

# Climate change and human occupation in the northernmost Chilean Altiplano over the last ca. 11 500 cal. a BP

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**ABSTRACT:** This interdisciplinary study represents an approximation towards understanding how regional human cultural systems may have been affected by climate change in the northernmost Chilean Altiplano (>3600 m) over the last ca. 11 500 cal a BP. We compare the archaeological record from Hakenasa cave with the lake record from Lago Chungará sediment cores, located 50 km to the south. By integrating both of these archives in conjunction with regional palaeoclimate and archaeological data, we provide new evidence for the role of changing environmental and climatic conditions in human settlement patterns. The first human occupation of the entire Altiplano occurs at Hakenasa and is dated to  $9980 \pm 40$  <sup>14</sup>C a BP (11 265–11 619 cal. a BP), and took place under wetter regional climate conditions. An archaeologically sterile deposit occurs at Hakenasa between 7870 and 6890 cal. a BP. Constituted by sands and gravels, these sediments are interpreted as a flood event. This time period is synchronous with alternating short dry and wet events recorded in the Lake Chungará sedimentary sequence. Human activity resumes and increases in importance at Hakenasa by ca. 6000 cal. a BP. This corresponds to wetter conditions indicated by the Chungará record. Even though the lake record indicates intense volcanic activity over the last 6000 cal. a BP, this had little or no impact on the human population present at Hakenasa. This study shows that even in this extreme environment human settlement patterns do not always respond in a linear fashion to environmental change. Copyright © 2008 John Wiley & Sons, Ltd.



**KEYWORDS:** Altiplano; Central Andes; palaeoclimate; lake sediments; human ecosystems; Holocene.

## Introduction

Establishing links between cultural history and environmental change has quickly grown into a major field of inquiry which has generated a collaborative effort between palaeoclimatologists and archaeologists throughout the world (e.g. Sandweiss, 2003; Burroughs, 2005; Dirksen and van Geel, 2005; Grosjean *et al.*, 2005; Méndez and Jackson, 2006; Turney and Hobbs, 2006; Shennan and Edinborough, 2007). This research is driven by important questions, such as: How and when does climate become an important factor for human settlement and establishment? To what extent can we use past climate fluctuations (and other environmental fluctuations such as

volcanic activity) to actually predict past human settlement patterns?

Recent case studies have provided ample evidence for the role of environmental or climatic shifts in bringing about cultural collapse and other negative consequences for regional human populations. These are manifested as either widespread abandonment of a region or substantial alterations in subsistence strategies and settlement systems (Hodell *et al.*, 2001; Núñez *et al.*, 2002; Haug *et al.*, 2003). In other cases, major palaeoenvironmental changes that quash resource availability along with increased population are clearly related to intensification of production (Kirch, 2005). In some instances, environmental factors may have no significant impact on cultural processes, and certainly ancient societies can flourish or collapse independently of climate fluctuations, motivated by other factors such as population increase coupled with social and economic reorganisation, along with transformation in belief systems, etc. (Allison, 1996; Anderson *et al.*, 2007). Extreme drought, floods or pronounced temperature

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variations, however, can be especially detrimental in human societies, where the resulting famine and disease are capable of undermining key social structures (Binford *et al.*, 1997; Hodell *et al.*, 2001; Haug *et al.*, 2003).

As well-dated, high-resolution Holocene palaeoclimate records from South America become increasingly available, detailed chronologies of cultural change are now constantly associated with climate change over the last few millennia. Of particular interest for establishing links between climate and human occupation is the Altiplano of South America, a broad highland region with an average altitude of 3600 m. This region has experienced a succession of wet and arid phases that were spatially and temporally complex, as documented by numerous palaeohydrological reconstructions across the region (Abbott *et al.*, 1997; Valero-Garcés *et al.*, 1999; Baker *et al.*, 2001, 2005; Grosjean *et al.*, 2001; Latorre *et al.*, 2003, 2005; Servant and Servant-Vildary, 2003; Maldonado *et al.*, 2005). Thus, many robust palaeoclimate records with accurate chronologies are now being developed across the region. The influence of past climate changes on the way of life of hunter-gatherers should, however, be accomplished at a local spatial scale of analysis as we attempt here – a basic step before making any regional generalisations. Several recent publications have appeared dealing with this issue, mainly focused on the South-Central Andes (21–24° S) (see a review in Grosjean *et al.*, 2007). The links between climate and human occupation in the northern Chilean Altiplano (18–21° S) remain poorly investigated (Fig. 1).

Here, we present a case study employing an interdisciplinary approach integrating archaeological, palaeoecological and palaeolimnological data, all of which are necessary for understanding the possible influence of climate change on regional cultural systems in the northernmost Chilean Altiplano. To achieve our goal we combine a high-resolution lake record obtained at Lago Chungará and the nearby chronologically well-dated human archaeological occupation at Hakenasa cave. The Chungará sedimentary sequence provides a detailed reconstruction of the lacustrine sedimentary evolution over the last 12 000 cal. a BP (Moreno *et al.*, 2007; Sáez *et al.*, 2007; Giralt *et al.*, 2008). The Hakenasa archaeological sequence extends from the Early Archaic (11 265–11 619 cal. a BP), to the Late Period-Inka related epoch, dated to the 16th century AD (Santoro, 1987; Santoro and Núñez, 1987; Núñez and Santoro, 1988, 1990; LeFebvre, 2004). This site, along with Las Cuevas and Quebrada Blanca

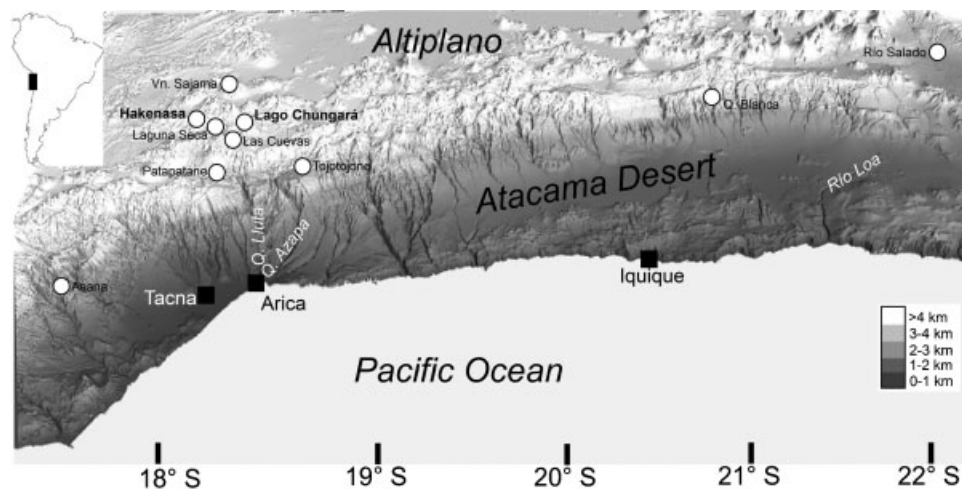
(Fig. 1), contains the earliest high-altitude (>3500 m) human occupation yet excavated in northernmost Chile and southernmost Peru (Aldenderfer, 1999; Santoro, 1989).

Both Hakenasa and Lago Chungará are located on the Chilean Altiplano, an extreme environment where rough topography combines with high altitude, severe daily temperature variations and scant vegetation (Lambrinos *et al.*, 2006). This region has also been very sensitive to past climate changes (e.g. Baker *et al.*, 2001). The integration of these archives makes for a strong combination that will let us inquire into the relationship between human occupation and the rapidly changing palaeoenvironments over the last 11 500 a.

