Lake-level variability in Salar de Coipasa, Bolivia during the past ~40,000 yr

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Abstract

Various paleoclimatic records have been used to reconstruct the hydrologic history of the Altiplano, relating this history to past variability of the South American summer monsoon. Prior studies of the southern Altiplano, the location of the world's largest salt flat, the Salar de Uyuni, and its neighbor, the Salar de Coipasa, generally agree in their reconstructions of the climate history of the past ~24 ka. Some studies, however, have highly divergent climatic records and interpretations of earlier periods. In this study, lake-level variation was reconstructed from a ~14-m-long sediment core from the Salar de Coipasa. These sediments span the last ~40 ka. Lacustrine sediment accumulation was apparently continuous in the basin from ~40 to 6 ka, with dry or very shallow conditions afterward. The fossil diatom stratigraphy and geochemical data ($\delta^{13}C$, $\delta^{15}N$, %Ca, C/N) indicate fluctuations in lake level from shallow to moderately deep, with the deepest conditions correlative with the Heinrich-1 and Younger Dryas events. The stratigraphy shows a continuous lake of variable depth and salinity during the last glacial maximum and latter stages of Marine Oxygen Isotope Stage 3 and is consistent with environmental inferences and the original chronology of a drill core from Salar de Uyuni.

Keywords: South America; Altiplano; Paleoclimate; Paleohydrology; Andes; Paleolake

INTRODUCTION

The Altiplano is a large, endorheic basin located between the Cordilleras Oriental and Occidental of the tropical Andes. Lake Titicaca, the world's largest high-altitude lake, is located in the seasonally wet northern Altiplano, whereas large salt flats are located in the more arid southern Altiplano (Fig. 1). Early scientific investigations in the region reported on a series of carbonate benches (formed in shallow water as algal bioherms or "tufas") above the plain of Salar de Uyuni and Salar de Coipasa, as well as elevated deposits above the shoreline of modern Lago Poopó and Lake Titicaca. These were considered evidence of ancient lakes much larger than those of today (Forbes, 1861; Agassiz and Garman, 1876; Musters, 1877; Minchin, 1882; Pompecki, 1905; Bowman, 1914). More recently, multiple studies have explored the timing of long-term hydrologic change based on examination of the paleoshoreline deposits (Servant, 1977; Rondeau, 1990; Risacher and Fritz, 1991; Bills et al., 1994; Sylvestre et al., 1999; Placzek et al., 2006) and sediment cores from Lake Titicaca and Salar de Uyuni (Wirrmann and Mourguiart, 1995; Baker et al., 2001a, 2001b; Fornari et al., 2001; Fritz et al., 2004, 2007) and related reconstructions of regional hydrologic variation to processes at local to global scales. Baker et al. (2001a, 2001b) hypothesized that regional precipitation variation, associated with the South American summer monsoon (SASM), was linked to variation in North Atlantic sea-surface temperature (SST) gradients at multiple temporal scales, a conclusion also supported by more recent stratigraphic and modeling studies (Blard et al., 2011; Placzek et al., 2013).

Most prior studies in the region agree about the ages and relative depths of the paleolakes on the southern Altiplano during the past ~24 ka yr. From 24 to 15 ka, a paleolake continuously occupied the Salar de Uyuni and Salar de Coipasa basins (Baker et al., 2001b; Fritz et al., 2004). The paleolake was likely moderately shallow—no tufas within this age range were observed higher than 15 m above the modern surface of Salar de Uyuni (m asu) until near its termination, when the paleolake reached a level of ~110 m asu

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coincident with the Heinrich 1 stadial (~18–14 ka). The paleolake dried in the Bølling-Allerød interstadial and refilled during the Younger Dryas event (12.9–11.6 ka), attaining a maximum level of ~45 m asu at that time (Sylvestre et al., 1998; Placzek et al., 2006; Blard et al., 2011).

In contrast to its more recent history, the timing of lake-level variation on the southern Altiplano prior to 24 ka is contentious and the nomenclature of the paleolakes is confusing. Based on radiocarbon ages of shells found in outcropping sediments, Servant and Fontes (1978) identified a paleolake that they called Minchin, dated at 32 to 30 ka. Rondeau (1990) observed tufas in the Salar de Coipasa basin that he attributed to paleolake Minchin, which had U/Th dates between 44 and 34 ka, with reported errors of a few thousand years. In contrast, Placzek et al. (2006, 2013) suggested that, between 80 and 25 ka, the basin was occupied by a paleolake only for a short-period at ~46 ka based on their U-Th dating of paleoshoreline deposits. Yet, continuous drill cores from Salar de Uyuni show lacustrine sediment and evidence of a long-lived lake of moderate depth, perhaps the equivalent of Servant's "Minchin" paleolake, between ~46 and 38 ka, based on coherent radiocarbon and U-series isochron dating of an ~11-m-thick bed of lacustrine mud, as well as two later short-lived lacustrine phases between ~33 and 28 ka (Baker et al., 2001b; Fritz et al., 2004). These lacustrine intervals, marked by deposition of mud containing a rich diatom flora and abundant carbonate brine shrimp fecal pellets, are separated by beds of salt, both halite and gypsum, representing periods of desiccation with deposition in shallow saline lakes or salt pans (Fritz et al. 2004).

The great value of lake-level reconstruction using elevated shoreline deposits and tufas is that these deposits yield actual minima datums for paleo-lake level when properly accounting for isostasy and neotectonics (Bills et al., 1994), as well as sediment back-stripping. Yet, unlike lacustrine sediment cores, elevated shoreline deposits are highly discontinuous in occurrence and impossible to sample to completeness. It is also often difficult to discriminate multiple high stands that reoccupied the same lake level. Thus, the absence of such paleoshoreline deposits should not by itself be used to infer the absence of a paleolake, shallow or deep, at that date. Furthermore, paleoshoreline deposits, unlike lacustrine sediment, do not follow the rule of superposition.

Placzek et al. (2013) also suggested a revised chronology of the Salar de Uyuni drill core (Fritz et al., 2004) for the interval prior to 24 ka based solely on an Ar-Ar date of 191 ka on an interbedded tuffaceous sandstone in a similar drill-core sequence from the Salar de Uyuni. This date was determined by Fornari et al. (2001) on a different drill core recovered in 1986 (Risacher and Fritz 1991) taken from almost exactly the same geographic location. Our original U-series chronology placed the same interval at 59 ka (Fritz et al., 2004). The Placzek et al. (2013) vacation of our chronology (Fritz et al., 2004) is not well supported, because it dismisses a sequence of internally consistent U-Th ages on salts that also overlap and are concordant with radiocarbon ages, and because it requires a major change in an otherwise steady sedimentation

rate that is not suggested by the stratigraphy (Baker and Fritz, 2015).

Additional records of the timing of hydrologic variability on the southern Altiplano can be used to evaluate regional climate variability more clearly and help to resolve discrepancies in interpretation of regional history. Here, we discuss a new high-resolution analysis of a sediment core from Salar de Coipasa that continuously spans nearly all the past ~40 ka and contains geochemical and paleobiotic evidence of fluctuations in lake level. This record extends previous reconstructions of the paleohydrology of the Salar de Coipasa (Sylvestre et al., 1999), which only covered the deglaciation and early Holocene (15.5–8.5 ka). We use this record to evaluate the paleohydrology of Salar de Coipasa within the context of other records from the Altiplano, particularly for the interval during and prior to the LGM.

