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Late Quaternary hydrological and ecological changes in the hyperarid core of the northern Atacama Desert (~21°S)

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ABSTRACT

The hyperarid core of the Atacama Desert possesses important reserves of "fossil" or ancient groundwater, yet the extent and timing of past hydrologic change during the late Quaternary is largely unknown. *In situ* and/or short-distance transported leaf-litter deposits abound along relict fluvial terraces inserted within four dry and unvegetated valleys that drain into the endorheic basin of Pampa del Tamarugal (PDT, 21°S, 900–1000 m), one of the largest and economically important aquifers in northern Chile. Our exceptional archive offers the opportunity to evaluate the response of low-elevation desert ecological and hydrological systems to late Quaternary climate variability. Three repeated expansions of riparian/wetland ecosystems, and perennial rivers occurred along the southernmost PDT basin between 17.6–14.2 ka, 12.1–11.4 ka and from 1.01–0.71 ka. Both early and late archaic archaeological artefact are present in clear association with our fossil riparian/wetland assemblages, which suggests that these palaeoenvironmental changes facilitated past human occupations in the hyperarid core of the Atacama Desert. Using modern analogues, we estimate that these ecological and hydrological changes were triggered by a threefold increase in rainfall along the headwaters of what are presently inactive canyons. Comparisons with other regional palaeoclimatic records from the central Andes indicate that these changes were synchronous with the widespread pluvial stages now termed the Central Andean Pluvial Event (CAPE— 17.5–14.2 ka and 13.8–9.7 ka). In addition, we summarize new evidence for perennial runoff, riparian ecosystems and a major human settlement during the latest Holocene. Our findings clearly show that local hydrological changes in the PDT were coupled with precipitation variability in the adjacent eastern highlands during the late Quaternary. The long-term dynamics of low-elevation desert ecological and hydrological systems are likely driven by changes in moisture sources, with one source tied to the Amazon region (N–NE mode) and the other to the Gran Chaco region (SE mode). We conclude by linking ENSO-like variability and moisture variations over the Gran Chaco to the three major regional-scale recharge events over the last 18 ka in the PDT basin. We conclude by asserting that an important portion of the groundwater resources in the PDT is indeed fossil, inherited from past pluvial events. We recommend that the relationship between ancient recharge, together with palaeoclimate records of past headwater rainfall fluctuations should be incorporated into future water-balance models and evaluation of groundwater potential in northern Chile.

Contents

Abbreviations: PDT, Pampa del Tamarugal; CAPE, Central Andean Pluvial Event; WAC, Western Andean Cordillera; SM, Sierra de Moreno; AdP Fm, Alto de Pica Formation; SASM, South American Summer Monsoon; QM, Quebrada Maní; QS, Quebrada Sipuca; QT, Quebrada Tambillo; LdS, Lomas de Sal; SI, Similarity Index; SD, standard deviation; SDA, Salar de Atacama; SPN, Salar de Punta Negra; mBGL, meter Below Groundwater Level.

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1. Introduction

By definition, arid regions are always under permanent negative water balance. Yet, these regions also experience major fluctuations in potential evapotranspiration and/or precipitation at different timescales (*e.g.* Lioubimtseva, 2004). The dry central Andes Mountains and adjacent hyperarid Atacama Desert (16°–28°S) have not been an exception. During the late Quaternary, these regions experienced an alternation of arid and wetter conditions (aka pluvial events). Two families of hypotheses have been proposed to explain these patterns. The first is that these resulted as a consequence of low latitude insolation changes over South America and changes in north Atlantic sea surface temperatures (*e.g.* Martin et al., 1997; Baker et al., 2001; Fritz et al., 2004). The second set of hypothesis proposes that pluvial events are driven by insolation changes over the tropical Pacific coupled with atmospheric circulation anomalies along eastern subtropical South America (*e.g.* Latorre et al., 2002; Rech et al., 2002; Quade et al., 2008). According to this hypothesis, the wet (dry) phases in the Atacama Desert are linked to sustained increases (decreases) in summer rainfall forced by enhanced (decreased) tropical Pacific SST gradient and/or increased (decreased) moisture availability in the Gran Chaco basin. Both mechanisms are known major drivers of modern inter-annual and inter-decadal rainfall variability over the central Andes (Vuille et al., 2000; Garreaud et al., 2003; Vuille and Keimig, 2004).

Due to the sensitivity of the central Andes and Atacama Desert to ENSO-like variability, palaeoclimatic reconstructions in these areas have helped elucidate the role of the tropics in driving global climate changes at millennial timescales (Cane and Clement, 1999; Clement and Cane, 1999; Clement et al., 1999; Latorre et al., 2006; Placzek et al., 2006; Quade et al., 2008; Placzek et al., 2009). Furthermore, these reconstructions in concert with palaeoecological studies have provided new insights into the long-term dynamics of local aquifers and lacustrine systems and revealed the extraordinary adaptive capacity of regional ecosystems as well as human societies.

Dramatic changes occurred at 18–9.7 ka in rodent populations and in the latitudinal and altitudinal distributions of plant communities above 2000 m of elevation throughout the western slope of the Andes between 22° and 25°S (Betancourt et al., 2000; Kuch et al., 2002; Latorre et al., 2002, 2003, 2005; Maldonado et al., 2005; Latorre et al., 2006; González, 2008; Quade et al., 2008; Latorre et al., 2009). Palaeohydrological evidence from the central Atacama Desert (22°–24°S) indicates major changes in local water table heights between 15.9 and 9 ka (Betancourt et al., 2000; Bobst et al., 2001; Rech et al., 2002; Lowenstein et al., 2003; Quade et al., 2008). Past lake level fluctuations inferred from abandoned beach terraces indicate several highstands between 18 and 11 ka across the Altiplano (Geyh et al., 1999; Sylvestre et al., 1999; Placzek et al., 2006; 2009). Indeed, such widespread evidence and matching chronologies between these different records have led several authors to postulate that a "Central Andean Pluvial Event" (CAPE) occurred more or less synchronously throughout the region (Latorre et al., 2006; Quade et al., 2008; Placzek et al., 2009).

The impact that these multi-millennial changes in precipitation had on the adjacent lowlands (<2000 m) remains poorly known. Palaeoclimate studies on the timing and impact of past rainfall variability in the lower elevation Atacama Desert are practically non-existent. Examples of questions about potential impacts for which answers are lacking include: did enhanced precipitation at higher altitudes generate a series of flushing events in their aquifers, shifting surface runoff, local water tables and distribution of biota? Is there a relationship between climate change in the lower elevation desert and in the highland central Andes during the late Quaternary? How did past rainfall variability affect the long-term dynamics of these hydrological systems and associated ecosystems? What are the implications of past climate changes for the biogeography of desert communities and modern hydrology?

To answer these questions, we have been studying organic-rich deposits collected along abandoned fluvial terraces inset within hyperarid and plantless canyons that drain into the low-elevation endorheic basin of Pampa del Tamarugal (PDT). In a preliminary report, we presented a palaeoenvironmental and geomorphologic interpretation of fluvial terraces and associated chronology (Nester et al., 2007). Among our major findings were that between 17.4–14.2, ~11.8 and around 1.1–0.7 ka, three repeated expansions of riparian vegetation, associated perennial river-flow and increased local groundwater tables, occurred in the PDT that were synchronous with major pluvial events in the central Andes.

In this paper, we: (1) expand our previous reconstructions on the timing and impact of past climate changes in the northern Atacama Desert with new radiocarbon and macrofossil analyses obtained from 18