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Chronology, stratigraphy and hydrological modelling of extensive wetlands and paleolakes in the hyperarid core of the Atacama Desert during the late quaternary

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ABSTRACT

The halite-encrusted salt pans (*salars*) present at low elevations in the hyperarid core of the Atacama Desert in northern Chile are unique features of one of the driest and possibly oldest deserts on Earth. Here we show that these landscapes were shallow freshwater lakes and wetlands during the last glacial period and formed periodically between ~46.9 ka and 7.7 ka. The moisture appears to have been sourced from increased Andean runoff and most of our chronologies for these deposits were coeval with the Central Andean Pluvial Event (17.5–14.2 ka and 13.8–9.7 ka), but we also find evidence for older as well as slightly younger wet phases. These environments supported a diverse hygrophytic-halophytic vegetation, as well as an array of diatoms and gastropods. Using a regional hydrological model, we estimate that recharge rates from 1.5 to 4 times present were required to activate and maintain these wetlands in the past. Activation in the late Pleistocene was part of a regional enhancement of water resources, extending from the Andes, downstream and through riparian corridors, to the lowest and most arid portions of the desert itself. This fundamentally unique environment was encountered by the earliest human explorers in the region, and most likely facilitated migration and encampments on a landscape that at present lacks macroscopic life on its surface.

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1. Introduction

The Atacama Desert has experienced hyperarid, and nearly lifeless, conditions for much of the past several million years (Hartley et al., 2005; Jordan et al., 2014). The most severe aridity has been maintained in an inland forearc basin known as the Central Depression (Fig. 1), where an absolute desert (e.g. without

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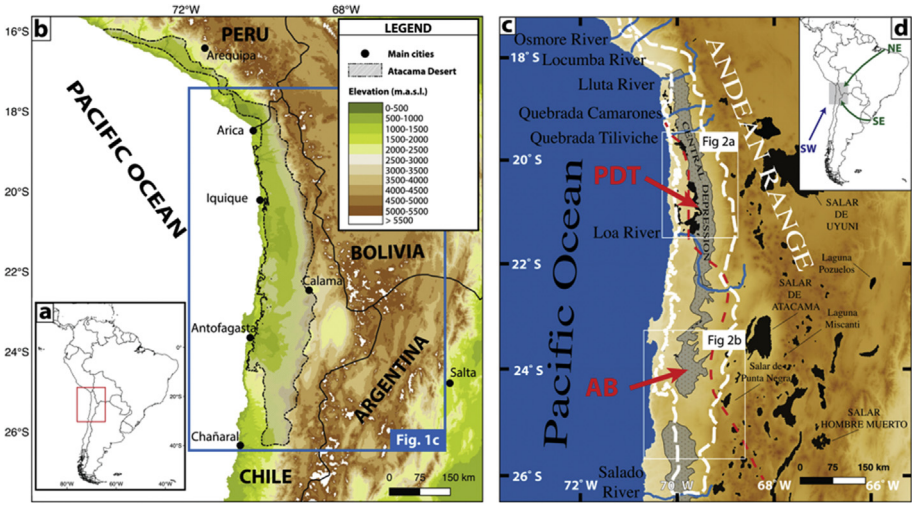

Fig. 1. a) Map of South America showing the location of the Atacama Desert, red box corresponds to b) altitudinal map showing the location of the Atacama Desert in southern Peru and northern Chile with inset box of figure in c) overview map of the Atacama Desert and the Central Andes Region illustrating the location of salars (black polygons), perennial streams (blue lines), the Central Depression (dotted gray polygons), the absolute desert (dashed white line), the boundary (red dashed line) between summer (north-east) and winter (south-west) precipitation sources and the location of the Pampa del Tamarugal (PDT) and Aguas Blancas (AB) basins. Salars discussed in the text are labelled. The two insets correspond to details of the PDT and AB basins detailed in Fig. 2a and b respectively. d) Map of South America showing the moisture sources that impact the Atacama Desert and Central Andes Region. Tropical (summer) sources are indicated in green, and the extra tropical (winter) source is indicated in blue. The gray box corresponds to the inset of figure in 1c. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

macroscopic life across most of its surface) presently exists (18–26° S) (Gajardo, 1994; Marquet et al., 1998; Luebert and Pliscoff, 2006). In the Central Depression, the presence of Miocene and Pliocene alluvial deposits impregnated with highly soluble salts attests to the limited dilution by rainwater during a protracted interval (Rech et al., 2003b; Ewing et al., 2006; Amundson et al., 2012; Jordan et al., 2014).