Regional description

The Salar de Coipasa (68°8′W, 19°23′S), at an elevation of 3,656 m above sea level (asl), is the second largest salt flat (2500 km²) on the Bolivian Altiplano, which is an internally drained intermontane basin (187,000 km²) located between the Cordillera Oriental and the Cordillera Occidental in the southern tropical Andes. The Salar de Coipasa lies northwest of the Salar de Uyuni, and together they form the ultimate terminal basin of the Altiplano (Fig. 1), receiving water from the northern Altiplano during past periods of overflow of Lake Titicaca and Lago Poopó. The Salar de Coipasa basin is filled with late Tertiary to Quaternary age alluvial, volcanic, and evaporitic deposits (Ericksen et al., 1978; Risacher and Fritz, 1991; Clapperton, 1993; Sylvestre et al., 1998; Banks et al., 2004) and is capped by a salt crust that has a thickness of 2.5 m near its center and tapers to <0.5 m at the margin of the salar (Risacher and Fritz, 1991).

Climate and hydrology

Modern climate on the Altiplano is arid to semi-arid, with rainfall ranging from 800 to 1000 mm/yr in the north near Lake Titicaca to <100 mm/yr in the south in the vicinity of the Salar de Uyuni. Most precipitation falls during the austral summer from December to March, with a long dry season from April to November. Annual average precipitation at Salar de Coipasa is 100–200 mm/yr. The major inflow to Salar de Coipasa is the Rio Lauca, with an annual discharge of 0.14×10^9 m³ (Servicio Nacional de Meterología e Hidrología de Bolivia), which today often creates a shallow lake in the portion of the Salar de Coipasa near the mouth of the river. Typically, the salar surface becomes completely flooded during the rainy season and then dries nearly completely during the subsequent dry season.

During multi-annual phases of increased effective moisture, Lake Titicaca rises above its outlet (3810 m asl) and overflows via the Rio Desaguadero into the central basin of the Altiplano, providing increased riverine input to the
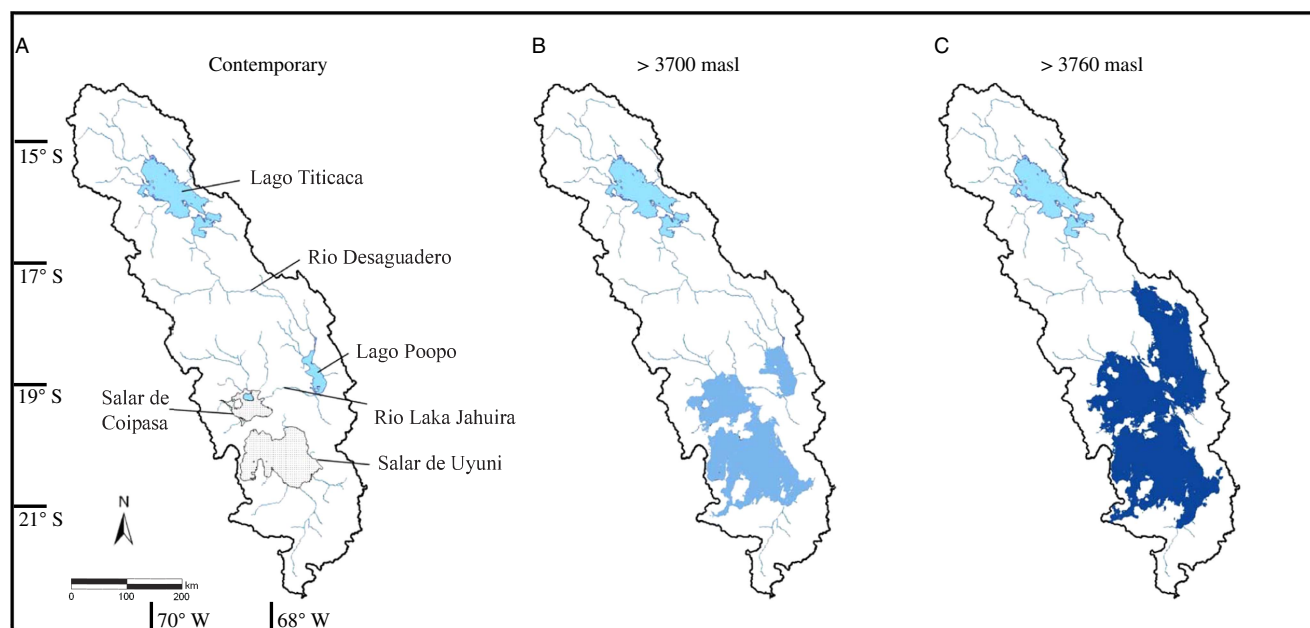
Figure 1. Map of the Altiplano showing (a) the location of Salar de Coipasa and other major hydrologic features mentioned in the text. The adjoining two panels show the size of paleolakes in the region (shaded blue) during intervals of increased effective moisture that raised lake levels to (b) 3700 m asl, which would connect Lago Poopó, Salar de Coipasa, and Salar de Uyuni via narrow straits, and (c) to 3760 m asl, the elevation of paleolake Tauca, as inferred from paleoshoreline deposits in the region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

downstream Lago Poopó (3686 m asl). On paleoclimate timescales, higher local runoff combined with enhanced flow from the north caused Lago Poopó to fill until its surface water elevation was ~3700 m asl. At this elevation, Lago Poopó overflowed westward via the Rio Laka Jahuira into the Salar de Coipasa (Fig. 1b). The surface of Salar de Coipasa is only ~3 m above that of the Salar de Uyuni (Risacher and Fritz, 1991). The two salars are today separated by a sill that is only about 2 m above the surface of the Salar de Coipasa. If this sill height remained similar for the past 40 ka, water depth in the Coipasa basin would have been limited to only 2 m over a wide range of values of effective moisture. With vastly increased and prolonged periods of effective moisture, reaching the level of paleolake Tauca (ca. 3760 m asl) the Poopó, Coipasa, and Uyuni basins formed a single lake connected by broad straits (Fig. 1c).

METHODS

Core collection

In July 2010, we collected a ~14-m core from beneath the surficial salt at Salar de Coipasa using a Russian corer. Each section was recovered by reentry into the same borehole. The 30-cm halite cap was broken using a hand pick, retaining a portion of the salt for analysis. Beneath the crust, recovery in the uppermost sediments was incomplete, because of a 16-cm-thick salt bed encountered at 0.94 m below the salar surface (Fig. 2). Below this salt bed, we recovered ~13 m of

continuous lacustrine sediment, stopping because of the increasingly stiff nature of the deep sediment. Sixteen 0.25–1.00 m drives (SC-0 through SC-16) were collected for a total stratigraphic length of 13.84 meters. The cores were photographed and described on site before being wrapped for shipment and storage. More detailed core description was carried out in the laboratory at Duke University, and the cores were subsampled for various analyses within a few months of core collection.

Chronology

Accelerator mass spectrometry radiocarbon measurements were made on 17 bulk organic matter samples and one macrophyte sample at the National Ocean Sciences Accelerator Mass Spectrometry Facility at Woods Hole Oceanographic Institute (Table 1). Ages are corrected for stable isotope fractionation but are not adjusted for reservoir effects, which have been estimated to be relatively small for the large paleolakes on the Altiplano (Sylvestre et al., 1999; Baker et al., 2001a). The close agreement between radiocarbon and U/Th ages on young tufas in the Coipasa/Uyuni basin (Placzek et al., 2006) supports this conclusion.