## Previous studies linking culture and climate in the Chilean Altiplano

Palaeoindian sites (defined in chronological terms – see Núñez *et al.*, 2002; Sandweiss, 2003; Grosjean *et al.*, 2005) are extremely scarce from the Altiplano of southernmost Peru and northernmost Chile. In contrast, the evidence for early Palaeoindian occupation in southern South America may have occurred as early as 14 600 cal. a BP (Dillehay, 2002; Dillehay *et al.*, 2008). Other important palaeoindian sites are also known from the southern coast of Peru (Sandweiss, 2003; DeFrance and Umire, 2004) and the central Atacama highland or *Puna de Atacama* (Núñez *et al.*, 2002; Grosjean *et al.*, 2005). Only during the Early Archaic (11 000–8000 cal. a BP) did small, mobile bands of foragers begin to occupy the Altiplano by moving seasonally from the upland valleys to the caves and rock shelters at higher altitude (Santoro, 1989). Similarly, in the central Atacama region (21–25° S), Late Pleistocene exploration camps have been well documented at lower elevations (3000–3200 m), whereas the high Andes (>4000 m) were not occupied until well into the early Holocene (Núñez *et al.*, 2002; Grosjean *et al.*, 2005).

By 9000 cal. a BP, high Andean palaeolakes had dried out (Geyh *et al.*, 1999; Placzek *et al.*, 2006) and steppe grassland vegetation retreated upslope under drier climatic conditions (Latorre *et al.*, 2005, 2006). Numerous authors working in the period known as the Middle Archaic (8000–6000 cal. a BP) have published archaeological records that show changes in the settlement patterns both in the northern Altiplano as well as



**Figure 1** Oblique view looking east across northern Chile, the central Andes and the Altiplano. Localities discussed in the text (white circles) and major cities (black squares) are shown

in the Atacama and Loa basins (Santoro and Núñez, 1987; Aldenderfer, 1988; Baied and Wheeler, 1993; Núñez *et al.*, 1996; Grosjean *et al.*, 1997, 2005; De Souza, 2004). One of the more well-known cultural changes seems to have occurred in the central Atacama, where the abrupt reduction of human activities along with widespread abandonment of certain areas within the region has been coined the '*silencio arqueológico*' (archaeological silence) linked to widespread severe aridity during the middle Holocene (Núñez *et al.*, 2002; De Souza, 2004; Grosjean *et al.*, 2005, 2007). The '*silencio*' remains controversial in northern Chile. For example, Middle Archaic settlement patterns and cultural processes in the northern Atacama (16–21° S) show almost no or very little impact from climate (Aldenderfer, 1988, 1989; Santoro *et al.*, 2005). Based on newer evidence from rodent middens and past groundwater table fluctuations (Betancourt *et al.*, 2000; Quade *et al.*, 2001; Rech *et al.*, 2002, 2003), even the presence of 'mid Holocene' severe aridity in the central Atacama has been disputed. Although we do not attempt to resolve this important issue here we note that: (1) regional climate change in the central Atacama during the Holocene may be considerably more complex than previously assumed (Latorre *et al.*, 2006) – this will thus require a much more solid chronology of the duration of the '*silencio*'; and (2) other factors that explain human subsistence in the Atacama, such as technological advances (or lack thereof), must be taken more fully into account.

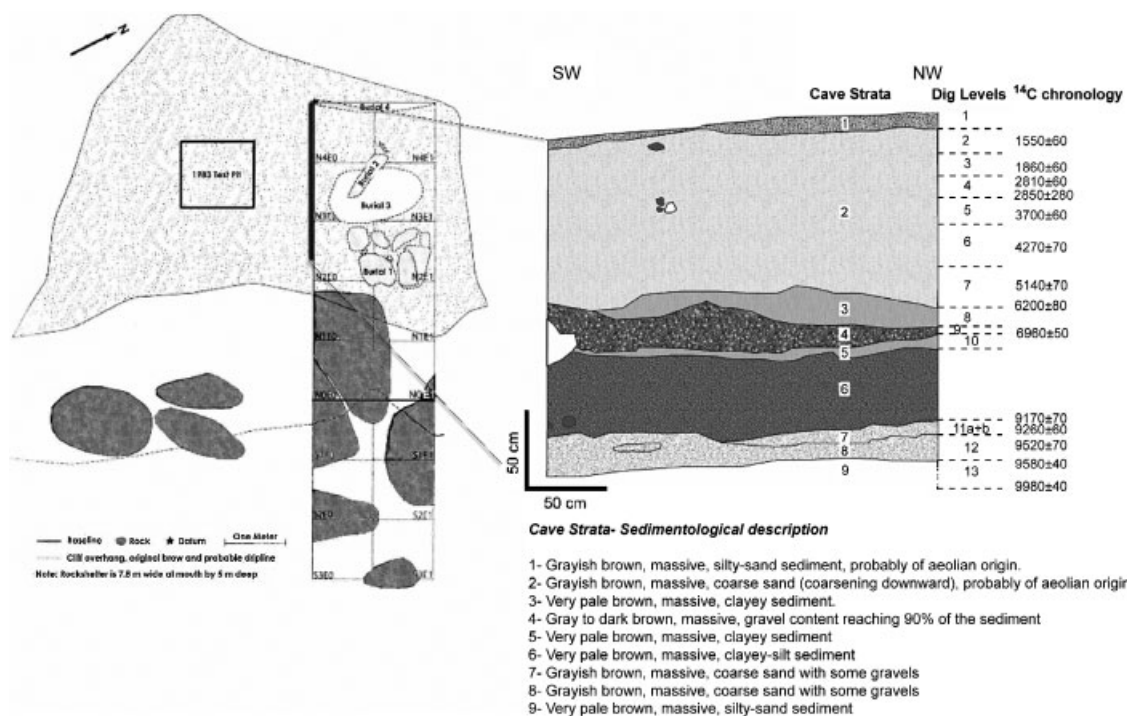
Interestingly, central Atacama hunting and gathering societies during the Late Archaic and the subsequent early Formative period experienced dramatic cultural changes after the '*silencio*'. These include a new economic system supported by agriculture and pastoralism, new technologies (ceramics, metallurgy, textiles, interregional exchange) and the materialisation of new ideas expressed as more complex forms of social organisation and ideology (Agüero, 2005; Núñez, 2005). This cultural transformation ca. 5000–3000 cal. a BP has been correlated with an increase in atmospheric moisture, allowing for a circumscribed intensification of production in the form of pastoralism and horticulture (Grosjean *et al.*, 2001, 2003,

2007; Núñez *et al.*, 2006). In contrast, many well-dated records from the mid to lower elevations along the Pacific Andean slope evince either increased groundwater discharge between 8000 and 3000 cal. a BP (Bobst *et al.*, 2001; Rech *et al.*, 2002, 2003; Lowenstein *et al.*, 2003) or interludes of increased rainfall between 7500–6500 and 4500–3000 cal. a BP based on rodent midden evidence (Latorre *et al.*, 2002, 2003, 2005). Thus the causative relationship (if any) between environmental and cultural changes in the central Atacama remains unclear and constitutes a major challenge for future research. Yet, it is interesting to note that the cultural intensification of the Late Archaic is correlated with increased El Niño–Southern Oscillation (ENSO) frequency and intensity (Kerr, 1999; Sandweiss *et al.*, 2001; Moy *et al.*, 2002; Turney and Hobbs, 2006; Williams *et al.*, 2008).

## Geology and climate

At 4100 m, Hakenasa cave (17° 50' S, 69° 22' W) is emplaced along a bluff of faulted rhyolitic ignimbrite (LeFebvre, 2004) (Figs 1 and 2). The site overlooks a *bofedal* – a high-altitude wetland that constitutes the best habitat on the Altiplano in use even today by traditional pastoralists. Located ~50 km to the south, Lago Chungará (18° 15' S, 69° 09' W, 4520 m) is emplaced in the highest and westernmost fluviolacustrine basin within the Altiplano (Fig. 1). The lake sits in the central portion of a small hydrologically closed sub-basin at the northeastern edge of the Cenozoic Lauca Basin. The lake was created by the partial collapse of the Parinacota Volcano, the resulting avalanche blocking the paleo-Lauca River some time between 20 000 and 13 000 cal. a BP (Seyfried *et al.*, 1998; Hora *et al.*, 2007; Sáez *et al.*, 2007).

