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Evidence for multiple Plio-Pleistocene lake episodes in the hyperarid Atacama Desert

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A B S T R A C T

Cosmogenic nuclide exposure dating of ancient shoreline terraces of the Quillagua-Llamara Soledad Lake in the central Atacama Desert of northern Chile provides new insights in the paleohydrology of the driest desert on Earth. The lake developed in a paleo-endorheic drainage system in the Central Depression prior to draining into the Pacific due to incision of the Río Loa canyon. The durations of lake stages were sufficiently long to form wave-erosion induced shoreline terraces on the wind-exposed slopes of former islands. Successively younger shoreline levels are preserved over an elevation range of 250 m due to progressive uplift of the islands coeval with the lake stages. Cosmogenic ^{10}Be- and ^{21}Ne-derived exposure ages of the shorelines reveals that the hyperarid conditions in the Río Loa catchment were interspersed by several pluvial stages during the Pliocene and Pleistocene, which generated a large and persistent lake in the Quillagua-Llamara basin. The exposure ages of the final lake stage provide the maximum age for the incision of the Río Loa canyon (274 ± 74 ka) and the subsequent breaching of the Coastal Cordillera.

1. Introduction

The Atacama Desert of northern Chile is one of the driest places on Earth; the extreme hyperarid core (Coastal Cordillera, Central Depression; Fig. 1) receives less than 10 mm/yr of precipitation (Houston and Hartley, 2003). While the main factors controlling hyperaridity in the Atacama Desert are established, the onset and permanence of hyper-aridity remain a matter of debate (e.g., Sillitoe and McKee, 1996; Sáez et al., 1999; Hartley and Chong, 2002; Rech et al., 2003; Dunai et al., 2005; Nishiizumi et al., 2005; Latorre et al., 2006; Rech et al., 2006; Kober et al., 2007; Nester et al., 2007; Evenstar et al., 2009; Placzek et al., 2010; Gayo et al., 2012; Sáez et al., 2012; Jordan et al., 2014; Evenstar et al., 2017). The nearly stable position of the South American continent over the last 150 million years (Hartley et al., 2005) and the establishment of the Peru-Chile Current system at around 50 Ma (Cristini et al., 2012) support the notion that predominantly arid conditions persisted since the early Miocene (Dunai et al., 2005), and potentially even earlier (Hartley et al., 2005). Secular variations of the global climate system during the Cenozoic (Zachos et al., 2001) led to punctuations of the prevailing hyperarid climate in the Atacama Desert by wetter (though still arid) periods (e.g., Betancourt et al., 2000; Dunai et al., 2005; Nester et al., 2007; Rech et al., 2010; Sáez et al., 2012; Jordan et al., 2014; Evenstar et al., 2017). These pluvial phases are evident from Miocene-Pliocene lacustrine and fluvial sediments in the Central Depression (e.g. Gaupp et al., 1999; Sáez et al., 2012; Kirk-Lawlor et al., 2013).

Here we present new insights into the timing of relatively wet periods in the Central Depression based on exposure dating of former shoreline terraces of the Quillagua-Llamara-Soledad lake. These terraces are preserved by uplift of topographic highs in the Quillagua-Llamara basin (QLB). New cosmogenic ^{10}Be and ^{21}Ne data constrain the timing of the most recent lacustrine phases, and the eventual draining of the Quillagua-Llamara-Soledad Lake by the incision of the Río Loa canyon.

2. Background

2.1. Regional geology

The central Atacama Desert is located in the fore-arc region of the Central Andes in northern Chile (Fig. 1). The area includes three morphotectonic units; the Coastal Cordillera, Central Depression, and Precordillera. The latter is bordered by the Western Cordillera, forming an active volcanic arc (Fig. 1). The study area is located in the southern Central Depression, bound to the west by the Coastal Cordillera and to the east by the Precordillera. The Central Depression is a N-S elongated

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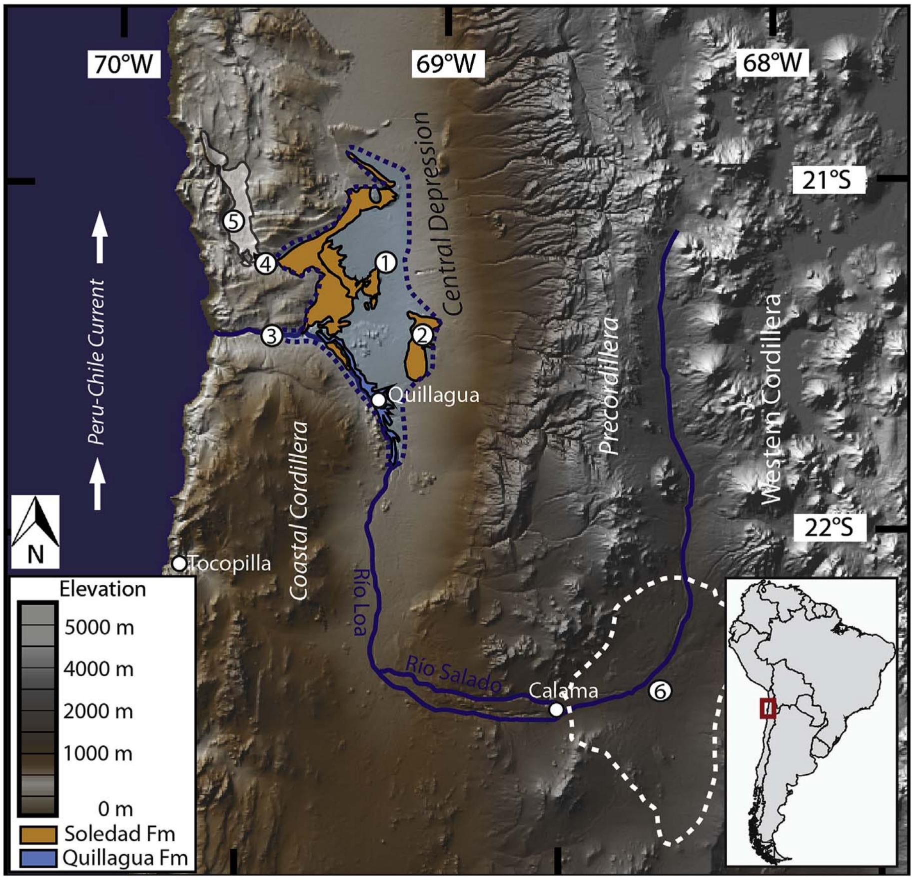