An age model for the core was generated using Bayesian analysis in Bacon (Version 2.2; Blaauw and Christen, 2011). Radiocarbon ages were calibrated with the SHCal13 curve (Hogg et al., 2013). Based on the sedimentology (see below), a hiatus was placed at a salt layer between 94 and 110 cm depth, with the length of the hiatus estimated to be ~2000 yr based on bracketing radiocarbon ages at 85 and 110 cm depth
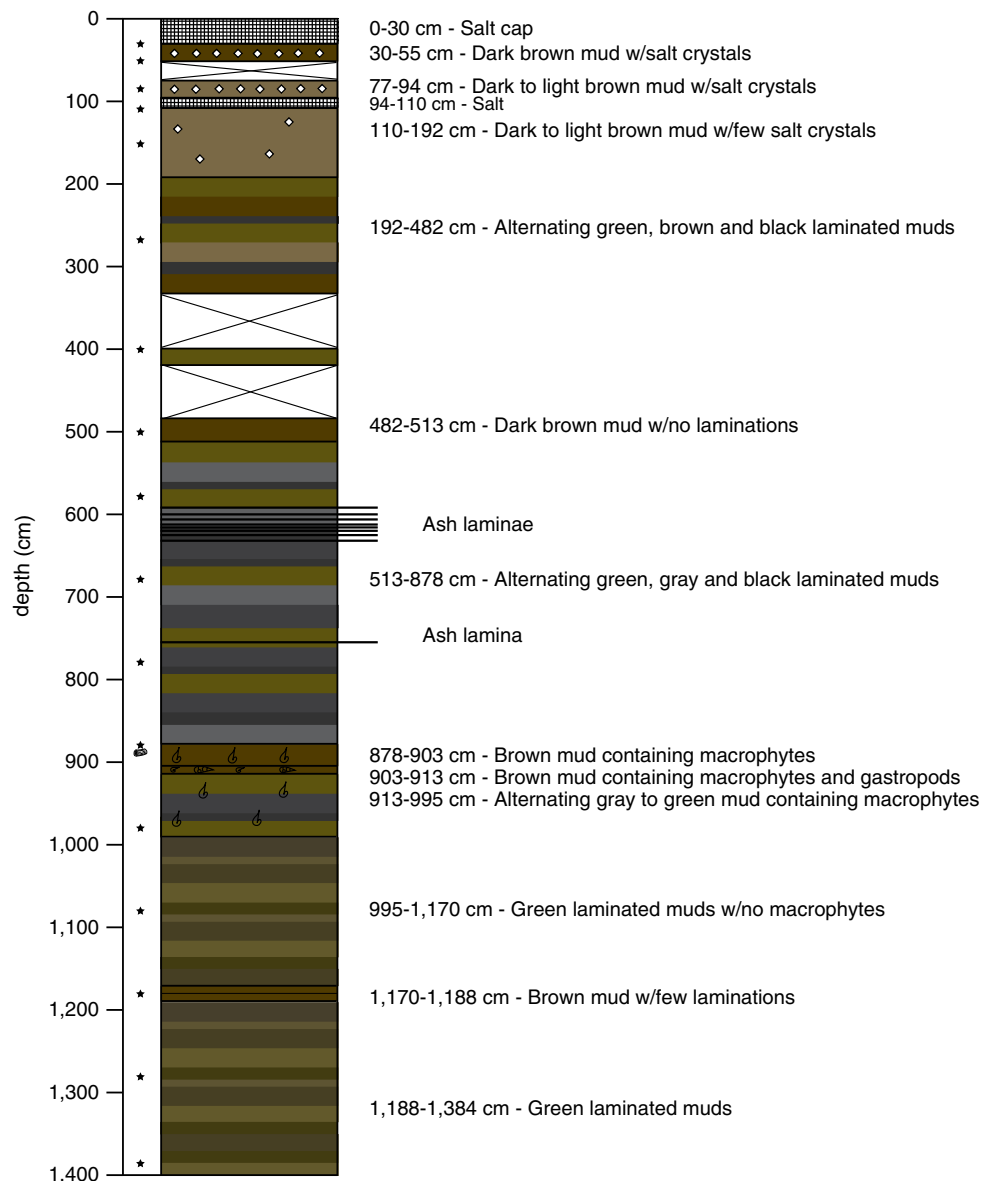
Figure 2. (color online) The stratigraphy of the Salar de Coipasa core. The stars indicate the position of the radiocarbon samples (see Table 1).

(Table 1). The age-depth relationship changes between three stratigraphic intervals: (1) core top to the top of the salt bed at 94 cm depth; (2) a section of slow sedimentation from the base of the salt bed at 110 to ~336 cm depth; and (3) the remainder of the core. Initial accumulation rates for the Bayesian analysis were set to 30 yr/cm for section 1, 70 yr/cm for section 2, and 20 yr/cm for section 3, with standard Bacon settings for the memory beta distribution (strength = 4, mean = 0.7) for all three sections, which are values appropriate for use in lake sediments (Blaauw and Christen, 2011). Sections 2 and 3 were separated by an artificial 10-yr hiatus at 336-cm depth, the base of a unit with uniform lithology (see Fig. 2). This forced hiatus allowed the model to incorporate the change in sedimentation rate, and the resetting of sedimentation rate memory over this interval allowed for an optimized estimate of sediment accumulation rates for each

of the three individual sections of the core. One radiocarbon age at 4.06 m was eliminated from the final age model, because it was from a core section with incomplete core recovery (see Fig. 2), thus we are uncertain of its original stratigraphic position.

Geochemistry

Samples were analyzed for stable carbon and nitrogen isotopic ratios and total carbon and nitrogen content (on a carbonate-free basis) at the Duke Environmental Stable Isotope Laboratory. The core was subsampled at 2-cm resolution. Each sample was dried at 60°C, powdered, homogenized, and weighed into silver cups and transferred into a desiccator containing a beaker of 12N HCl (Schubert

and Nielsen, 2000). The samples were placed in an acid fume for at least 72 hours to remove any sedimentary carbonate. Samples were dried, transferred into pressed 5 × 9-mm tin caps, and combusted at 1020°C in a Carlo-Erba NA1500 elemental analyzer. Purified, chromatographically separated N_2 and CO_2 gases were delivered to a ThermoFinnigan Delta + XL continuous flow isotope ratio mass spectrometer via a ThermoFinnigan Conflo III interface. Reproducibility for both isotopes is approximately 0.1 per mil at 1 SD. C/N ratios are reported as a molar ratio.

Calcium content (as weight percent of the total sample) was determined by digesting powdered samples in 1 N HCl and analyzing the leachate for Ca^{2+} by flame atomic absorption spectroscopy (Perkin Elmer 5000). Mean relative error for $CaCO_3$ determination is approximately 2% for known standard values.

Diatom analysis

Diatom samples were analyzed at the University of Nebraska-Lincoln at 8-cm resolution throughout the core. Samples were processed by treatment with 10% HCl to dissolve carbonates, followed by a cold H_2O_2 treatment to oxidize organic matter. The prepared samples were rinsed repeatedly to remove oxidation by-products. Slurries of the prepared sample were dried onto coverslips, and the coverslips were mounted onto slides with Naphrax. Diatoms were counted at 1000× magnification on a Zeiss Axioskop 2 microscope with differential interference contrast. Where possible, at least 300 diatom valves were identified and counted. In samples where diatom concentration was low, at least one whole slide was scanned for diatom enumeration. Diatom abundance is expressed as a percentage relative to the total number of counted valves in each sample.

RESULTS

Stratigraphy

The Salar de Coipasa is topped by a salt cap that was ~30-cm-thick at the core site and consists of coarse halite crystals (Fig. 2). Just below the salt cap, the recovered sediments consist of brown mud with large salt crystals. A second bed of coarse crystalline halite was encountered from 94–110 cm. Below this bed lies a continuous sequence of lacustrine sediments consisting of green, brown, and black muds. Some units below 192 cm were laminated, suggesting temporal variability in sediment source and sufficiently deep conditions for preservation of sedimentary structures. The laminations averaged from <1 to 2 mm in thickness. Core recovery was poor from 336–482 cm, with just a small amount of mud recovered from ~400 cm that may have been shifted upward or downward as suggested by its incongruent radiocarbon age (see Table 1; Fig. 2). Elsewhere recovery was nearly complete. Several ash layers were recovered between 595 and 765 cm. These ranged in thickness from 1 mm to 1 cm and were located at the following core depths: 595, 600, 603, 611.5, 612, 613, 616.5, 619, and 765 cm. Between 878 and 995 cm, the lacustrine muds contained abundant macrophytes and gastropods indicative of shallow-water conditions.

