclimate anomalies seen in the PdT basin. Diverse SST-reconstructions evince a warming of North Atlantic between 2300 and 1500 cal yr BP (Eiriksson et al., 2006; Andersson et al., 2003; Sicre et al., 2008; Cronin et al., 2003; Norgaard-Pedersen and Mikkelsen, 2009). Planktonic foraminiferal Mg/Ca ratios in a marine core from the Feni Drift (NE Atlantic Ocean), however, suggest that such conditions did not end before 1390 cal yr BP (Richter et al., 2009). Taken together, these observations show that the timing of the positive anomalies seen at the PdT (and by extension the western Andean cordillera) cannot be explained through links to a weakened AMOC and its influence on the ITCZ (sensu Ekdahl et al., 2008; Baker et al., 2001a, b; Fritz et al., 2004).

5   Summary and conclusions

We present evidence for variations in hydrological conditions in the low-elevation Atacama Desert over the past 2500 yr. Garnered from relict tree mounds, fossil rodent burrows and archaeological remains preserved in an inactive tributary of the southern Pampa del Tamarugal basin (21° S; PdT), we show that positive hydroclimatic anomalies occurred at 2500–2040; 1615–1350 and 1050–680 cal yr BP.

The similarity in timing of these hydroclimate changes in the low-elevation desert with other records from the western Andean slope argue for the existence of important pluvial events on regional spatial scales for the past 2500 yr. The synchronous and rapid response of biotic and hydrological components from the southern PdT basin to positive hydrological budgets at higher elevations implies that these rainfall anomalies quickly impacted the hydrology, productivity and human-landscape relationships in the hyperarid Atacama core. The remarkable synchronicity displayed between paleoclimate changes along the western Andean slope over the

past two and a half millennia also reinforces the use of PdT geohistorical records as feasible proxies for tracing past hydroclimatic change in the central Andes on multiple different time-scales.

Comparisons with a diverse array of proxy records from around the world indicate that the positive hydroclimate anomalies observed in the PdT during the MCA and at the RWP onset and RWP-DACP transition were likely forced by prevailing negative SST gradients in the tropical Pacific (La Niña-like conditions). Thus, ENSO-like variability seems to be the first-order driving force for climate variability in this region over the last 2500 yr.

The link between hydroclimate conditions in the low-elevation desert and past ENSO activity documented here has profound implications for further evaluations on the sensitivity of the central Andes hydroclimate to equatorial Pacific SST-gradients. The fact that a similar mechanism could be operating on centennial, as well as annual and inter-decadal timescales, provides additional support for the role of tropical Pacific SST gradients as the primary mechanism responsible for centennial/millennial hydroclimate fluctuations in the Atacama Desert.

Finally, we point out that the existence of wetter conditions at different locations in the Atacama matches abrupt increases in the number of sites and total number of cultural radiocarbon dates over the past 13 000 yr. These numbers have been previously interpreted as an intensification of human activities and population size (Williams et al., 2008). The paleoenvironmental implications for understanding the dynamic relation between human societies and environment (Zaro et al., 2008) are promising, and clearly demonstrated by our data. In particular, changes in the cultural history of the people that inhabited the PdT and the Atacama Desert in general can be better understood by combining different kinds of archives.