Our sites are located in the dry *puna* of the arid South-Central Andes (Troll, 1958). Tropical summer rain brings moisture to this region from the Amazon Basin, the frequency of which is



**Figure 2** Floor plan of Hakenasa cave (after LeFebvre, 2004, based on Santoro field notes). Inset: vertical profile with the stratigraphy and <sup>14</sup>C dates of the SW–NW trench. Cave strata and dig levels are indicated (after Santoro field notes)

chiefly tied to the seasonal southward migration of the subtropical jet and the intensification of the Bolivian High (Garreaud *et al.*, 2003). Mean annual rainfall averages 300–350 mm; mean annual temperature is 4.2°C. The average monthly minimum temperature is –2°C, with a monthly average maximum of 5.1°C and a diurnal range of as much as 25–30°C (Rundel and Palma, 2000). A significant fraction of the interannual variability in summer precipitation at present is related to the ENSO (Vuille, 1999). Wet (dry) summers on the western Andean Altiplano are associated with anomalous cooling (warming) of the equatorial Pacific such as that present during La Niña (El Niño) events. Local vegetation is characterised by low cover values (<30%) and dominated by tussock-like grasses (*Festuca*, *Nassella*, *Deyeuxia*), shrubs of the Asteraceae, Solanaceae and Verbenaceae families, and the dwarf tree *Polylepis* (Rosaceae), as well as extensive soligenous bofedales dominated by cushion sedges (Villagrán *et al.*, 1999).

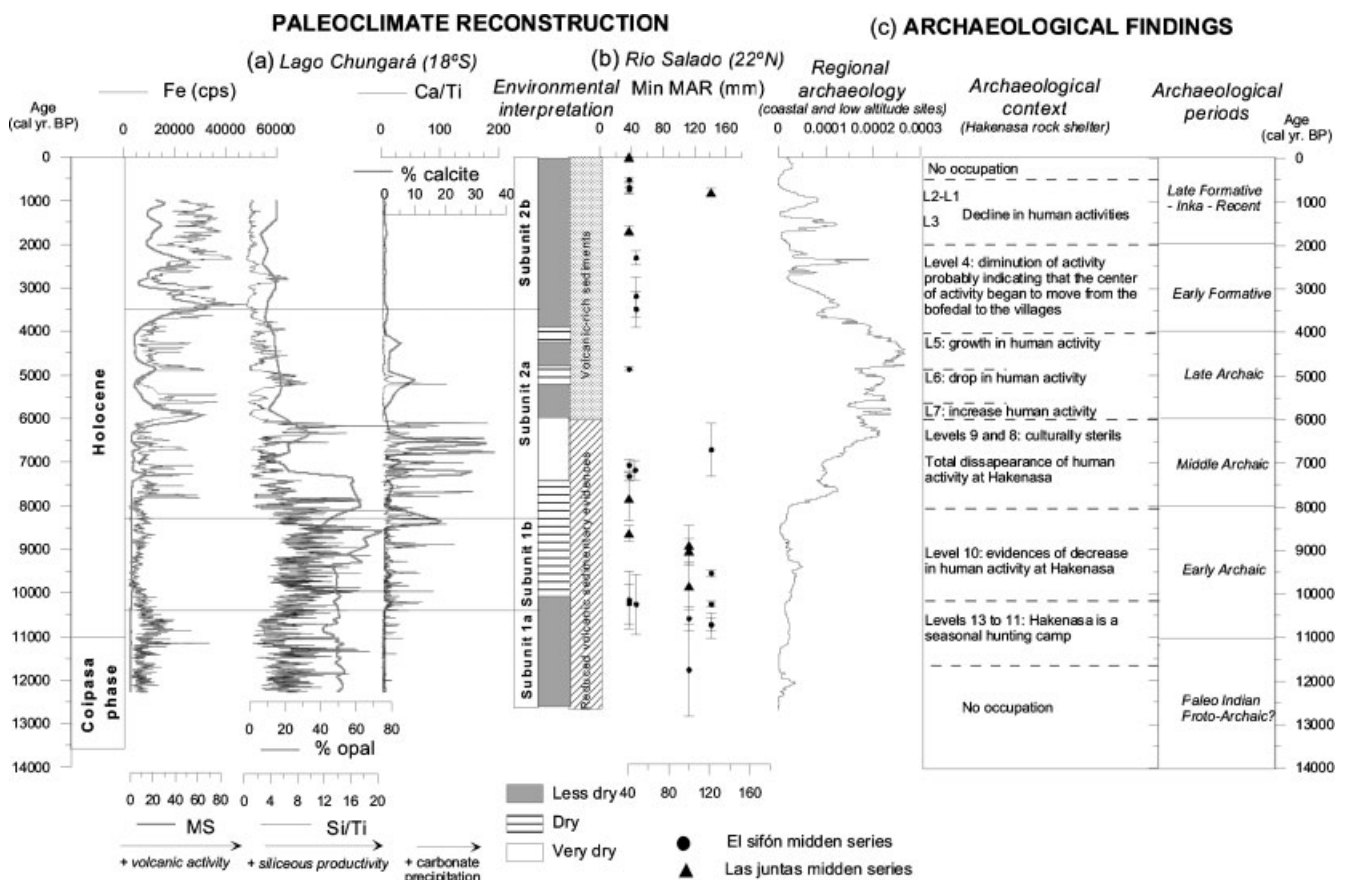
### The Lago Chungará and Hakenasa cave records: methods and chronology

In November 2002, 15 sediment cores were retrieved from Lago Chungará, analysed for physical properties and macroscopically described for texture, colour and sedimentary structures. Subsamples were taken for mineralogical, chemical

and biological analyses (see Moreno *et al.*, 2007, for methods) and core archive halves were measured using an X-ray fluorescence (XRF) core scanner for light (Al, Si, S, K, Ca, Ti, Mn and Fe) and heavy (Sr, Zr, Sn and Ba) elements.

From stratigraphical correlation and seismic stratigraphy, two main lithostratigraphic units were defined in the Chungará sequence (Fig. 3) and published by Sáez *et al.* (2007). Unit 1 was deposited after the volcanic event that created the lake and consists of diatomaceous ooze with variable types (calcite, aragonite) and quantities of carbonates and amorphous organic matter. Unit 1 is divided in two subunits: Subunit 1a, with green and white laminations and no carbonate; and Subunit 1b, with brownish to white laminations and endogenic carbonates that occur in low concentrations. Unit 2 is mainly composed of massive to slightly banded diatomaceous ooze frequently intercalated by tephra layers (Fig. 3). Subunit 2a is composed of brownish-red massive to slightly banded sapropelic diatomaceous ooze with common calcitic crystals (silt grain-sized) and carbonate-rich layers. Subunit 2b consists of dark-grey diatomaceous ooze with frequent macrophyte remains alternating with massive black tephra layers, mainly composed of plagioclase, glass and mafic minerals.

Obtaining a reliable chronology of Lago Chungará sequence is complicated by (1) the lack of terrestrial macrofossils and (2) the variable reservoir effect (Moreno *et al.*, 2007; Giralto *et al.*, 2008). Owing to the lack of terrestrial macrofossils, 17 accelerator mass spectrometric (AMS) <sup>14</sup>C dates were obtained from bulk organic matter from the central plain cores



**Figure 3** (a) From Lago Chungará record: Fe (cps) and magnetic susceptibility as indicators of volcanic input; Si/Ti ratio and opal percentages as indicators of siliceous biomass production and Ca/Ti ratio and calcite percentage as indicators of carbonate precipitation. Lithostratigraphic subunits and qualitative evaluation of environmental moisture conditions and volcanic activity are also plotted. (b) Minimum mean average rainfall (MAR) estimates obtained from past distributions of plant species found in rodent middens in the Río Salado basin (see Latorre *et al.*, 2006). Errors on ages are at two standard deviations. (c) Archaeological contexts, including the summed probability distribution of 111 <sup>14</sup>C dates from coastal and low-altitude areas in northern Chile over the last 14 000 a; compilation of the main interpretations from Hakenasa (levels L13–L1) and summary of the archaeological periods in this area

and aquatic organic macrofossils picked from littoral cores (Table 1). The similarities in the sedimentary facies among the cores and the presence of key tephra layers allow transfer of obtained dates to a single composite depth (Sáez *et al.*, 2007). A reservoir effect was subtracted from the ages before calibration. This effect was established by dating the dissolved inorganic carbon (DIC) in present-day water ( $2320 \pm 40$   $^{14}\text{C}$  a BP) and correcting that value for the nuclear bomb effect at the year of sampling (Geyh *et al.*, 1999). The final value, 3620 a (Giralt *et al.*, 2008), is very similar to that obtained previously by Geyh *et al.* (1999) in Lago Chungará. The age model used here is the same as that previously published by Giralt *et al.* (2008).