Chronology

Radiocarbon age determinations indicate that the age of the bottom of the 13.84-m sediment core is 39,200 ^{14}C yr BP. The age model (Fig. 3) suggests that linear sediment accumulation rates were moderately high in the basal sediments, with rates averaging 0.043 cm/yr below 8.7 m (>26,900 cal yr BP) and somewhat higher average rates (0.064 cm/yr)

Table 1. Radiocarbon ages for the Salar de Coipasa core.

| Accession #	Core-section, depth (cm)	Depth (m)	Material	^{14}C age (yr BP)	Age error (yr)	δ^{13}C
OS-82925	SC1-S0, 30	0.3	Sediment organic carbon	925	15	−17.32
OS-82926	SC1-S1, 10–12	0.4	Sediment organic carbon	2450	15	−16.67
OS-82927	SC1-S2, 8–10	0.85	Sediment organic carbon	2610	15	−16.6
OS-83651	SC1-S3, 110–120	1.1	Sediment organic carbon	4700	25	−20.99
OS-82928	SC1-S4, 46–48	1.66	Sediment organic carbon	10,400	50	−24.95
OS-82929	SC1-S5, 50–52	2.7	Sediment organic carbon	16,350	110	−20.41
OS-82930	SC1-S6, 86–88	4.06	Sediment organic carbon	13,450	75	−20.2
OS-82931	SC1-S7, 86–88	5.06	Sediment organic carbon	17,500	130	−18.93
OS-82932	SC1-S8, 50–52	5.7	Sediment organic carbon	18,800	150	−18.26
OS-82933	SC1-S9, 50–52	6.7	Sediment organic carbon	20,300	190	−21.1
OS-82934	SC1-S10, 50–52	7.7	Sediment organic carbon	20,800	200	−20.29
OS-82935	SC1-S11, 50–52	8.7	Sediment organic carbon	20,500	200	−18.64
OS-83177	SC1-S11M, 60–65	8.8	Plant/wood	20,400	180	−11.62
OS-82936	SC1-S12, 50–52	9.7	Sediment organic carbon	28,500	550	−19.3
OS-83025	SC1-S13, 50–52	10.7	Sediment organic carbon	36,600	2500	−25
OS-83027	SC1-S15, 50–52	12.7	Sediment organic carbon	35,200	2100	−19.82
OS-83028	SC1-S16, 98–100	13.82	Sediment organic carbon	37,800	2900	−20.33
OS-83026	SC1-S14, 50–52	11.7	Sediment organic carbon	> 48,000	10900	−22.23
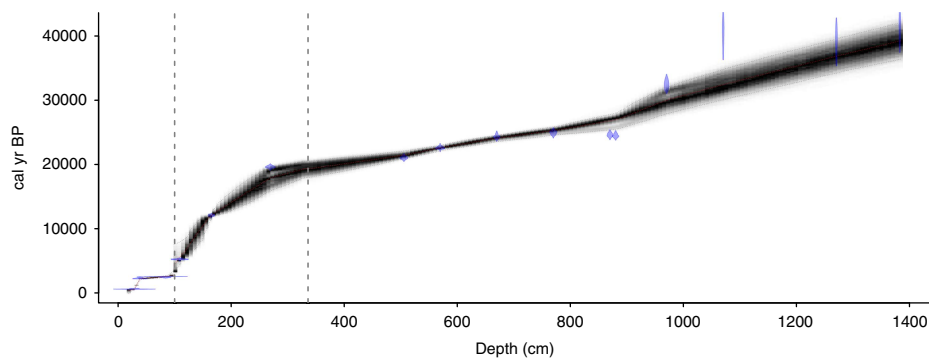
Figure 3. A Bayesian age-depth model for the core generated with Bacon (Blaauw and Christen, 2011), showing the calibrated ^{14}C ages (blue diamonds), the age error (gray shading), and the best fit model (red line). The dotted lines are hiatuses used in generating the age model (see text for further information). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
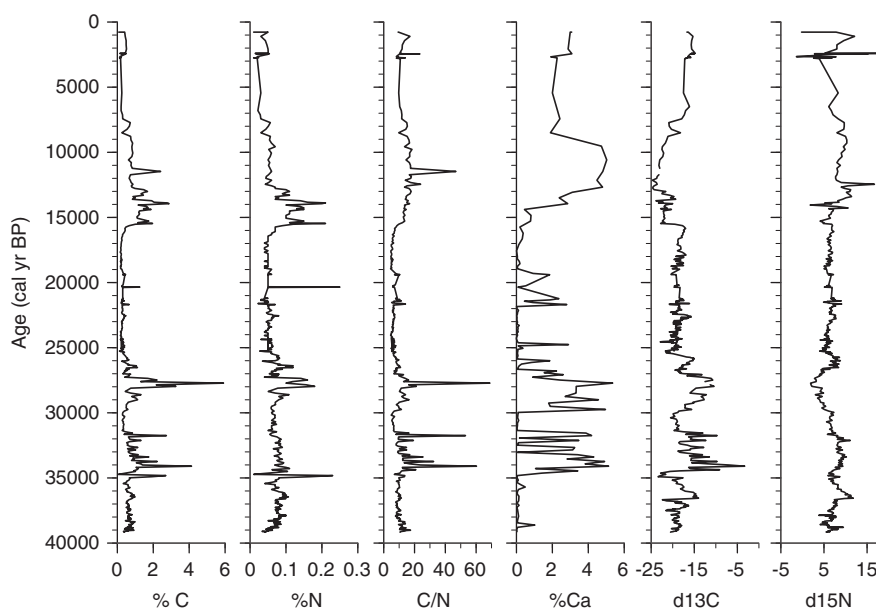

Figure 4. Geochemical data plotted on an age scale (cal yr BP).

above (3.36–8.7 m; 19,400–26,900 cal yr BP). The chronology suggests much slower sediment accumulation in the upper part of the core, with rates of 0.019 cm/yr between 13,600 and 19,400 cal yr BP and 0.008 cm/yr between 5,400 and 13,600 cal yr BP at the base of the salt layer (110 cm).

Geochemistry

$\delta^{13}C$ values of bulk organic carbon in the Salar de Coipasa core range from –3.3 to –24.7‰, with a mean value of –18.38‰ (Fig. 4). In Lake Titicaca, $\delta^{13}C$ values of organic carbon from deep-water sediments of pelagic origin are generally between –15 and –25‰ (Cross et al., 2000; Rowe et al., 2002). This suggests that the organic matter in the Coipasa core is composed primarily of algal carbon (in both

lakes, it is believed that terrestrial input of particulate organic carbon is minor).

In the lower unit of the core, between 8 and 14 m (~25,800–39,200 cal yr BP), $\delta^{13}C$ values are more variable than in overlying sediments. Within this lower zone two distinct intervals exhibit markedly enriched $\delta^{13}C$ values: 8–9.5 m (~25,800–29,300 cal yr BP) and 10.4–11.6 m (31,600–34,400 cal yr BP). The former unit (8–9.5 m) contains abundant rooted macrophytes, indicative of shallow-water environments. A macrophyte sampled at 8.8 m depth (~27,100 cal yr BP) had a $\delta^{13}C$ value of –11.62‰. In Lake Titicaca sediments, macrophytes generally have high $\delta^{13}C$ values (> –15‰) relative to algae (Cross et al., 2000), consistent with the values here. The relatively high $\delta^{13}C$ values in the Salar de Coipasa sediments between 10.4 and 11.6 m are likely due to increasing salinization of the lake during this period (an inference that we discuss later).