The Atacama is an extreme environment where changes in water availability were ingeniously managed by prehistoric populations. In the case of QM, this included the opening of extensive farming fields, irrigated by a network of several kilometres of stone-lined channels cut into the ground. This interaction created a vegetated landscape that can only be fully explained by the intervention of natural forces, both local and regional, coupled with human activities.
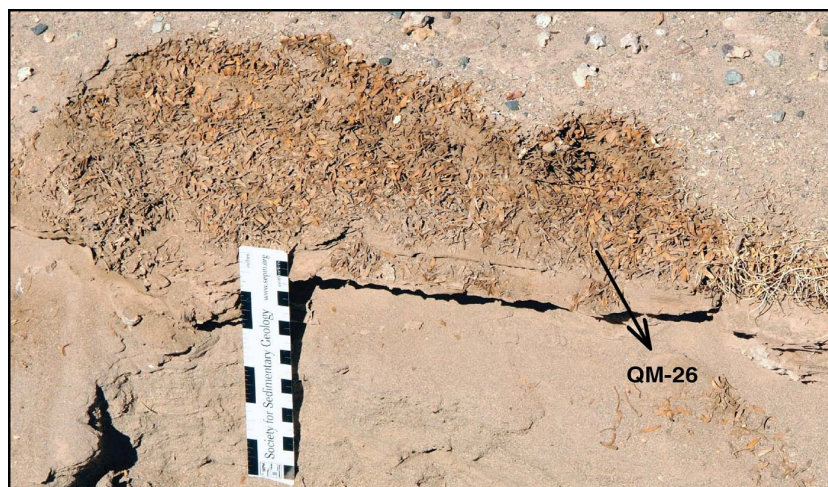
Appendix A

Fig. A1. Detail from an in situ leaf-litter deposit. Note the presence of abundant woody materials.
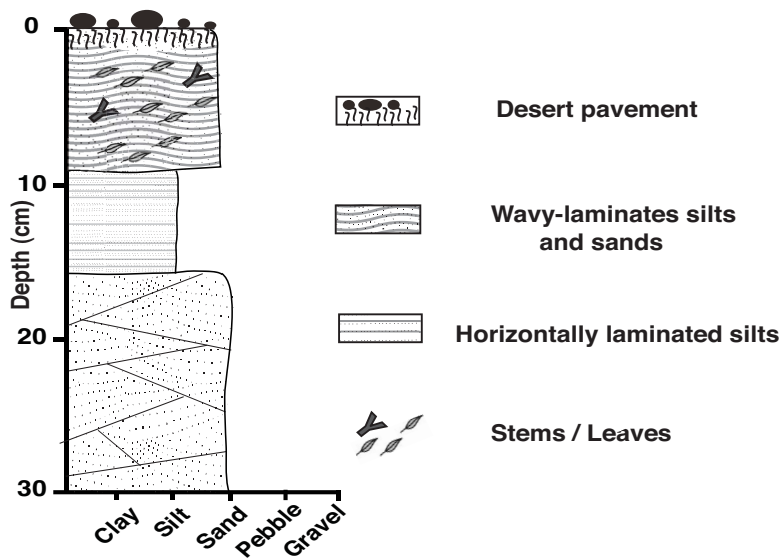