Once the  $^{14}\text{C}$  dates were corrected for any reservoir effects (see Giralt *et al.*, 2008, for further details), they were calibrated using INTCAL04, provided by the CALIB 5.02 software package (Reimer *et al.*, 2004), selecting the median of 95.4% of the distribution ( $2\sigma$  probability interval). A reliable age–depth model was established after removing the two reversals

(Table 1, ‘Reservoir corrected and calibrated age  $2\sigma$ , cal. a BP’ column), using the interpolation method described in Heegaard *et al.* (2005).

A  $1\text{ m}^2$  test pit was excavated, sieved and curated by C. Santoro and P. Dauelsberg from Hakenasa rock shelter in 1983. This yielded a stratigraphic sequence of  $\sim 2\text{ m}$  deep that spanned from the Early Archaic ( $\sim 11\,000$  cal. a BP) to the present (Santoro, 1987, 1989; Santoro and Núñez, 1987; Núñez and Santoro, 1988, 1990). In 2001,  $16\text{ m}^2$  were excavated and analysed by C. Santoro and R. LeFebvre. Readers are referred to LeFebvre’s PhD dissertation (LeFebvre, 2004) for more detailed information on the cultural and faunal remains selected from the 2001 excavations. Seventeen charcoal  $^{14}\text{C}$  dates constitute the chronology of Hakenasa cave sediments (three from the 1983 excavation, 11 from 2001 (LeFebvre, 2004) and three obtained in 2007; Table 1). These dates were recalibrated at  $2\sigma$  using the same methods as the Chungará samples (INTCAL04 – CALIB 5.02) (Reimer *et al.*, 2004).

**Table 1** Radiocarbon and calibrated dates from Hakenasa rock shelter and Lago Chungará sediments

Level	Laboratory ID	Type of sample	$^{14}\text{C}$ age (a BP)	Reservoir corrected and calibrated age ( $2\sigma$ ) (cal. a BP)
<b>Hakenasa rock shelter</b>				
2**	B-187525	1	$1,550 \pm 60$	1,316–1,551
3**	B-187526	1	$1,860 \pm 60$	1,689–1,930
4**	B-187527	1	$2,810 \pm 60$	2,771–3,078
4*	I-13229	1	$2,850 \pm 280$	2,334–3,645
5**	B-187528	1	$3,700 \pm 60$	3,875–4,182
6**	B-187529	1	$4,270 \pm 70$	4,781–4,980
9*	I-13230	1	$4,380 \pm 120$	4,789–5,319
7**	B-187530	1	$5,140 \pm 70$	5,710–6,021
Top 8 – Base 7***	B-219700	1	$6,200 \pm 80$	6,891–7,273
Top 10 – Base 9***	B-219701	1	$6,960 \pm 50$	7,683–7,872
23*	I-13287	1	$8,340 \pm 300$	8,578–9,960
10**	B-187531	1	$8,789 \pm 60$	9,595–9,959
11a**	B-187532	1	$9,170 \pm 70$	10,219–10,515
11b**	B-187533	1	$9,260 \pm 60$	10,257–10,577
12**	B-187534	1	$9,520 \pm 70$	10,646–11,106
13**	B-187535	2	$9,580 \pm 40$	10,741–11,107
13***	UGAMS2953	1	$9,980 \pm 40$	11,265–11,619
<b>Lago Chungará sediments</b>				
Water	Beta-188745	DIC (surface water)	$2,320 \pm 40^a$	–
Subunit 2b	37	Poz-8726	$4,620 \pm 40$	1,470–2,430
	42	Poz-8720	$4,850 \pm 40$	1,585–2,565
	67	AA56904	$6,635 \pm 39$	2,075–3,420
	95	Poz-8721	$7,290 \pm 50$	2,575–4,350
2a	257	Poz-8723	$8,920 \pm 50$	5,285–7,500
	344	AA56903 <sup>b</sup>	$10,000 \pm 50$	6,245–8,335
	436	Poz-8724	$10,860 \pm 60$	7,055–9,245
1b	490	Poz-7170	$8,570 \pm 50$	7,630–9,975
	550	Poz-8647	$9,860 \pm 60$	8,360–10,865
	615	Poz-7171	$11,070 \pm 70$	9,155–11,605
Subunit 1a	665	AA56905	$4,385 \pm 100$	–
	675	Poz-8725	$8,810 \pm 50$	–
	697	Poz-11891	$11,460 \pm 60$	9,605–12,275
	742	Poz-13032	$10,950 \pm 80$	9,685–12,685
	785	Poz-11982	$11,180 \pm 70$	9,740–13,260
	827	Poz-13033	$12,120 \pm 80$	10,206–13,675
	865	Poz-7169	$13,100 \pm 80$	10,215–14,615

*Italic* samples were excluded from the age model. 1, charcoal; 2, bone; 3, bulk organic matter; 4, aquatic organic macrofossils.

\*1983 test excavation;

\*\*dates in LeFebvre’s thesis (2004) and Grosjean *et al.* (2007);

\*\*\*AMS dating in 2007.

<sup>a</sup>3620 a (after nuclear bomb correction).

<sup>b</sup>At 344 cm, there is one available U/Th date that gives an age of  $6,730 \pm 974$  years BP, coherent with the  $^{14}\text{C}$  date once corrected for the reservoir effect and calibrated. All dates from Lago Chungará are published in Giralt *et al.* (2008).

## Climate change and cultural processes in the northern Chilean Altiplano

### Initial human occupation

Human occupation at Hakenasa began as early as 11 265–11 619 cal. a BP (Table 1, level 13), along with other examples of initial human occupation in the Altiplano during the early Holocene, which includes *Las Cuevas* (11 180–10 300 cal. a BP,  $2\sigma$  range) and the open camp at *Quebrada Blanca* (11 180–10 740 cal. a BP,  $2\sigma$  range) (Santoro, 1989; Grosjean *et al.*, 2007). Lithic artefacts show a technically well-developed unifacial stone industry that used percussion, pressure and thermo-percussion techniques to elaborate a toolkit that includes points, knives, cutting tools and scrapers linked to hunting and subsequent butchering and hide processing (Santoro, 1987, 1989; Santoro and Núñez, 1987; LeFebvre, 2004). LeFebvre (2004) has shown changes in the toolkit from the Late Archaic period, confirming previous observations from Hakenasa and other sites of the zone. This is reflected by a general tendency to produce more expedite artefacts (Santoro, 1987, 1989; Santoro and Núñez, 1987; LeFebvre, 2004).

Faunal remains found at Hakenasa (Lefebvre, 2004; C. Salas, pers. comm.), as well as at *Las Cuevas* (Santoro and Núñez, 1987) and *Quebrada Blanca* (Grosjean *et al.*, 2007), include those of camelids, cervids, vizcachas (*Lagidium* sp.) and other artiodactyls and rodents. No macrobotanical remains have been identified so far in the analysed archaeological remains, whereas a microbotanical search is yet to be done.