Above 8 m (25,800 cal yr BP), $\delta^{13}C$ values are notably less variable than during the preceding interval. Between 2.25–8 m (15,500–25,800 cal yr BP), values range between −21 and −18‰. From 1.8–2.25 m (13,000–15,500 cal yr BP) $\delta^{13}C$ values are lower and range between −19 and −24‰. At ~1.8 m (13,000 cal yr BP) slightly higher $\delta^{13}C$, values (−19 to −20‰) persist for a brief interval (1.2–1.8 m, 6500–13,000 cal yr BP) before $\delta^{13}C$ again shifts to lower values, with a minimum of −24.7‰. This interval of more negative $\delta^{13}C$ is coincident with an increase in % planktic diatoms (see below) to almost 100%, which suggests a deep lake. For the uppermost section of the core (0–1.2 m, <6500 cal yr BP), $\delta^{13}C$ values are relatively constant between approximately −15 and −17‰.

Nitrogen isotopes in the sediment column range from 0–17.6‰, with an average of 6.83‰ (Fig. 4). Values are positively correlated with $\delta^{13}C$ values for the intervals 2.5–8 m (16,900–25,800 cal yr BP) and 10–14 m (30,600–39,200 cal yr BP), which are both units of laminated sediments. $\delta^{15}N$ in sediments for the intervals 0–2.5 m (non-laminated mud; 0–16,900 cal yr BP) and 8–10 m (macrophyte-bearing mud; 25,800–30,600 cal yr BP) is negatively correlated with $\delta^{13}C$. $\delta^{15}N$ values between 1.0–2.5 m (4100–16,900 cal yr BP) are high (~10‰), coincident with an excursion to more negative $\delta^{13}C$ and increased % planktic diatoms, %Ca, C/N, and weight percent organic carbon (TOC) and nitrogen (TN). Shifts in $\delta^{15}N$ in lake sediments can have several causes, including changes related to rates of nitrogen fixation by algae, nitrification or denitrification of the lake, ammonia volatilization, or change in nitrogen source (Talbot, 2001).

Most C/N values in the core are between 5–10 (Fig. 4), a range characteristic of phytoplankton, which are relatively N rich (Cross et al., 2000, Talbot, 2001). Two C/N spikes >50 between 10 and 12 m (30,600–35,200 cal yr BP) are the apparent result of an increase in TOC and coincide with an increase in %Ca and more positive $\delta^{13}C$ values, possible indicators of a decrease in lake volume. A C/N spike of 68 at 9 m (27,700 cal yr BP) is likely due to an increase of organic carbon from the macrophyte remains found at this depth.

Calcium carbonate content (reported as weight percent Ca) ranges up to 15 wt% of the sediment. There are three carbonate-rich intervals: 10.5–11.8 m (31,800–34,800 cal yr BP), 8.5–9.8 m (26,600–30,200 cal yr BP), and 1.5–2.0 m (10,600–14,050 cal yr BP). In the two deeper intervals, most of the $CaCO_3$ occurs as gastropod shells, and the high values represent periods of shallow and perhaps more saline lacustrine conditions. The upper carbonate-rich interval does not contain any shells; instead the carbonate here occurs as micrite. This carbonate-rich interval coincides with a deep and fresher lacustrine phase based on interpretations from diatom analysis.

Diatoms

The diatom flora of Salar de Coipasa consists of a mixture of planktic and benthic species, characteristic of a lake of variable depth and salinity through time (Fig. 5). The most
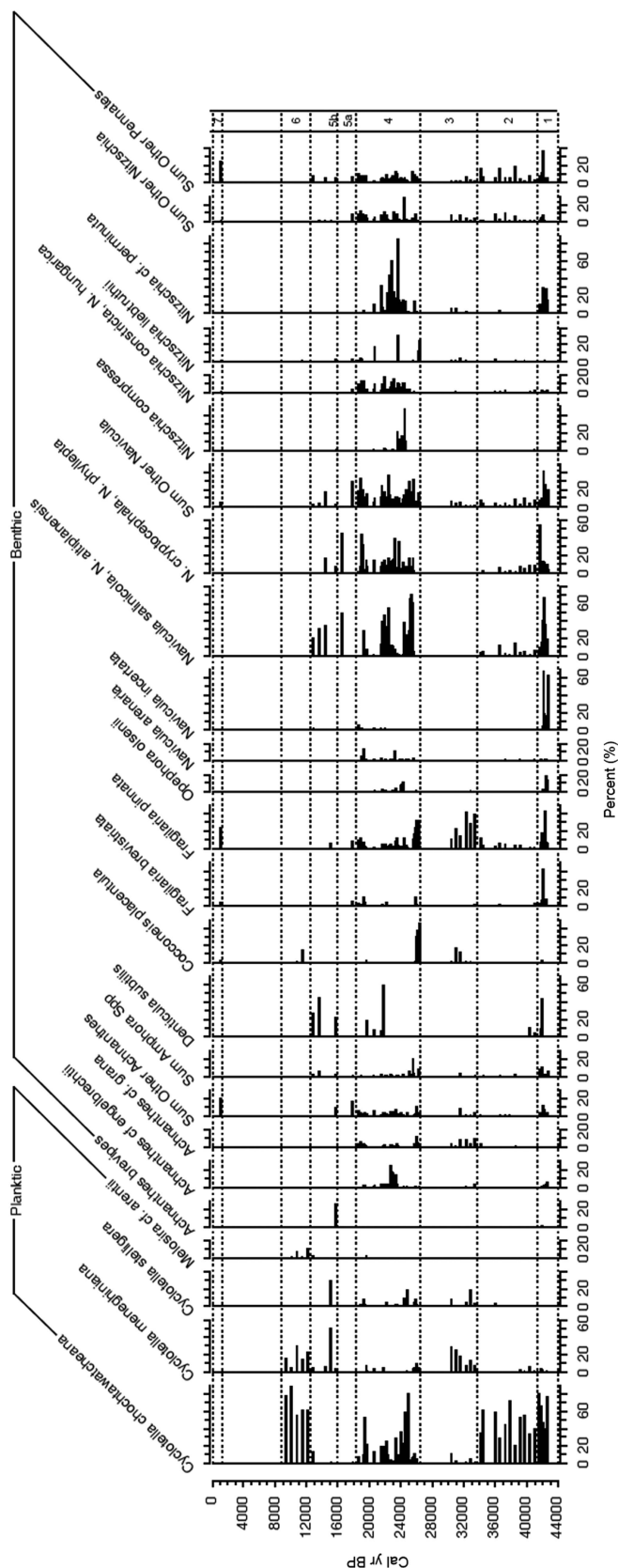
Figure 5. Diatom stratigraphy of major taxa expressed as relative abundance and plotted versus age (cal yr BP).

common planktic taxon is *Cyclotella chochtawatcheana*, which occurs in abundance in deep stably stratified saline lakes (Fritz et al., 1993), brackish estuaries, and in nearshore marine systems (Prasad, 1990). Also present in moderate abundance is *Cyclotella meneghiniana*, which grows in lakes of varied depth and salinity but is common in shallow systems (Fritz et al., 1993). *Discostella stelligera* is characteristic of fresh to hyposaline (<10 g/L) waters and occurs in lakes that are of shallow to moderate depth, as well as in nearshore regions of large deep lakes (Tapia et al., 2003). In the planktic-dominated intervals of the Salar de Coipasa core, we interpret high relative abundance of *C. chochtawatcheana* to represent a deep chemically stratified lake. Salinity is likely lower in the intervals with a high abundance of *D. stelligera*.

The attached diatom flora of Salar de Coipasa is diverse. It includes tychoplanktic species, such as *Pseudostaurosira brevistriata* and *Staurosirella. pinnata*, which can be entrained into the plankton by mixing. The attached benthic species include several taxa characteristic of higher salinity, such as *Denticula subtilis* and *Achnanthes brevipes*; *Cocconeis placentula*, which grows on macrophytes; and high representation by species in the genera *Navicula* and *Nitzschia*.

