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Lake highstands on the Altiplano (Tropical Andes) contemporaneous with Heinrich 1 and the Younger Dryas: new insights from ^{14}C, U–Th dating and $\delta^{18}O$ of carbonates

P.-H. Blard [a,b,*], F. Sylvestre [c], A.K. Tripati [b,d,e], C. Claude [c], C. Causse [f], A. Coudrain [g], T. Condom [h], J.-L. Seidel [i], F. Vimeux [f,i], C. Moreau [j], J.-P. Dumoulin [j], J. Lavé [a]

[a] Centre de Recherches Pétrographiques et Géochimiques (CRPG), UPR 2300, CNRS, Université de Lorraine, Vandoeuvre-lès-Nancy, France
[b] Division of Geological and Planetary Sciences, California Institute of Technology (Caltech), Pasadena, USA
[c] Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE), UMR 6635, CNRS, IRD, Aix-Marseille Université, Aix-en-Provence, France
[d] Department of Earth and Space Sciences, Institute of the Environment, University of California (UCLA), Los Angeles, USA
[e] Department of Atmospheric and Oceanic Sciences, Institute of the Environment, University of California (UCLA), Los Angeles, USA
[f] Institut Pierre Simon Laplace (IPSL), Laboratoire des Sciences de Climat et de l'Environnement (LSCE), UMR 8212 (CEA-CNRS-UVSQ), Gif-sur-Yvette, France
[g] Institut de Rercherche pour le Développement (IRD), Marseille, France
[h] Laboratoire d'étude des Transferts en Hydrologie et Environnement (LTHE), UMR 5564, Université Joseph Fourier – Grenoble 1, IRD, CNRS, G-INP, Grenoble, France
[i] Institut de Recherche pour le Développement (IRD), Laboratoire HydroSciences Montpellier (HSM), UMR 5569 (CNRS-IRD-UM1-UM2), Université de Montpellier, Montpellier, France
[j] Laboratoire de Mesure du Carbone 14 (LMC14), UMS 2572 (CEA, CNRS, IRD, IRSN et Ministère de la Culture et de la Communication), Saclay, Gif-sur-Yvette, France

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ABSTRACT

This study provides new geochronological and stable isotope constraints on Late Pleistocene fluctuations in lake level that occurred in the closed-watershed of the Central Altiplano between ~25 and ~12 ka. U-series isochrons and ^{14}C ages from carbonates are used to confirm and refine the previous chronology published (Placzek et al., 2006b). Our new data support three successive lake highstands during the Late Pleistocene: (i) the Lake Sajsi cycle, from ~25 to 19 ka, that culminated at 3670 m at about 22 ka, almost synchronously with the global last glacial maximum, (ii) the Lake Tauca cycle, that lasted from 18 to 14.5 ka and was characterized by the highest water level, reached at least 3770 m from 16.5 to 15 ka, (iii) the Lake Coipasa cycle, from 12.5 to 11.9 ka, that reached an elevation of ~3700 m, 42 m above the elevation of the Salar de Uyuni (3658 m). These high amplitude lake level fluctuations are in phase with the cold–warm oscillations that occurred in the North Atlantic and Greenland during the Late Pleistocene (Heinrich 1, Bølling–Allerød, Younger Dryas). Such temporal coincidence supports the hypothesis that wet events recorded in the Central Altiplano are controlled by the north–south displacement of the Inter Tropical Convergence Zone resulting from changes in the meridional temperature gradient. Finally, the oxygen isotope ratios measured in these lacustrine carbonates allows for calculation of the $\delta^{18}O$ value of paleolake waters. Estimates of water $\delta^{18}O$ (V-SMOW) are $-2.8 \pm 0.7‰$ for Lake Tauca and $-1.6 \pm 0.9‰$ for Lake Coipasa. These data are used to constrain changes in lake hydrology and can be interpreted to indicate that the proportion of precipitation arising from local water recycling was less than 50%.