Climate change as inferred from the nearby Lago Chungará sediments can shed some light for early Holocene peopling of the Altiplano. At ca. 11 500–10 500 cal. a BP, a major climate change occurred at the boundary between Subunit 1a (green and white laminations and no carbonate) and Subunit 1b (brownish to white laminations and authigenic carbonates) (Fig. 3). At this boundary, several proxies indicate a general increase in lake biomass production (Si/Ti ratios and percentage biogenic opal increases, Fig. 3). Lake biomass production remained high throughout the early Holocene until 7000–6000 cal. a BP, when a decrease in the proxies concurs with maximum carbonate precipitation as evidenced from higher Ca/Ti ratios and calcite percentage. This coincides with the increase in volcanic activity at about 6000 cal. a BP, represented by the Fe and magnetic susceptibility profiles (Fig. 3).

Increase in lake biomass production (11 000–7000 cal. a BP) was interpreted here as the result of a positive water balance (Moreno *et al.*, 2007; Giralt *et al.*, 2008). This implies more rainfall in the catchment region and increased runoff (more soil erosion) and consequent higher nutrient input into the lake. A higher nutrient input would create significant diatom blooms. In contrast, low rainfall values (or increased evaporation rates) would lead to lower water levels, resulting in increased salinity along with carbonate precipitation. Hence both Si/Ti and Ca/Ti ratios have been used as climate proxies at this particular lake (Moreno *et al.*, 2007).

Wetter climate conditions throughout the Lateglacial (ca. 13 000 cal. a BP) to the early Holocene (ca. 8500 cal. a BP) have also been inferred from several different proxies analysed from Lago Titicaca sediments (Baker *et al.*, 2001; Fritz *et al.*, 2006) and from changes in the Rio Ilave discharge (Rigsby *et al.*, 2003). In addition, a  $\sim 4\text{‰}$  increase in  $\delta^{18}\text{O}$  values at 11 500 cal. a BP in the nearby Sajama ice core would seem to indicate increased temperatures at the onset of the Holocene (Thompson *et al.*, 1998). Sajama ice core  $\delta^{18}\text{O}$  values, however, are influenced strongly by the amount of precipi-

tation, air temperature and moisture source variability, and the relative contribution of each of these signals in this part of the world is not at all resolved (Bradley *et al.*, 2003; Vuille *et al.*, 2003). Although past variations in the hydrological cycle can apparently be teased out from geohistorical records, temperature changes in the central Andes at the onset of the Holocene remain unclear.

The aforementioned palaeoclimate records indicate that Hakenasa was probably first occupied at a time of stable regional climatic conditions, characterised by conditions wetter than today at the end of the last glacial cycle (e.g. Coipasa lake cycle, 13 000–11 000 cal. a BP; Placzek *et al.*, 2006). Thus the date obtained from a small hearth on a shallow hollow at the rocky base of the cave (Table 1, 11 265–11 619 cal. a BP) may be considered the first human incursion in the northern Chilean Altiplano. Increased hydrological output would have incremented plant biomass production and game animal populations as well as creating very suitable conditions on the Altiplano for early peopling.

A dry event occurred at ca. 9500 cal. a BP in the Lago Chungará record against an overall wetter climate conditions. This corresponds to the first peaks of Ca/Ti and calcite percentage (Fig. 3) that point to the presence of endogenic carbonate deposits indicative of increased salinity as lake level dropped and littoral areas became increasingly exposed (Moreno *et al.*, 2007). This dry event at Lago Chungará is coeval with a similar dry phase indicated by increased percentage of benthic diatoms at Lago Titicaca (Baker *et al.*, 2001) and by the *Laguna Seca* pollen record (see Fig. 1 for location), in the immediate vicinity of Lago Chungará beginning at ca. 9000 cal. a BP (Baied and Wheeler, 1993). Clearly, the northern Chilean Altiplano was affected by at least one major dry spell around 9500–9000 cal. a BP. Even this 500–1000 a dry spell seems to have influenced human occupation at Hakenasa, as clearly shown by an overall decrease in tool count in a later phase of the Early Archaic at Hakenasa (level 10; 9960–9595 cal. a BP; LeFebvre, 2004).

### A possible gap in the human occupation sequence at Hakenasa cave

Juxtaposed between the first human occupational levels of the cave (Early Archaic) and the Late Archaic period, two culturally sterile episodes, embodied by stratigraphic levels 8 and 9, occur (Table 1 and Fig. 2). These levels are constituted by sands and gravels of fluvial origin which coarsen first then fine upwards. Initial sedimentary analyses indicated that the sequence resulted from a single flood event (LeFebvre, 2004). Hence the lack of cultural remains at this time interval was interpreted by LeFebvre (2004, p. 51) as resulting from the erosion of older archaeological levels from the cave. In contrast, based on new AMS radiocarbon dates we believe that this interpretation is now incorrect. The gravels and sands most likely accumulated continuously without a major break in cave sedimentation or removal of cave sediment. Thus, the most likely explanation for the lack of human remains is a gap in the cultural occupation of the cave.

Dates from the 2001 excavation (along with three dates from 1983) (Table 1) were based on material extracted from a single quadrat. These dates bracketed the flood as occurring between 9960 and 5710 cal. a BP. Radiocarbon samples obtained in 2007 from adjoining quads (N1E0 and N2E1) at the junctures of levels 7 and 8, and 9 and 10 (8 and 9 were sterile), date the flood more precisely from 7870 to 6890 cal. a BP (Table 1). The juncture of these levels had a few scant charcoal remains,

micro-flakes and some bones, but no artefacts. Therefore, the top of level 10 – base of the sterile level 9 and the top of level 8 – and the base of the cultural level 7 are considered the last and first human occupation of the cave, before and after the flood, respectively.

Coeval with the Hakenasa cultural gap, offshore carbonate precipitation reaches a maximum at Lago Chungará (Fig. 3). This major sedimentological change indicates extreme aridity at about 7500 cal. a BP in the Lago Chungará watershed (Moreno *et al.*, 2007) which lasted until ca. 6500 cal. a BP (the phase marked as 'very dry' in Fig. 3). Dry conditions, however, were not sustained over this period but characterised instead by a series of short and rapid dry spells, marked by Ca/Ti or calcite percentage peaks. These relatively short intervals of alternating arid and wet events are indicative of increased climate variability with occasional extreme events. Catastrophic floods, such as the one recorded by gravel and sandy sediment layers at Hakenasa, are to be expected under such a climate.

Many different (and contradictory) interpretations of mid Holocene climate have arisen from the diverse palaeoclimate records across northern Chile (see Grosjean *et al.*, 2003, 2005, 2007; Latorre *et al.*, 2005, 2007). The long-held view is that arid conditions prevailed from the early (ca. 9000 cal. a BP) to mid Holocene (ending at about 4000 cal. a BP). This view has been challenged repeatedly by different researchers (Betancourt *et al.*, 2000; Holmgren *et al.*, 2001; Grosjean, 2001, *versus* Quade *et al.*, 2001; Placzek *et al.*, 2001; Latorre *et al.*, 2002, 2003, 2005; Rech *et al.*, 2002, 2003). For example, slight differences exist between the timing of low lake levels at Lago Titicaca (8500–4500 cal. a BP, with the lowest lake levels occurring from 6000 to 5000 cal. a BP; Baker *et al.*, 2001; Cross *et al.*, 2001; Tapia *et al.*, 2003) and Lago Chungará (7500–6500 cal. a BP). These differences could arise either by discrepancies between the different chronologies or as a result of a complex mid Holocene climate signal recorded in different environments and palaeoclimate proxies. For example, estimates of minimum annual rainfall obtained from past plant species distributions at Río Salado (22°S) along the upper margin of the Atacama Desert indicate several pronounced episodes of increased rainfall between 7600 and 6700 cal. a BP (Fig. 3 and Latorre *et al.*, 2006). Temperatures also may have increased on the Altiplano by as much as 3°C, as witnessed by the greater pollen influx of cloud forest taxa, most likely resulting from elevated treeline (which today lies ~600 m below the elevation of the lake today) into the Titicaca Basin between 7960 and 3100 cal. a BP (Paduano *et al.*, 2003). Interestingly, human cultures flourished in coastal and low-altitude areas of northern Chile during the mid Holocene period (ca. 8000–5000 cal. a BP) (Fig. 3; Standen *et al.*, 2004; Santoro *et al.*, 2005).

