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Hydrologic variation during the last 170,000 years in the southern hemisphere tropics of South America

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Abstract

Despite the hypothesized importance of the tropics in the global climate system, few tropical paleoclimatic records extend to periods earlier than the last glacial maximum (LGM), about 20,000 years before present. We present a well-dated 170,000-year time series of hydrologic variation from the southern hemisphere tropics of South America that extends from modern times through most of the penultimate glacial period. Alternating mud and salt units in a core from Salar de Uyuni, Bolivia reflect alternations between wet and dry periods. The most striking feature of the sequence is that the duration of paleolakes increased in the late Quaternary. This change may reflect increased precipitation, geomorphic or tectonic processes that affected basin hydrology, or some combination of both. The dominance of salt between 170,000 and 140,000 yr ago indicates that much of the penultimate glacial period was dry, in contrast to wet conditions in the LGM. Our analyses also suggest that the relative influence of insolation forcing on regional moisture budgets may have been stronger during the past 50,000 years than in earlier times.

Keywords: Quaternary, paleohydrology, paleoclimate, diatoms, oxygen isotopes, evaporites, tropics, South America, Andes, Altiplano

Introduction

Understanding the patterns and forcing of climate variation at orbital, millennial, and submillennial time scales requires long well-dated time series of paleoclimatic data, particularly from areas of the globe thought to be critical centers of climatic action. Changes in the rate of meridional overturning ocean circulation (Stocker, 2000), tropical production of carbon dioxide, methane, and especially water vapor (Blunier et al., 1995 and Wielicki et al., 2002), and modes of tropical ocean–atmosphere interaction (Cane and Clement, 1999 and Peterson et al., 2000) have been posited as sources of intrinsic climate variability. Likewise, variations in solar radiation

may have externally forced climate on both orbital (Berger, 1978) and suborbital (Bond et al., 2001) time scales. The relative roles of these different components of the climate system are still unclear; moreover, their respective contributions may have changed with time (Gallup et al., 2002 and McManus et al., 1999).

The South American tropics are an important component of the tropical climate system, and accordingly the number of published paleoclimatic records from this region has increased in recent years (e.g., Baker et al., 2001a; Baker et al., 2001b; Betancourt et al., 2000; Bobst et al., 2001; Maslin and Burns, 2000; Mayle et al., 2000; Peterson et al., 2000 and Seltzer et al., 2000). Even so, very few continental records extend to

intervals significantly earlier than the last glacial maximum (LGM), approximately 20,000 yr ago. One prominent exception is a pollen sequence spanning over a million years from Sabana de Bogota in Columbia (Hooghiemstra et al., 1993), which shows a strong relationship between vegetation change and orbital forcing, although it is unclear what environmental factor(s) (e.g., CO_2 , temperature, precipitation) affected the vegetation changes. The limited number of long continental records makes it difficult to evaluate (1) whether the tropics have experienced the same high-frequency climate variation evident in ice cores from northern high latitudes and some marine sediment cores, (2) whether climate during the LGM and subsequent deglaciation are similar to previous glacial–interglacial periods, and (3) what the role of the South American tropics might have been in affecting atmospheric gas concentrations. Here, we present a well-dated 170,000-yr time series of hydrologic variation from Salar de Uyuni in tropical

South America that extends from modern times through most of the penultimate glacial period (marine oxygen isotope stage 6, MIS 6).

The Salar de Uyuni (20°S 68°W , 3653 m above sea level), the world's largest salt flat, is located on the Bolivian Altiplano, a high-elevation plateau between the eastern and western cordilleras of the central Andes (Figure 1). Water inputs to the modern Salar are from local precipitation and river runoff. Today, Lake Titicaca overflows southward via the Rio Desaguadero into Lago Poopo. During extremely wet periods of the past, Lago Poopo discharged into Salar de Coipasa and Salar de Uyuni, thus establishing a hydrologic connection between the northern and central Altiplano. The Salar de Uyuni is underlain by hundreds of meters of sediment, which consist of muds, deposited in perennial lakes, that alternate with salts (halite and gypsum), deposited in shallow hypersaline lakes or salt pans. This sequence of muds and salts registers respectively, wet versus dry periods and provides a long-term record of the hydrologic history of the basin. We previously reported on the timing of wet and dry periods in the ^{14}C -dated portion of the Salar de Uyuni record, spanning the past 50,000 years (Baker et al., 2001a). Here, we apply the U/Th isochron method (Ku, 2000), which allows us to date salt intervals accurately over the past 170,000 yr. Furthermore, we present new paleobiotic and geochemical data that enable us to estimate the water depth of the paleolakes and precipitation variation through time.

Climatic setting

Modern mean annual temperature at Salar de Uyuni is 5°C , mean annual precipitation is about 150 mm yr^{-1} , and potential evapotranspiration exceeds precipitation. The majority of precipitation over the basin occurs during December through March as part of the South American summer monsoon (Zhou and Lau, 1998). In the austral summer, the easterly trade winds strengthen in the Atlantic, which increases moisture transport from the Atlantic onto the continent. Moisture is then advected in low-level winds across the Amazon, then southward down the eastern flank of the Andes into an intensifying surface low, known as the Gran Chaco low, located immediately east of the Altiplano. Near the eastern slope of the Andes, convective heating lifts this moist air from the lowlands onto the Altiplano. The intense summer heating of the continental interior and the resultant latent heat release by precipitation over the Amazon and Altiplano give rise to the Bolivian high, a warm-core anticyclone in the upper troposphere that is centered above the Altiplano (Lenters and Cook, 1997). The position and strength of the Bolivian high has been linked to changes in equatorial Pacific sea-surface temperatures associated with ENSO and is thought to modulate the easterly penetration of winds bringing moisture from the Amazon onto the Altiplano (Garreaud et al., 2003 and Vuille et al., 2000), thereby affecting interannual precipitation variation on the Al-