A deep to moderately deep lake dominated by *C. chochtawatcheana* characterized the basin from 29,900 to 39,200 cal yr BP (zones 1 and 2; 9.70–13.82 m), with a few brief periods within zone 1 (11.66–13.82 m; 34,500–39,200 cal yr BP) that were slightly shallower based on moderate percentages of benthic diatoms. Between 26,400 and 29,900 cal yr BP (zone 3; 8.38–9.70 m), the mixture of *C. meneghiniana*, *S. pinnata*, and benthic taxa indicates a moderately shallow system with extensive macrophyte beds, as suggested by the epiphytic *Cocconeis placentula*. During the LGM (~18,700 to 26,400 cal yr BP; zone 4; 3.02–8.38 m), variation in the relative abundance of planktic and benthic taxa suggests that lake level fluctuated from moderately deep in the *C. chochtawatcheana*-dominated zones to shallower in samples with higher relative abundance of benthic diatoms. Benthic diatoms dominated most of the period from 18,700 to 13,500 cal yr BP (zone 5; 1.90–3.02 m), which suggests generally shallow conditions, including some intervals of higher salinity when the relative abundance of *Denticula subtilis* was high. Yet one sample in zone 5b, dated at 14,800 cal yr BP, is distinctive in the high percentages of the planktic species *D. stelligera* and *C. meneghiniana*. This suggests a moderately deep freshwater lake and is correlative with the terminal part of the paleolake Tauca phase in the basin (Baker et al., 2001a). Immediately above this, the high representation of *C. choctawatcheana* and the low abundance of benthic diatoms suggest that from ~13,100–10,600 cal yr BP (zone 6; 1.50–1.86 m) a deep chemically stratified lake occupied the basin. Diatoms are absent from most of the Holocene samples in the upper part of the core, except for the uppermost sample (diatom zone 7; 0.30 m), which dates from ~800 cal yr BP. The barren samples are those with high concentrations of halite.

DISCUSSION

The most notable feature of the Salar de Coipasa record is the continuous presence of lacustrine sediments in the basin from ~40,000 to 5500 cal yr BP, with no evidence of complete desiccation in that interval. The geochemical, sedimentological, and paleobiotic composition of these sediments (Fig. 6) is consistent with the existence of a permanent lake of varied depth and salinity in the basin.

In the following discussion, we rely primarily on diatom assemblages and carbon isotopic composition of organic carbon to form our inferences about lake level. Our basis for inference of lake level using $\delta^{13}C$ relies on studies that show a strong correlation (generally higher than 0.8) between $\delta^{13}C$ and $\delta^{18}O$ of carbonate sediments formed in closed-basin lakes (Talbot, 1990; Li and Ku, 1997). In most tropical settings, $\delta^{18}O$ of carbonate sediments is strongly dependent on $\delta^{18}O$ of lake water and, in turn, on precipitation amount (e.g., Baker et al., 2009). We reason that $\delta^{13}C$ of lacustrine algae behaves similarly and will be dependent on evaporative concentration, lake level, and ultimately, precipitation amount. This inference assumes that the organic carbon is of purely algal origin, and this could be verified by future studies that consider isolated fractions of the total organic carbon pool. That said, most intervals of the core are dominated by lacustrine algae, rather than macrophyte- or terrestrial-derived carbon.

Hydrologic conditions in the Coipasa basin during the interval between 40,000 and 29,000 cal yr BP were highly variable, fluctuating between deep lake phases dominated by *Cyclotella chochtawatcheana* and with depleted $\delta^{13}C$ values (<−18‰) and moderately shallow lake phases. In particular,

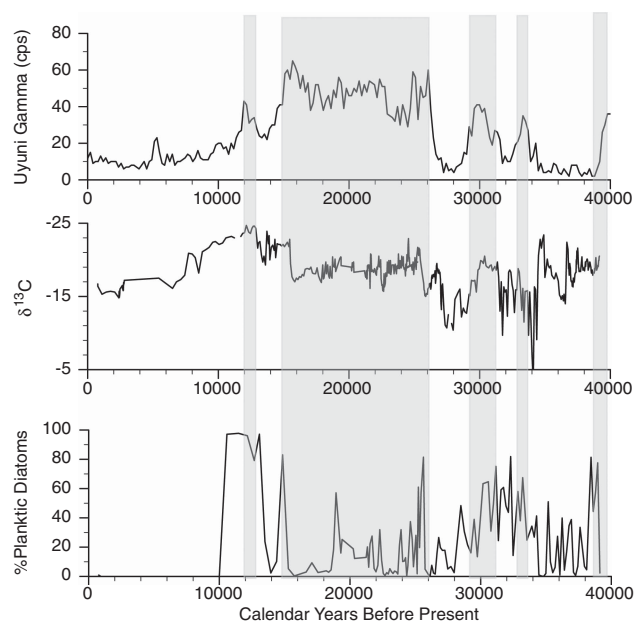**Figure 6.** Comparison of the Salar de Coipasa $\delta^{13}C$ and planktic diatom records with the lake-level history of Salar de Uyuni as inferred from the measurement of gamma radiation in the drill core (Baker et al., 2001a). Shaded zones are the lacustrine units identified in the Salar de Uyuni drill core.

multiple short intervals of lowered lake level occurred between 34,400 and 31,600 cal yr BP, marked by enriched $\delta^{13}C$ values (−18 to −3‰), and higher proportions of benthic diatoms, including the saline taxon, *Denticula subtilis*. Lacustrine sedimentation was continuous, indicating that at no time during this period was the lake completely desiccated.

Between ~29,000 and 25,600 cal yr BP, $\delta^{13}C$ values in the Salar de Coipasa sediments are relatively high (> −18‰) and constant, benthic diatoms and the shallow-water planktic taxon *Cyclotella meneghiniana* are relatively abundant, and C/N values are also elevated to values common in macrophytes (Cross et al., 2000; Rowe et al., 2002). Rooted macrophytes occurred in the sediments of this interval (Fig. 2), coupled with the epiphytic diatom *Cocconeis placentula*, which grows attached to macrophytes. Together the data indicate a persistently shallow lake with abundant aquatic plants.

Between ~25,000 and 16,000 cal yr BP, $\delta^{13}C$ values are relatively depleted (<−18‰) and constant, whereas the diatom species composition is quite variable, suggesting that although a lake persisted through this interval, it varied considerably in depth. Afterward, a rapid decrease in $\delta^{13}C$ values accompanied by the highest abundance within the entire record of the freshwater planktic diatom, *Discostella stelligera,* at ~14,800 cal yr BP signals a freshening of the lake, coincident with paleoshoreline evidence of the highest lake stand of the last glacial cycle, paleolake Tauca (Servant and Fontes, 1978; Sylvestre et al., 1999), which reached a maximum elevation of ~3760 m asl (ca. 110 m deep). This high stand is correlative with the end of the Northern Hemisphere Heinrich 1 event, which increased precipitation on the Altiplano through teleconnections with meridional North Atlantic SST gradients that increased the advection of moisture onto the continent and intensified the SASM (Baker et al., 2001a, 2001b; Baker and Fritz, 2015).

Between ~13,000 and 10,600 cal yr BP, coincident with the Younger Dryas, $\delta^{13}C$ values are more negative (−20 to −24‰), reflecting lake filling that produced the Coipasa highstand, which attained water depths of ~45 m (Servant and Fontes, 1978; Sylvestre et al., 1999). The dominance of *Cyclotella chochtawatcheana* suggests that the lake was moderately deep and more saline than during the Tauca high stand. After ~10,000 cal yr BP, $\delta^{13}C$ values become more enriched, which suggests gradual evaporative drawdown of the lake. Diatoms are not preserved in the upper part of the core, likely because of elevated pH and salinity.