Finally, increased volcanic activity as deduced from the rise of Fe and the presence of several tephra layers in the Lago Chungará sedimentary sequence began at 6000 cal. a BP (Figs 3 and 4). Although increased volcanic activity in terms of ash and smoke may have impacted and/or influenced occupation of Hakenasa cave, this is refuted somewhat by the resettlement of people in the area after 6000 cal. a BP (increase in artefacts in

level 7; LeFebvre, 2004), despite intense volcanic activity, and the avenue of newly cultural traditions.

Additionally, environmental conditions on the Altiplano seemed to have improved at the beginning of the Late Archaic (6000 cal. a BP). Sustained wetter climate conditions are inferred from the palaeoclimate record at Lago Chungará, mainly by the decrease of carbonate precipitation in the lake (Fig. 3 and Moreno *et al.*, 2007). However, the dominance of volcanic layers in the Chungará record during the last 5000 a precludes a clear climate interpretation for this period. Therefore, other factors may be considered to explain the intensification of human activity at Hakenasa (LeFebvre, 2004), as well as Asana (Aldenderfer, 1998); Patapatane, Piñuta, Guañure and Puxuma (Santoro, 1987, 1989; Santoro and Núñez, 1987).

By the same token, in the succeeding level 6 at Hakenasa (4770–4620 cal. a BP), there is an important drop in total tool count and weight of faunal remains (LeFebvre, 2004). This change in the archaeological record corresponds to evidence for short droughts in the Lago Chungará record, related to the precipitation of authigenic calcite at ca. 4300 and 5200 cal. a BP (Fig. 4 and Table 2). This also coincides chronologically with the second most arid period on the Lago Titicaca record at about 4500 cal. a BP (Baker *et al.*, 2001) and with the drought at 4865 cal. a BP at Río Salado (Latorre *et al.*, 2006). Consistent with regional cultural processes, the appearance of ceramics in level 5 (4230–3870 cal. a BP) (LeFebvre, 2004) marks the end of the Late Archaic and certainly resulted in changes in food preparation and storage, and the introduction of new objects and technologies (pottery, beads, metal pieces; Santoro and Núñez, 1987).

## Conclusions

The combination of palaeoclimate and archaeological data from different sources provides a solid interdisciplinary framework for understanding palaeoclimate as a driving agent along with other factors in prompting cultural change. We also point out that the pattern of regional climate change in northern Chile was complex and stress the need for further increased high-resolution records of past climate that could lead to additional relationships with local records of past cultural change. In general terms, the sequence of Lago Chungará with wet (11 000–7500; 6000–4000 cal. a BP) and dry phases (the driest period at 7500–6000 cal. a BP; shorter dry spells at about 9500, 4300 and 5200 cal. a BP) coincides with important changes in the cultural history of the Altiplano as seen in Hakenasa (Table 2) and other caves.

Human colonisation of highland habitats observed at Hakenasa cave at 11 265–11 619 cal. a BP coincides with a high lake biomass production phase as inferred from the Lago Chungará palaeoclimate record between 11 000 and 7500 cal. a BP. This is in agreement with other records such as Lago Titicaca and Río Salado, which indicate the onset of the

**Table 2** Palaeoclimatic variation and major cultural epochs for the northern Chilean Altiplano

Time period (cal. a BP)	Palaeoecological condition	Cultural epoch
12,000–7,500	Wetter and warmer (with short dry episodes starting at about 9500 cal. a BP)	Early Archaic
7,500–6,000	Very dry and unstable	Middle Archaic
6,000–4,000	Wetter and with more volcanic activity. Two short dry episodes at 4300 and 5200 cal. a BP	Late Archaic

Holocene as characterised by wet climate conditions in the northern Chilean Altiplano. Under those circumstances, human colonisation of the upper ecological zones along the western slopes of the Andes was feasible.

From 7500 to 6500 cal. a BP, a dry and highly unstable climate is clearly documented in the Lago Chungará record. Such conditions may have triggered catastrophic floods like the one recorded at Hakenasa, creating a cultural gap in the human occupational sequence. At this point, and considering that Hakenasa is the first site in the dry Puna where this gap is well defined chronologically, we propose a period of short abandonment. If this is the case, changes in the Early Archaic cultural dynamics would have been the consequence of diminished biotic resources in the region owing to prolonged drought interrupted by short catastrophic floods that provoked the inundation of the cave. This would have made the shelter unfeasible as a base hunting camp site, for roughly over a millennium (levels 8 and 9; 7500–6500 cal. a BP; Tables 1 and 2).

Finally, increased human activity at Hakenasa evident in level 7 (6000 cal. a BP) and later is not clearly related to local environmental change. In fact, other environmental factors such as volcanic activity intensified throughout the mid to late Holocene but these did not have any noticeable deleterious effects at Hakenasa. In conclusion, it is clear that early human settlement patterns responded to fluctuating climatic conditions before 6000 cal. a BP in this extreme environment. Posterior climate changes and volcanic activity, however, seemed to have had little or no impact on the Hakenasa cave cultural sequence.

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## References

- Abbott MB, Seltzer GO, Kelts K, Southon J. 1997. Holocene paleohydrology of the tropical Andes from Lake Records. *Quaternary Research* **47**: 70–80.
- Agüero C. 2005. Aproximación al asentamiento humano temprano en los oasis de San Pedro de Atacama. *Estudios Atacameños* **30**: 29–60.
- Aldenderfer MS. 1988. Middle Archaic period domestic architecture from southern Peru. *Science* **241**: 1828–1830.
- Aldenderfer MS. 1989. The archaic period in the South-Central Andes. *Journal of World Prehistory* **3**: 117–158.
- Aldenderfer MS. 1998. *Montane Foragers: Asana and the South-Central Andean Archaic*. University of Iowa Press: Iowa City, IA.
- Allison JR. 1996. Comments on the impacts of climatic variability and population growth on Virgin Anasazi cultural development. *American Antiquity* **61**: 414–418.
- Anderson D, Maasch K, Sandweiss D. 2007. *Climate Change and Cultural Dynamics: A Global Perspective on Mid-Holocene Transitions*. Academic Press: San Diego, CA.
- Baied CA, Wheeler JC. 1993. Evolution of high Andean Puna ecosystem environment, climate and culture change over the last 12 000 years in the Central Andes. *Mountain Research and Development* **13**: 145–156.
- Baker PA, Seltzer GO, Fritz SC, Dunbar RB, Grove MJ, Tapia PM, Cross SL, Rowe HD, Broda JP. 2001. The history of South American tropical precipitation for the past 25 000 years. *Science* **291**: 640–643.
- Baker PA, Fritz SC, Garland J, Ekdahl E. 2005. Holocene hydrologic variation at Lake Titicaca, Bolivia/Peru, and its relationship to North Atlantic climate variation. *Journal of Quaternary Science* **20**: 655–662.
- Betancourt JL, Latorre C, Rech JA, Quade J, Rylander KA. 2000. A 22,000-year record of monsoonal precipitation from Northern Chile's Atacama Desert. *Science* **289**: 1542–1546.
- Binford MW, Kolata AL, Brenner M, Janusek JW, Seddon MT, Abbott M, Curtis JH. 1997. Climate variation and the rise and fall of an Andean civilisation. *Quaternary Research* **47**: 235–248.
- Bobst AL, Lowenstein TK, Jordan TE, Godfrey LV, Ku TL, Luo S. 2001. A 106 ka paleoclimate record from drill core of the Salar de Atacama, northern Chile. *Palaeogeography, Palaeoclimatology, Palaeoecology* **173**: 21–42.
- Bradley R, Vuille M, Hardy DR, Thompson LG. 2003. Low latitude ice cores record Pacific sea surface temperatures. *Geophysical Research Letters* **30**: 1174.
- Burroughs WJ. 2005. *Climate Change in Prehistory: The End of the Reign of Chaos*. Cambridge University Press: Cambridge, UK.
- Cross SL, Baker PA, Seltzer GO, Fritz SC, Dunbar RB. 2001. Late Quaternary climate and hydrology of tropical South America inferred from an isotopic and chemical model of lake Titicaca, Bolivia and Peru. *Quaternary Research* **56**: 1–9.
- DeFrance SD, Umire A. 2004. Quebrada Tacahuay: un sitio marítimo del Pleistoceno tardío en la costa sur del Perú. *Chungara Revista de Antropología Chilena* **36**: 257–278.
- De Souza P. 2004. Cazadores recolectores del Arcaico Temprano y Medio en la cuenca superior del río Loa: Sitios, conjuntos líticos y sistemas de asentamientos. *Estudios Atacameños* **27**: 7–43.
- Dillehay TD. 2002. Climate and human migrations. *Science* **298**: 764–765.
- Dillehay TD, Ramirez C, Pino M, Collins MB, Rossen J, Pino-Navarro JD. 2008. Monte Verde: seaweed, food, medicine, and the peopling of South America. *Science* **320**: 784–786.
- Dirksen VG, van Geel B. 2005. Mid to late Holocene climate change and its Influence on cultural development in south central Siberia. In *Impact of the Environment on Human Migration in Eurasia*. Scott EM, Alekseev AY, Zaitseva G (eds). Springer: Amsterdam; 291–307.
- Fritz SC, Baker A, Tapia PM, Garland J. 2006. Spatian and temporal variation in cores from Lake Titicaca, Bolivia/Peru during the last 13 000 yrs. *Quaternary International* **158**: 23–29.
- Garreaud RD, Vuille M, Clement AC. 2003. The climate of the Altiplano: observed current conditions and mechanisms of past changes. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 5–22.
- Geyh MA, Grosjean M, Núñez L, Schotterer U. 1999. Radiocarbon reservoir effect and the timing of the Late-Glacial/Early Holocene Humid phase in the Atacama desert Northern Chile. *Quaternary Research* **52**: 143–153.
- Giralt S, Moreno A, Bao R, Sáez A, Prego R, Valero-Garcés BL, Pueyo-Mur JJ, González-Sampérez P, Taberner C. 2008. A statistical approach to disentangle environmental forcings in a lacustrine record: the Lake Chungará case (Chilean Altiplano). *Journal of Paleolimnology* **40**: 195–215.
- Grosjean M. 2001. Mid-Holocene climate in the South-Central Andes: humid or dry? *Science* **292**: 2391–2392.
- Grosjean M, Núñez L, Cartajena I, Messerli B. 1997. Mid-Holocene climate and culture change in the Atacama Desert, northern Chile. *Quaternary Research* **48**: 239–246.
- Grosjean M, van Leeuwen JFN, van der Knaap WO, Geyh MA, Ammann B, Tanner W, Messerli B, Núñez L, Valero-Garcés BL, Veit H. 2001. A 22 000 <sup>14</sup>C year BP sediment and pollen record of climate