1. Introduction

Many recent observations have led to a reconsideration of the role of the tropics in paleoclimate. The tropics are now recognized to be the driver of high frequency climatic variability, including El Niño-Southern Oscillation (ENSO) (Chiang, 2009). It has also been proposed that the tropics may be an amplifier of the abrupt millennial changes recorded in the Greenland ice and in the sediments of the Northern Atlantic (e.g. Leduc et al., 2007). In particular, several paleoprecipitation records (Cruz et al., 2005) have led to the suggestion that the north–south oscillation of the tropical rainfall belt might be a key mechanism for a tropical "butterfly effect" (e.g. Peterson et al., 2000; Leduc et al., 2007). According to this hypothesis, millennial scale fluctuations in moisture transport across the Isthmus of Panama may modulate the North Atlantic freshwater budget and therefore serve as a positive feedback into abrupt climate changes. Accurate and well-dated records of tropical

* Corresponding author. Centre de Recherches Pétrographiques et Géochimiques (CRPG), UPR 2300, CNRS, Université de Lorraine, Vandoeuvre-lès-Nancy, France.
E-mail address: blard@crpg.cnrs-nancy.fr (P.-H. Blard).

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precipitation are thus of critical importance to improve our understanding of the role the tropical hydrologic cycle may have as a driver or amplifier of climate change. Records of past lake levels reflect temporal and spatial changes in precipitation patterns. Paleoshorelines provide direct benchmarks of water depth and can thus be used as quantitative records of regional hydrological budget.

In the closed Titicaca–Altiplano watershed (Central Andes), numerous very well-preserved paleoshorelines and carbonate deposits represent direct and spectacular archives of significant changes in net moisture over the southern tropical Andes. Several studies conducted over the two last decades have allowed chronological constraints to be placed on the timing and causes of these large fluctuations in lake level and demonstrated their abruptness (e.g. Sylvestre et al., 1999; Baker et al., 2001; Placzek et al., 2006a, 2006b). In particular, comprehensive studies based on a large number of U–Th and radiocarbon dates from paleolake carbonates permitted identification of two large oscillations in lake level synchronous with the abrupt millennial cooling events recorded in the North Atlantic, namely Lake Tauca (coincident with the Heinrich 1 event, 17–15 ka) and Lake Coipasa (coincident with the Younger Dryas, 13–12 ka) (Sylvestre et al., 1999; Placzek et al., 2006a, 2006b). Sr and U isotopes have also recently been used to characterize the spatial pattern of these pluvial events (Placzek et al., 2011). However, several questions remain unanswered:

i) What is the timing of other oscillations in lake level? The majority of existing U–Th and ^{14}C data belongs to the Lake Tauca cycle, but the chronologies of the other oscillations in lake level are not as well established. This is notably the case for the lowstand episode between the so-called Sajsi episode (25–18 ka) and the Lake Tauca cycle (17.5–15 ka), as both the amplitude and duration of the Sajsi–Tauca lowstand is still unclear (Placzek et al., 2006b). Similarly, the chronology and amplitude of the Coipasa cycle needs to be better characterized.
ii) What triggered the lake highstands in this region, and how do oscillations in lake level reflect changes in atmospheric circulation (Sylvestre et al., 1999; Placzek et al., 2006b)? Various isotopic systems have been used to propose several models for precipitation patterns over the Altiplano (Coudrain et al., 2002; Placzek et al., 2011), but many questions remain open about these highstands, particularly over the amount of local water that was recycled, thus impacting the hydrological budget of these lakes.

In this contribution we present a new set of ^{14}C and U–Th ages of the Altiplano lake cycles that occurred during the late Pleistocene (Sajsi, Tauca and Coipasa cycles). We combine these new ages with published datasets (Sylvestre et al., 1999; Placzek et al., 2006b). These new data are crucial to refine the chronology of these episodes and to establish coherent regional scenarios for net precipitation changes. We also provide new stable isotope data (δ^{18}O and δ^{13}C) from well-dated lake carbonates. These data allow calculation of the δ^{18}O of past lake waters and are used to constrain the contribution of local recycling to the hydrologic budget of the lake.