Two intervals of salt deposition occur in the upper part of the core: ~5500–2800 and <1,000 cal yr BP. The former interval is consistent with widespread evidence for a dry mid-Holocene (Baker et al., 2001b). Yet, after 4500 cal yr BP, Lake Titicaca rose, whereas lake levels remained shallow in Salar de Coipasa and Salar de Uyuni was dry (Baker et al., 2001a).

Overall the Salar de Coipasa stratigraphy is remarkably coherent with that of the nearby Salar de Uyuni (Fig. 6), excepting two intervals: (1) from ~34,400–38,000 cal yr BP when lake levels fluctuated from shallow to moderately deep in Salar de Coipasa, whereas the Salar de Uyuni was dry or occupied by a salt-saturated lake; and (2) in the early Holocene when the Salar de Uyuni apparently desiccated more quickly than Salar de Coipasa. The differences in hydrology in these intervals may be a function of the larger surface area of Uyuni and the larger flux of rivers draining into Coipasa (e.g., Rio Lauca and paleo-Rio Laka Jahuira) compared with those draining into Uyuni (e.g., Rio Grande). Consistent with the evidence from paleoshoreline deposits and the Salar de Uyuni drill core, the microfossil and geochemical ($\delta^{13}C$, $\delta^{15}N$, %Ca, and C/N) data suggest the deepest conditions in Salar de Coipasa occurred during the terminal phase of paleolake Tauca and at the time of paleolake Coipasa.

The general coherence of the stratigraphy of the Salar de Coipasa and Salar de Uyuni drill cores in the period prior to ~24,000 cal yr BP supports the original chronology of the Salar de Uyuni drill core (Baker et al., 2001a; Fritz et al., 2004; Baker and Fritz, 2015) and suggests that the drill-core radiocarbon dates in this interval are not in error by more than a few thousand years, not tens of thousands of years, as suggested by Placzek et al. (2013). The drill-core lacustrine units in this interval are correlative with tufa samples of similar ages originally identified as paleolake "Minchin" from outcrops in the Salar de Uyuni and Salar de Coipasa basins (Servant and Fontes, 1978; Rondeau, 1990). Although contamination of samples with younger radiocarbon is certainly possible, the parsimonious explanation is that the radiocarbon measurements are relatively robust within the measurement errors given the consistency among multiple measurements on different materials (shells, tufa, and lake sediment) and in different locations.

In addition to the dating of lacustrine sediments in drill cores and outcrops from the salars, several other regional records point to elevated effective moisture during the LGM and the latter parts of MIS 3, which would have maintained lakes in the southern Altiplano and increased glacial mass balance. Paleoclimatic data indicate that Lake Titicaca was deep, fresh, and overflowing during this entire interval (Baker et al., 2001a; Fritz et al., 2007, 2010), providing significant discharge to the central and southern Altiplano (Nunnery, 2012). Other Altiplano records also corroborate the inference of moderate to high effective moisture in this interval, including the presence of lacustrine sediments in drill cores in the Rio Desaguadero valley (Rigsby et al., 2005) and regional glacial advance (Blard et al., 2014). Neighboring regions under similar climatic influences were also wet at the same time, based on perennial lake deposits in northwestern Argentina (22°S, 66°W; McGlue et al., 2013), evidence of frequent climate-driven landslides in the Santa Maria Basin of northwestern Argentina (24°S, 66°W; Trauth et al., 2003), lacustrine sediments in a drill core from Salar de Atacama (23°S, 68°W; Bobst et al., 2001), and speleothem records from throughout the SASM domain (Cheng et al., 2013). Thus, multiple lines of evidence are inconsistent with the inference of general aridity in the southern Altiplano during MIS 3, as suggested by Placzek et al. (2013), and

instead support the inference of sufficient moisture to support shallow to moderately deep lakes in the salars of the Altiplano during most of this period. These findings highlight the importance of developing multiple regional records to evaluate divergent interpretations of paleoclimatic history more completely.

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REFERENCES

Agassiz, L., Garman, S.W., 1876. Exploration of Lake Titicaca. *Bulletin of the Museum of Comparative Zoology at Harvard College* 3, 273–349.

Baker, P.A., Fritz, S.C., Burns, S.J., Ekdahl, E.J., Rigsby, C.A., 2009. The nature and origin of decadal to millennial scale climate variability in the southern tropics of South America: the Holocene record of Lago Umayo, Peru. In: F. Vimeux, F. Sylvestre, M. Khodri (Eds.), *Past Climate Variability in South America and Surrounding Regions from the Last Glacial Maximum to the Holocene. Developments in Paleoenvironmental Research*, Vol. 14. Springer Science+Business Media B.V., pp. 301–322.

Baker, P.A., Fritz, S.C., 2015. Nature and causes of Quaternary climate variation of tropical South America. *Quaternary Science Reviews* 124, 31–47.

Baker, P.A., Rigsby, C.A., Seltzer, G.O., Fritz, S.C., Lowenstein, T.K., Bacher, N.P., Veliz, C., 2001a. Tropical climate changes at millennial and orbital timescales on the Bolivian Altiplano. *Nature* 409, 698–700.

Baker, P.A., Seltzer, G.O., Fritz, S.C., Dunbar, R.B., Grove, M.J., Tapia, P.M., Cross, S.L., Rowe, H.D., Broda, J.P., 2001b. The history of South American tropical precipitation for the past 25,000 years. *Science* 291, 640–643.

Banks, D., Markland, H., Smith, P.V., Mendez, C., Rodriguez, J., Huerta, A., Sæther, O.M., 2004. Distribution, salinity and pH dependence of elements in surface waters of the catchment areas of the Salars of Coipasa and Uyuni, Bolivian Altiplano. *Journal of Geochemical Exploration* 84, 141–166.

Bills, B.G., de Silva, S.L., Currey, D.R., Emenger, R.S., Lillquist, K.D., Donnellan, A., Worden, B., 1994. Hydro-isostatic deflection and tectonic tilting in the central Andes: Initial results of a GPS survey of Lake Minchin shorelines. *Geophysical Research Letters* 21, 293–296.

Blaauw, M., Christen, J.A., 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6, 457–474.

Blard, P.-H., Lave, J., Farley, K.A., Ramirez, V., Jimenez, N., Martin, L.C.P., Charreau, J., Tibari, B., Fornari, M., 2014. Progressive glacial retreat in the Southern Altiplano (Uturuncu volcano, 22 S) between 65 and 14 ka constrained by cosmogenic 3He dating. *Quaternary Research* 82, 209–221.

Blard, P.-H., Sylvestre, F., Tripati, A.K., Claude, C., Causse, C., Coudrain, A., Condom, T., et al., 2011. Lake highstands on the Altiplano (Tropical Andes) contemporaneous with Heinrich 1 and the Younger Dryas: new insights from ^{14}C, U-Th dating and δ^{18}O of carbonates. *Quaternary Science Reviews* 30, 3973–3989.

Bobst, A.L., Lowenstein, T.K., Jordan, T.E., Godfrey, L.V., Ku, T-L., Luo, S., 2001. A 106 ka paleoclimate record from drill core of the Salar de Atacama, northern Chile. *Palaeogeography, Palaeoclimatology, Palaeoecology* 173, 21–42.

Bowman, I., 1914. The results of an expedition to the central Andes. *Bulletin of American Geographic Society* 46, 161.

Cheng, H., Sinha, A., Cruz, F.W., Wang, X., Edwards, R.L., d'Horta, F.M., Ribas, C.C., Vuille, M., Stott, L.D., Auler, A.S., 2013. Climate change patterns in Amazonia and biodiversity. *Nature Communications* 4, 1411.