- change from Laguna Miscanti (23° S), northern Chile. *Global and Planetary Change* **28**: 35–51.
- Grosjean M, Cartajena I, Geyh MA, Núñez L. 2003. From proxy data to paleoclimate interpretation: the mid-Holocene paradox of the Atacama Desert, northern Chile. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 247–258.
- Grosjean M, Núñez L, Cartajena I. 2005. Cultural response to climate change in the Atacama Desert. In *23° South: Archaeology and Environmental History of the Southern Deserts*, Smith M, Hesse P (eds). National Museum of Australia Press: Canberra; 156–171.
- Grosjean M, Santoro CM, Thompson LG, Núñez L, Standen VG. 2007. Mid-Holocene climate and cultural change in the South-Central Andes. In *Climate Change and Cultural Dynamics: A Global Perspective on Holocene Transitions*, Anderson G, Sandweiss DF, Maasch KA (eds). Academic Press: San Diego, CA; 51–115.
- Haug GH, Günther D, Peterson LC, Sigman DM, Hughen KA, Aeschlimann B. 2003. Climate and the collapse of Maya Civilization. *Science* **299**: 1731–1735.
- Heegaard E, Birks HJB, Telford RJ. 2005. Relationships between calibrated ages and depth in stratigraphical sequences: an estimation procedure by mixed-effect regression. *The Holocene* **15**: 612–618.
- Hodell DA, Brenner M, Curtis JH, Guilderson TP. 2001. Solar forcing of drought frequency in the Maya Lowlands. *Science* **292**: 1367–1370.
- Holmgren CA, Betancourt JL, Rylander KA, Roque J, Tovar O, Zeballos H, Linares E, Quade J. 2001. Holocene vegetation history from fossil rodent middens near Arequipa, Peru. *Quaternary Research* **56**: 242–251.
- Hora JM, Singer BS, Wörner G. 2007. Volcano evolution and eruptive flux on the thick crust of the Andean Central Volcanic Zone: <sup>40</sup>Ar/<sup>39</sup>Ar constraints from Volcán Parínacota, Chile. *GSA Bulletin* **119**: 343–362.
- Kerr RA. 1999. El Niño grew strong as cultures were born. *Science* **283**: 467–468.
- Kirch PV. 2005. Archaeology and global change: the Holocene record. *Annual Review of Environment and Resource* **30**: 409–440.
- Lambrinos JG, Kleier CC, Rundel PW. 2006. Plant community variation across a puna landscape in the Chilean Andes. *Revista Chilena de Historia Natural* **79**: 233–243.
- Latorre C, Betancourt JL, Rylander KA, Quade J. 2002. Vegetation invasions into Absolute Desert: A 45,000-yr rodent midden record from the Calama-Salar de Atacama Basins, northern Chile (22–24° S). *Geological Society of America Bulletin* **114**: 349–366.
- Latorre C, Betancourt JL, Rylander KA, Quade J, Matthei O. 2003. A vegetation history from the arid prepuna of northern Chile 22–23°S over the last 13 500 years. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 223–246.
- Latorre C, Betancourt JL, Rech JA, Quade J, Holmgren C, Placzek C, Maldonado A, Vuille M, Rylander KA. 2005. Late Quaternary history of the Atacama Desert. In *23° S: The Archaeology and Environmental History of the Southern Deserts*, Smith M, Hesse P (eds). National Museum of Australia Press: Canberra; 73–90.
- Latorre C, Betancourt JL, Arroyo MTK. 2006. Late Quaternary vegetation and climate history of a perennial river canyon in the Río Salado basin 22° S of northern Chile. *Quaternary Research* **65**: 450–466.
- Latorre C, Moreno PI, Maldonado AJ, Villa-Martínez R, Villagrán C, Armesto JJ, Vargas G, Pino M, Grosjean M, Núñez L. 2007. Late Quaternary environments and paleoclimate. In *The Geology of Chile*, Gibbons W, Moreno T (eds). London Geological Society: London; 311–330.
- LeFebvre RP. 2004. *Hakenasa: the archaeology of a rock shelter in the Altiplano of Northern Chile*. 226 pp, PhD dissertation. University Microfilms International, Ann Arbor, MN.
- Lowenstein TK, Hein MC, Bobst AL, Jordan TE, Ku TL, Luo S. 2003. An assessment of stratigraphic completeness in climate-sensitive closed-basin lake sediments: Salar de Atacama, Chile. *Journal of Sedimentary Research* **73**: 91–104.
- Maldonado A, Betancourt JL, Latorre C, Villagrán C. 2005. Pollen analyses from a 50 000-yr rodent midden series in the southern Atacama Desert 25° 30' S. *Journal of Quaternary Science* **20**: 493–507.
- Méndez CA, Jackson DG. 2006. Causalidad o concurrencia, relaciones entre cambios ambientales y sociales en los cazadores recolectores durante la transición entre el Holoceno medio y tardío (costa del semiárido de Chile). *Chungara Revista de Antropología Chilena* **38**: 173–184.
- Moreno A, Giral S, Valero-Garcés BL, Sáez A, Bao R, Prego R, Pueyo-Mur JJ, González-Sampériz P, Taberner C. 2007. A 14-kyr record from the tropical Andes: the Lago Chungara sequence 18° S, northern Chilean Altiplano. *Quaternary International* **161**: 4–21.
- Moy CM, Seltzer GO, Rodbell DT, Anderson DM. 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* **420**: 162–165.
- Núñez L. 2005. La naturaleza de la expansión aldeana durante el Formativo Tardío en la cuenca de Atacama. *Chungara Revista de Antropología Chilena* **37**: 165–193.
- Núñez L, Santoro C. 1988. Cazadores de la Puna Seca y Salada del Area Centro-Sur Andina (Norte de Chile). *Estudios Atacameños* **9**: 11–60.
- Núñez L, Santoro C. 1990. Primeros poblamientos en el cono sur de América. *Revista de Arqueología Americana* **1**: 91–139.
- Núñez L, Grosjean M, Messerli B, Schreier H. 1996. Cambios Ambientales Holocénicos en la Puna de Atacama y sus Implicancias Paleoclimáticas. *Estudios Atacameños* **12**: 31–40.
- Núñez L, Grosjean M, Cartajena I. 2002. Human occupations and climate change in the Puna de Atacama, Chile. *Science* **298**: 821–824.
- Nuñez L, Cartajena I, Carrasco C, de Souza P, Grosjean M. 2006. Emergencia de comunidades pastoralistas formativas en el sureste de la Puna de Atacama. *Estudios Atacameños* **32**: 93–117.
- Paduano GM, Bush MB, Baker PA, Fritz SC, Seltzer GO. 2003. A vegetation and fire history of Lake Titicaca since the Last Glacial Maximum. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 259–279.
- Placzek C, Quade J, Patchett PJ. 2006. Geochronology and stratigraphy of late Pleistocene lake cycles on the southern Bolivian Altiplano: implications for causes of tropical climate change. *Geological Society of America Bulletin* **118**: 515–532.
- Quade J, Rech J, Betancourt J. 2001. Reply to Comments by M. Grosjean, Mid-Holocene climate in the central Atacama: humid or dry? *Science* **292**: 2391–2392.
- Rech J, Quade J, Betancourt JL. 2002. Late Quaternary paleohydrology of the central Atacama Desert 22–24° S, Chile. *Geological Society of America Bulletin* **114**: 334–348.
- Rech J, Pigati JS, Quade J, Betancourt JL. 2003. Re-evaluation of mid-Holocene wetland deposits at Quebrada Puripica, northern Chile. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 207–222.
- Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Bertrand CJH, Blackwell PG, Buck CE, Burr GS, Cutler KB, Damon PE, Edwards RL, Fairbanks RG, Friedrich M, Guilderson TP, Hogg AG, Hughen KA, Kromer B, McCormac G, Manning S, Ramsey CB, Reimer RW, Remmele S, Southon JR, Stuiver M, Talamo S, Taylor FW, van der Plicht J, Weyhenmeyer CE. 2004. IntCal04 terrestrial radiocarbon age calibration, 0 to 26 cal. kyr BP. *Radiocarbon* **46**: 1029–1058.
- Rigsby CA, Baker PA, Aldenderfer MS. 2003. Fluvial history of the Rio llave valley, Peru, and its relationship to climate and human history. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 165–185.
- Rundel PW, Palma B. 2000. Preserving the unique puna ecosystems of the Andean Altiplano. *Mountain Research and Development* **20**: 262–271.
- Sáez A, Valero-Garcés BL, Moreno A, Bao R, Giral S, Pueyo-Mur JJ, Taberner C, Herrera C, Schwalb A, González-Sampériz P, Gilbert RO, Wörner G. 2007. Climatic and volcanic controls on the Holocene sedimentation of Chungará lake, Altiplano of Andes. *Sedimentology* **54**: 1191–1222.
- Sandweiss DH. 2003. Terminal Pleistocene through Mid-Holocene archaeological sites as paleoclimatic archives for the Peruvian coast. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 23–40.
- Sandweiss DH, Maasch KA, Burger RL, Richardson JB II, Rollins HB, Clement A. 2001. Variation in Holocene El Niño frequencies: climate records and cultural consequences in ancient Peru. *Geology* **7**: 603–606.
- Santoro C. 1987. *Settlement patterns of Holocene hunting and gathering societies in the South Central Andes*. Master's thesis, Department of Anthropology, Cornell University.