Fig. 1. Geographic setting of Quillagua-Llamara basin in the Central Depression (DEM based on ASTER GDEM data). Orange indicates outcrops of the Soledad Formation (Brüggen, 1950; Sáez et al., 2012; Quezada et al., 2013). Blue indicates outcrops of the Quillagua Formation (Sáez et al., 2012). (1) Cerro Soledad, (2) Lomas de Sal, (3) Westernmost extension of former lake, overflow of Río Loa, (4) Montón de Gloria Pass (831 m), (5) white area indicates Salar Grande, (6) dashed white line denotes the Calama basin. Translucent blue area indicates potential lake extension. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

topographic basin that contains the Pampa de Tamarugal (PDT) and includes the QLB in the south (Fig. 1 translucent blue area). The Coastal Cordillera acts as a topographic barrier, prohibiting any appreciable sediment transport from the Precordillera to the Pacific Ocean. This has enabled the exceptional preservation of many tectonic deformation features that are caused by the coupling between the subducting oceanic Nazca plate and the South American plate in the Coastal Cordillera. E-W tectonic deformation commenced at least 6 million years ago, with fault slip rates that are typically less than 0.5 mm/year (Allmendinger and Gonzalez, 2010).

The incision of the Río Loa canyon transformed the QLB from an endorheic into an exorheic basin, while parts of the northern PDT, north of Quebrada Guatacondo, remained endorheic. Based on the age of the Soledad Formation this could have occurred during the late Pleistocene (Sáez et al., 2012) or early Pliocene (Quezada et al., 2013). Relict deposits of the former lacustrine and evaporitic facies and/or corresponding diagenetic equivalents of the Quillagua-Llamara-Soledad Lake (QLSL) are regionally widespread in the southern PDT (Fig. 1). These may reflect pluvial periods in the last 10 million years (Sáez et al., 2012). Although the sediment sequences have been dated several times, some ages are contradictory and allow alternative environmental reconstructions (Sáez et al., 1999; Sáez et al., 2012; Quezada et al., 2013; Jordan et al., 2014).

The Central Depression is a forearc basin (Jordan et al., 2014; Evenstar et al., 2017), bound to the west by normal faults in the Coastal Cordillera. The basement of the Central Depression consists of Palaeozoic and Mesozoic rocks, which are locally uplifted above the present-day valley floor. In the study area, the depression is filled by up to 1000 m of Eocene to Pliocene alluvial and lacustrine sediments, interbedded with volcanoclastic deposits (Jensen et al., 1995; Sáez et al., 1999; Hartley and Evenstar, 2010; Jordan et al., 2010; Jordan et al., 2014). Alluvial fan deposits are derived almost exclusively from the Precordillera to the east (Carrizo et al., 2008; Nester, 2008; Jordan et al., 2014). The Tertiary PDT basin was formed by the combination of N-S and NW-SE orientated fault system activity, predominantly of currently supratenuous faults (Sáez et al., 1999). Neogene reverse faulting on the Precordillera fault zone has been confirmed for the northern PDT (Victor et al., 2004; Nester, 2008), as well for the southern part (Nester, 2008; Nester and Jordan, 2012). Studies indicate that fault systems in the Coastal Cordillera were reactivated during the past 6 Ma and their effects extend into the Central Depression (Allmendinger et al., 2005).

North to South trending elongated hills on Mesozoic basement in the PDT (Cerro Soledad Figs. 1 and 3, Cerro Challacollo, and Cerro Longacho, see Nester (2008)) protrude up to 300 m above the plain. Carrizo et al. (2008) identified low angle reverse faults near the Salar de Bellavista to be responsible for the uplift of topographic highs after 18-19 Ma (see Fig. 16a in Carrizo et al., 2008). Evidence for young deformation within the basin can be found at Lomas de Sal (Fig. 1) where, a ~100 m thick Plio-Pleistocene sequence has been uplifted by reverse faulting (Nester, 2008). Geomorphological evidence for tectonic deformation in the vicinity includes folded diatomites at the base of Cerro Mogote (Sáez et al., 1999; for location see Fig. 3).

The detailed kinematics of the inferred uplift and deformation around Cerro Soledad, Cerro Mogote and Cerros de Hilaricos is poorly known. Recent mapping by SERNAGEOMIN (Quezada et al., 2012) provide a large scale framework for the structural geology, but the resolution of this mapping is not fine enough to resolve the tectonic kinematics around those exceptional highs within the Central Depression. Statements about the precise occurrence of faults and their appearance in conjunction with folds remain approximations and require more detailed studies.