2. Regional settings

2.1. The Altiplano endorheic watershed

The Titicaca–Altiplano watershed (15–23°S, 66–70°W) is the largest endorheic basin of the Tropical Andes, with a total area of ~196,000 km^2 (Fig. 1). This large plateau, located at an average elevation of ~3800 m, is flanked by two north–south mountain ranges rising up to 6500 m: the Oriental and the Occidental Cordilleras. The Altiplano hydrological system may be divided in two main sub-catchments: the Titicaca basin (58,000 km^2) in the north and the Uyuni–Coipasa basin (138,000 km^2) in the south, with a lowest point situated at 3656 m. Since the Lake Titicaca (3810 m) is overfilled with a spillway in its south-western end, these two sub-basins are hydrologically connected through the Titicaca outlet, the Rio Desaguadero (Fig. 1). Current annual rainfall is controlled by the southward deflection of the Inter Tropical Convergence Zone (ITCZ) during the summer season (Garreaud et al., 2009). This atmospheric pattern implies a strong seasonality of precipitation: 80% of rainfall indeed occurs during the Austral summer, between October and April. Moreover, as the majority of precipitation originates from the northeast, the orographic effect is responsible for a strong northeast to southwest gradient: precipitation is 800 mm yr^{-1} in the northern Altiplano, over the lake Titicaca, and decrease below 100 mm yr^{-1} in the southern part, the Lipez region. Over the Altiplano, the mean annual potential evaporation is larger than 1000 mm yr^{-1} (Delclaux et al., 2007). Given that the present rainfall in the southern basin is less than 330 mm yr^{-1} (Condom et al., 2004), such intense evaporation implies that the hydrological balance of the southern Uyuni–Coipasa basin is in deficit, resulting in the presence of large dry salty basins: Salar de Uyuni and Salar de Coipasa.

In the southern sub-watershed (Uyuni–Coipasa basin), well-preserved paleoshorelines are present in many locations (Fig. 1) and meter-scale bioherms are often observed just below these paleoshorelines. Those features have been extensively described in many previous studies and were interpreted as relicts of giant paleolakes (Servant and Fontes, 1978; Rouchy et al., 1996; Sylvestre et al., 1999; Placzek et al., 2006a, 2006b) (Fig. 1). Detailed stratigraphic analyses, ^{14}C and U–Th dating of these deposits established that the highstand of the largest Pleistocene lacustrine episode, the Lake Tauca, occupied a total surface of 52,000 km^2 (water level at 3775 m) during about 1000 years between ~16 ka and 15 ka BP (Fig. 1) (Sylvestre et al., 1999; Placzek et al., 2006b). Several modeling studies have established that the average precipitation increase during this Lake Tauca episode could have reached 1.5–1.8 times the present average value (Hastenrath and Kutzbach, 1985; Blodgett et al., 1997; Coudrain et al., 2002; Blard et al., 2009).

2.2. Air and lake temperature data

A compilation of the rare available air temperature records for the Altiplano is shown in Table 1. Fig. 1 shows the location of these weather stations. Once corrected for elevation by using an annual lapse rate of 6.5 °C km^{-1} (Klein et al., 1999), the annual temperature means of the 7 weather stations are characterized by a regional average of 9 °C after normalization at 3770 m. Temperatures were scaled at this elevation because it corresponds to the altitude of the Lake Tauca highstand (Sylvestre et al., 1999; Placzek et al., 2006b). The low variability between these different weather stations (standard deviation of the annual means is only 1.2 °C) and the absence of a significant correlation between the spatial position and the temperature suggests that local climatic particularities are not significant. However, the seasonal amplitude (amplitude = $T_{DJF} - T_{JJA}$) is characterized by a significant variability between each location (Table 1). Although this seasonal amplitude seems to be anti-correlated with elevation ($R^2 = 0.7$), it is not clear whether this variability is not controlled by another parameter, such as the temporal and spatial fluctuations of cloudiness.

Since one of the goals of the present study is to provide reconstruction of paleolake δ^{18}O, it is important to rely on accurate reconstructions of paleolake temperature. For this, it is crucial to