Fig. A2. Stratigraphic section for QM-26 subsurface deposit of situ leaf-litter.
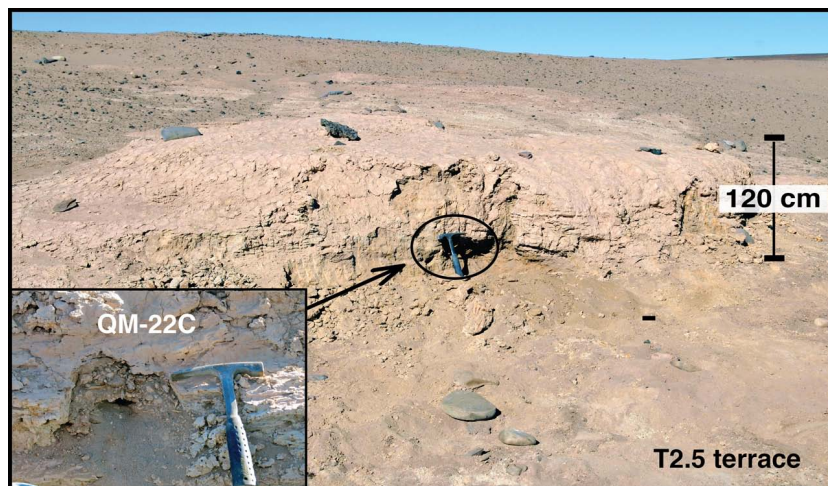
Fig. A3. Northern face of the remnant late Pleistocene paleowetland deposit containing rodent burrows. Arrow indicates where QM-22C rodent burrow was found.
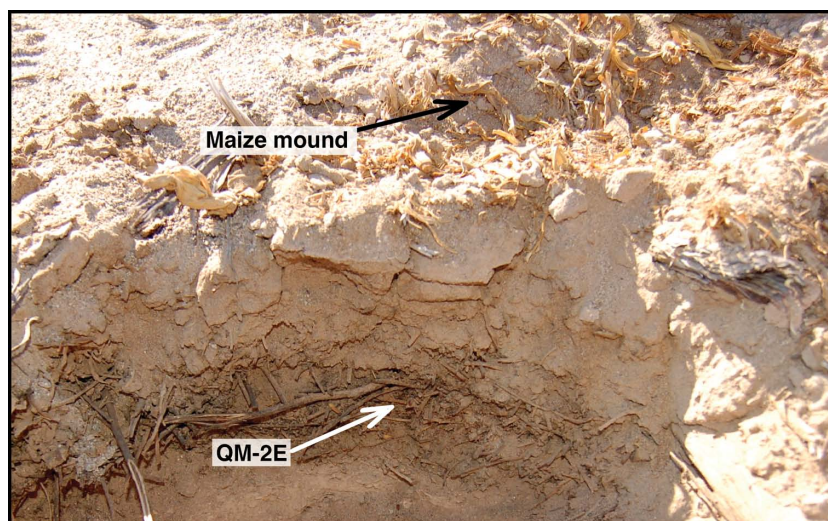

Fig. A4. Maize (*Zea mays*) litter (QM-2A) found in situ upon the QM-2E subsurface deposit.

Fig. A5. Collapsed semi-circular structure from which superficial and subsurface charcoal samples were recovered.

Fig. A6. Horseshoe-shaped dam extending over 18 m on T2.5. Location for the test pit is shown.
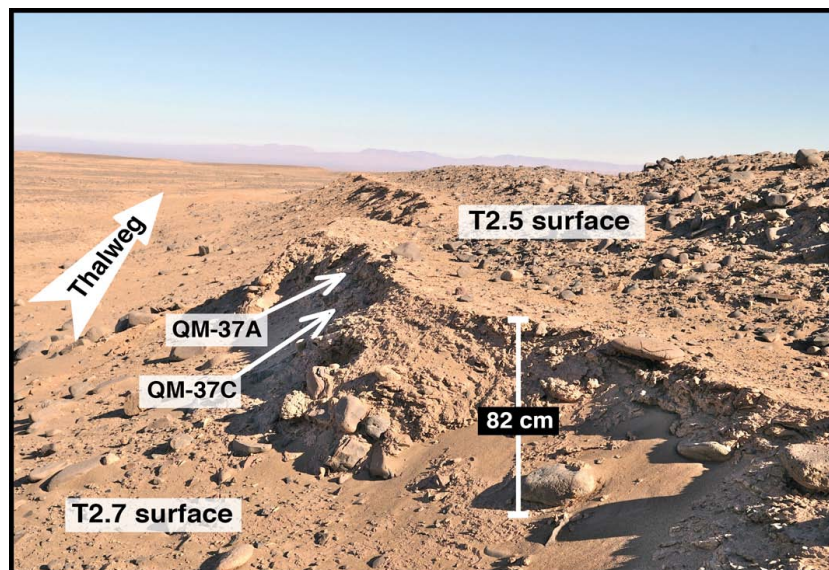
Fig. A7. Perched irrigation channel. The provenance of samples QM-37C and QM-37A is shown.

Fig. A8. QM-28 polygonal shaped leaf-bed (dotted line). Details for superficial *Prosopis* leaves are shown.

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