- Santoro C. 1989. Antiguos cazadores de la Puna. In *Culturas de Chile desde sus Orígenes hasta los Albores de la Conquista*, Hidalgo J, Niemeyer H, Schiappacasse V, Aldunate C, Solimano I (eds). Andrés Bello: Santiago. 33–56.
- Santoro CM, Núñez L. 1987. Hunters of the dry Puna and the salt Puna in northern Chile. *Andean Past* **1**: 57–109.
- Santoro CM, Standen VG, Arriaza BT, Marquet PA. 2005. Hunter-gatherers on the coast and hinterland of the Atacama Desert 17–27° south latitude. In *23° South: The Archaeology and Environmental History of the Southern Desert*, Smith M, Hesse P (eds). National Museum of Australia: Canberra; 172–185.
- Servant M, Servant-Vildary S. 2003. Holocene precipitation and atmospheric changes inferred from river paleowetlands in the Bolivian Andes. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 187–206.
- Seyfried H, Wörner G, Uhlig D, Kohler I, Calvo C. 1998. Introducción a la geología y morfología de los Andes en el norte de Chile. *Chungara Revista Antropología Chilena* **30**: 7–39.
- Shennan S, Edinborough K. 2007. Prehistoric population history: from the Late Glacial to the Late Neolithic in Central and Northern Europe. *Journal of Archaeological Science* **34**: 1339–1345.
- Standen V, Santoro CM, Arriaza BT. 2004. Síntesis y propuestas para el período Arcaico en el extremo norte de Chile. *Chungara Revista de Antropología Chilena Volumen Especial* **36** special supplement: 201–212.
- Tapia PM, Fritz SC, Baker PA, Seltzer GO, Dunbar RB. 2003. A late Quaternary diatom record of tropical climatic history from Lake Titicaca Peru and Bolivia. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 139–164.
- Thompson LG, Davis M, Mosley-Thompson E, Sowers T, Henderson KA, Zagorodnov VS, Lin P-N, Mikhailenko VN, Campen RK, Bolzan JF, Cole-Dai J, Francou B. 1998. A 25 000-year tropical climate history from Bolivian ice cores. *Science* **282**: 58–64.
- Troll C. 1958. Las Culturas Superiores Andinas y el Medio Geográfico, translated by C. Nicholson. *Revista del Instituto de Geografía* **5**: 3–49.
- Turney CSM, Hobbs D. 2006. ENSO influence on aboriginal populations in Queensland, Australia. *Journal of Archaeological Science* **33**: 1744–1748.
- Valero-Garcés BL, Grosjean M, Kelts K, Schreir H, Messerli B. 1999. Holocene lacustrine deposition in the Atacama Altiplano: facies models, climate and tectonic forcing. *Palaeogeography, Palaeoclimatology, Palaeoecology* **151**: 101–125.
- Villagrán C, Castro C, Sánchez G, Hinojosa F, Latorre C. 1999. La tradición altiplánica: estudio etnobotánico en los Andes de Iquique, Primera Región, Chile. *Chungara Revista Antropología Chilena* **31**: 86–186.
- Vuille M. 1999. Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the Southern Oscillation. *International Journal of Climatology* **19**: 1579–1600.
- Vuille M, Bradley RS, Healy R, Werner M, Hardy DR, Thompson LG, Keimig F. 2003. Modeling  $\delta^{18}\text{O}$  in precipitation over the tropical Americas. 2. Simulation of the stable isotope signal in Andean ice cores. *Journal of Geophysical Research* **108**: 4175.
- Williams A, Santoro CM, Smith MA, Latorre C. 2008. The impact of ENSO in the Atacama Desert and Australian arid zone: exploratory time-series analysis of archaeological records. *Chungara Revista de Antropología Chilena* **40**: (in press).