One of the prominent geomorphic features of the Central Depression are large salt-encrusted landscapes (salt flats-salt encrusted playa) that cover basins, which are termed *salar* in Spanish. These rough, and sometimes nearly impassable, landscapes have rugged efflorescent crusts of nearly pure halite up to 0.5 m in thickness. In general, it is well understood that salars form largely by the evaporation of shallow groundwater and the subsequent redeposition of salts (Stoertz and Ericksen, 1974; Finstad et al., 2014, 2016). Salt crusts, however, often extend beyond these groundwater-driven environments due to wind transport and deposition of salt (Finstad et al., 2018). Although salars clearly form from the evaporation of water, the timing of this events in the Central Depression of the Atacama Desert has been largely speculative, and the hydrological conditions that would have favoured their formation are unknown.

In recent years, a changing view of late Quaternary paleoclimate and hydrology of the Andes-Atacama Desert interface has emerged. Wetlands along stream margins have been documented at higher elevations (Betancourt et al., 2000; Rech et al., 2002; Quade et al., 2008), Pleistocene and Holocene terrace development along streams has been observed and dated (Nester et al., 2007; Gayo et al., 2012), and incredibly, the remains of late Pleistocene human occupation has been discovered on ancient fluvial terraces that are now entirely devoid of water and life (Latorre et al., 2013). These studies inspire questions about how regionally pervasive such changes in climate were, and how deeply into the Atacama Desert system did these events penetrate and persist.

In this study, we surveyed salars and surrounding landscapes in two differing parts of the Atacama Desert hyperarid core (Fig. 1): (1) salars in the semi-closed Pampa del Tamarugal (PDT) basin of the northern Atacama Desert, and (2) salars and drainage systems in the region surrounding Aguas Blancas (AB), in the southern part of the Desert (Fig. 1). Using field observations, GIS, paleoecological, geohydrological modelling, and radiocarbon dating, we report evidence of late Quaternary lakes and wetlands in the basins in both areas. Some of these fossil hydrological features are synchronous with the Central Andean Pluvial Event (CAPE – 17.5–14.2 ka and 13.8–9.7 ka), a widespread wet period consisting of two phases separated by a centennial-scale arid period that has been documented by numerous authors (Maldonado et al., 2005; Latorre et al., 2006; Nester et al., 2007; Quade et al., 2008; Placzek et al., 2009, 2013; Gayo et al., 2012; Díaz et al., 2012; De Porras et al., 2017). However, our observations also record earlier pluvials than the CAPE pointing to a deeper and richer history of desert hydrological response to Andean climate. In general, the picture that emerges is that the stark aridity of the present desert landscape is greatly dissimilar to the conditions during late Pleistocene wet events, where active streams drained the western slope of the Andes, and numerous wetlands and lakes were present in areas that today are absolute desert.

2. Regional setting

The Central Depression of the Atacama Desert is a broad longitudinal forearc depression that lies between a Coastal Range and the Andes between 18° and 27° S. Elevations range between 1000 and 1600 m above sea level (m a.s.l.). This paper is centered on two basins along this low elevation feature, the Pampa del Tamarugal (PDT) basin in the north, and the Aguas Blancas (AB) basin toward the south (Fig. 1).

Present rainfall in the region is a function of latitude and altitude (Houston, 2006a), and its relationship to modern regional climatology has been used as a clue to interpreting past conditions (Quade et al., 2008, Placzek et al., 2009, De Porras et al., 2017). There are two major climate patterns that bring precipitation to the region: in the north (and east), summer precipitation of tropical origin is derived from the Atlantic, whereas winter rain associated with a northward migration of extratropical storm fronts can occur during positive phases of ENSO (Garreaud and Aceituno, 2001), and

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