Clapperton, C.M., 1993. Nature of environmental changes in South America at the Last Glacial Maximum. *Palaeogeography, Palaeoclimatology, Palaeoecology* 101, 189–208.

Cross, S.L., Baker, P.A., Seltzer, G.O., Fritz, S.C., Dunbar, R.B., 2000. A new estimate of the Holocene lowstand level of Lake Titicaca, central Andes, and implications for tropical palaeohydrology. *The Holocene* 10, 21–32.

Ericksen, G.E., Vine, J.D., Ballón, R.A., 1978. Chemical composition and distribution of lithium-rich brines in Salar de Uyuni and nearby salars in southwestern Bolivia. *Energy* 3, 355–263.

Forbes, D., 1861. Report on the Geology of South America, Part I, Bolivia and Southern Peru, with notes on the fossils by Huxley, Seller and Jones. *Quarterly Journal of the Geological Society of London* 17, 7–62.

Fornari, M., Risacher, F., Feraud, G., 2001. Dating of paleolakes in the central Altiplano of Bolivia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 172, 269–282.

Fritz, S.C., Baker, P.A., Ekdahl, E., Seltzer, G.O., Stevens, L.R., 2010. Millennial-scale climate variability during the Last Glacial period in the tropical Andes. *Quaternary Science Reviews* 29, 1017–1024.

Fritz, S.C., Baker, P.A., Lowenstein, T.K., Seltzer, G.O., Rigsby, C.A., Dwyer, G.S., Tapia, P.M., Arnold, K.K., Ku, T-L., Luo, S., 2004. Hydrologic variation during the last 170,000 years in the southern hemisphere tropics of South America. *Quaternary Research* 61, 95–104.

Fritz, S.C., Baker, P.A., Seltzer, G.O., Ballantyne, A., Tapia, P., Cheng, H., Edwards, R.L., 2007. Quaternary glaciation and hydrologic variation in the South American tropics as reconstructed from the Lake Titicaca drilling project. *Quaternary Research* 68, 410–420.

Fritz, S.C., Juggins, S., Battarbee, R.W., 1993. Diatom assemblages and ionic characterization of lakes of the Northern Great Plains, North America: A tool for reconstructing past salinity and climate fluctuations. *Canadian Journal of Fisheries and Aquatic Sciences* 50, 1844–1856.

Hogg, A.G., Hua, Q., Blackwell, P.G., Buck, C.E., Guilderson, T.P., Heaton, T.J., Niu, M., et al., 2013. ShCal13 Southern Hemisphere

calibration, 0–50,000 cal yr BP. *Radiocarbon* 55. http://dx.doi.org/10.2458/azu_js_rc.55.16783.

Li, H.-C., Ku, R.-L., 1997. δ^{13}C-δ^{18}O covariance as a paleohydrological indicator for closed-basin lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 133, 69–80.

McGlue, M.M., Cohen, A.S., Ellis, G.S., Kowler, A.L., 2013. Late Quaternary stratigraphy and geochemistry of an underfilled lake basin in the Puna plateau (northwest Argentina). *Basin Research* 25, 638–658.

Minchin, J., 1882. Notes on a journey through part of the Andean tableland of Bolivia, *Proceedings of the Royal Geographic Society* 4, 67.

Musters, G.C., 1877. Notes on Bolivia to accompany original maps. *Journal of the Royal Geographical Society of London* 47, 207.

Nunnery, J.A., 2012. *A Reconstruction of Precipitation and Hydrologic Variability on the Peruvian and Bolivian Altiplano During the Late Quaternary.* PhD dissertation, Duke University, Durham, North Carolina.

Placzek, C.J., Quade, J., Patchett, P.J., 2006. Geochronology and stratigraphy of late Pleistocene lake cycles on the southern Bolivian Altiplano: implications for causes of tropical climate change. *Geology Society of America Bulletin* 118, 515–532.

Placzek, C.J., Quade, J., Patchett, P.J., 2013. A 130 ka reconstruction of rainfall on the Bolivian Altiplano. *Earth and Planetary Science Letters* 363, 97–108.

Pompecki, S.F., 1905. Mastodon-Reste aus dem interandien Hoclande von Bolivien. *Palaeontographica* 52, 17–56.

Prasad, A.K.S.K., 1990. The genus Cyclotella in Choctawatchee Bay, Florida with special reference to C. striata and C. choctawatchee. *Phycologia* 29, 418–436.

Rigsby, C.A., Bradbury, J.P., Baker, P.A., Rollins, S.M., Warren, M.R., 2005. Late Quaternary palaeolakes, rivers, and wetlands on the Bolivian Altiplano and their palaeoclimatic implications. *Journal of Quaternary Science* 20, 671–691.

Risacher, F., Fritz, B., 1991. Quaternary geochemical evolution of the salars of Uyuni and Coipasa, Central Altiplano, Bolivia. *Chemical Geology* 90, 211–231.

Rondeau, B., 1990. Geochimie isotopique et géochronologie des stromatolites lacustres quaternaires de l'Altiplano bolivien. M.Sc. thesis, Université du Quebec à Montreal, Montreal, Québec, Canada.

Rowe, H.D., Dunbar, R.B., Mucciarone, D.A., Seltzer, G.O., Baker, P.A., Fritz, S.C., 2002. Insolation, moisture balance and climate change on the South American Altiplano since the last glacial maximum. *Climate Change* 52, 175–199.

Schubert, C.J., Nielsen, B., 2000. Effects of decarbonation treatments on δ13C values in marine sediments. *Marine Chemistry* 72, 55–59.

Servant, M., 1977. La cadre stratigraphique du Plio-Quaternaire de l'Altiplano des Andes Tropicales en Bolivie. *Recherches Francaises sur le Quaternaire Bulletin de l'AFEQ* 50, 324–327.

Servant, M., Fontes, J.-C., 1978. Les lacs quaternaires des hauts plateaux des Andes Boliviennes premieres interpretations paleoclimatiques. *Cahiers ORSTOM Serie Geologie* 10, 9–23.

Sylvestre, F., Servant-Vildary, S., Servant, M., 1998. Le dernier maximum glaciaire (21,000–17,000 ^{14}C ans B.P.) dans les Andes tropicales de Bolivie d'apres l'etude des diatomes. *Comptes rendus de l'Académie des Sciences Paris* 327, 611–618.

Sylvestre, F., Servant, M., Servant-Vildary, S., Causse, C., Fournier, M., Ybert, J.P., 1999. Lake-level chronology on the southern Bolivian Altiplano (18°–23°S) during Late-Glacial time and the early Holocene. *Quaternary Research* 51, 54–66.

Talbot, M.R., 1990. A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates. *Chemical Geology* 80, 261–279.

Talbot, M.R., 2001. Nitrogen isotopes in paleolimnology. Last, W.M. and Smol, J.P. (Eds), Tracking Environmental Change Using Lake Sediments. Volume 2. Physical and Geochemical Methods. Kluwer Academic Press, Dordrecht, pp. 401–439.

Tapia, P.M., Fritz, S.C., Baker, P.A., Seltzer, G.O., Dunbar, R.B., 2003. A Late Quaternary diatom record of tropical climatic history from Lake Titicaca (Bolivia/Peru). *Palaeogeography, Palaeoclimatology, and Palaeoecology* 194, 139–164.

Trauth, M.H., Bookhagen, B., Marwan, N., Strecker, M.R., 2003. Multiple landslide clusters record Quaternary climate changes in the northwestern Argentine Andes. *Palaeogeography, Palaeoclimatology, and Palaeoecology* 194, 109–121.

Wirrmann, D., Mourguiart, P., 1995. Late Quaternary spatiotemporal limnological variations in the Altiplano of Bolivia and Peru. *Quaternary Research* 43, 344–354.