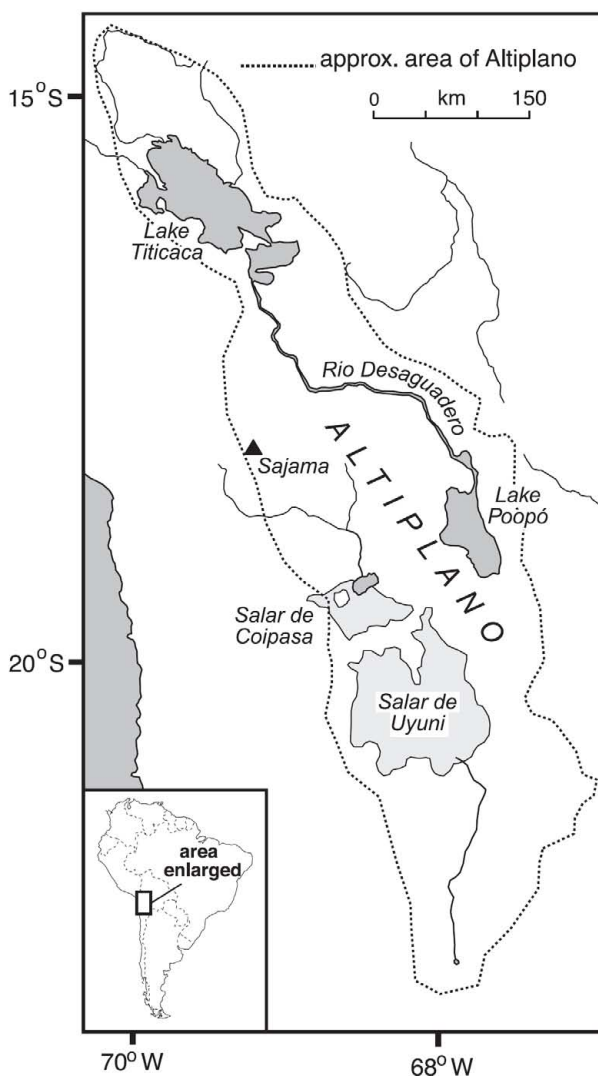


Figure 1. Map of the Altiplano, showing the Salar de Uyuni, Lake Titicaca, Sajama, and major rivers.

tiplano. On decadal and longer timescales, it is speculated that changes in tropical-Atlantic meridional sea-surface-temperature gradients also force precipitation variability in the Amazon (Nobre and Shukla, 1996), on the Altiplano (Baker et al., 2001a), and in the South Atlantic convergence zone (Robertson et al., 2000).

Methods

Field

In June 1999, we drilled and cored the uppermost 220.6 m of sediment in the central portion of the Salar de Uyuni (20°14.97'S, 67°30.03'W). Recovery was ~85%, and thus some gaps occur in the otherwise continuous sediment sequence caused by loss of material associated with fluid circulation in drilling. Following drilling, the stud-cased hole was logged at 10-cm intervals to a depth of 188.7 m sub-bottom with a tool that measures natural gamma radiation (Figure 2).

Dating

AMS radiocarbon measurements were made on the total organic carbon content of mud or salt from 17 samples in the uppermost 31 m of core. Dates were calibrated using Calib 4.3 (Stuiver et al., 1998) for ages <24,000 cal yr B.P. and the quadratic equation of Bard et al., 1998 for older samples. Ages are corrected for stable-isotope fractionation but are not adjusted for reservoir effects. The reservoir effect for the paleolakes in the Uyuni basin is not known but is assumed to be small, because there is little carbonate rock in the watershed, and because during the major lake phases, the large volume of inflow from Lake Titicaca and the large surface area to volume ratio of the paleolakes would have minimized the contribution of non-atmospheric carbon (for further details see Baker et al., 2001a, and Sylvestre et al., 1999). The U-series disequilibrium method, which can be used to date materials up to ~300,000 yr (Ku, 2000), was used to date 14 samples from salt units to a depth of 116.5 m. Salts for U-

series dating were screened by thin-section examination to avoid samples that had undergone diagenetic modification and to choose samples with minimal development of shallow subsurface halite cement. Age estimates for the core sequence are based on a fourth order polynomial equation fit to the combined radiocarbon and U-Th ages in the upper 100 m of core (Figure 3).

Stratigraphy

The core was measured and described in the field and subsequently described in more detail in the laboratory. One hundred thin sections of the evaporites were prepared for petrographic studies, using a diamond wire saw. X-ray diffraction was used for routine mineral identification.

Diatoms

Samples from mud units were processed for diatom analysis by treatment with 10% HCl to dissolve carbonates, followed by a cold hydrogen-peroxide 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 100x on a Leica DMRX microscope with differential interference contrast. Where possible, at least 300 diatom valves were 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.

Isotopes

Stable oxygen isotopic ratios of the carbonate fraction of mud samples were measured in the stable isotope laboratory at North Carolina State University. The precision of the analysis is $\pm 0.06\text{‰}$ based on replicate analyses of internal standards. In preparation for analysis, all samples were rinsed in reagent-grade water to remove soluble salts.

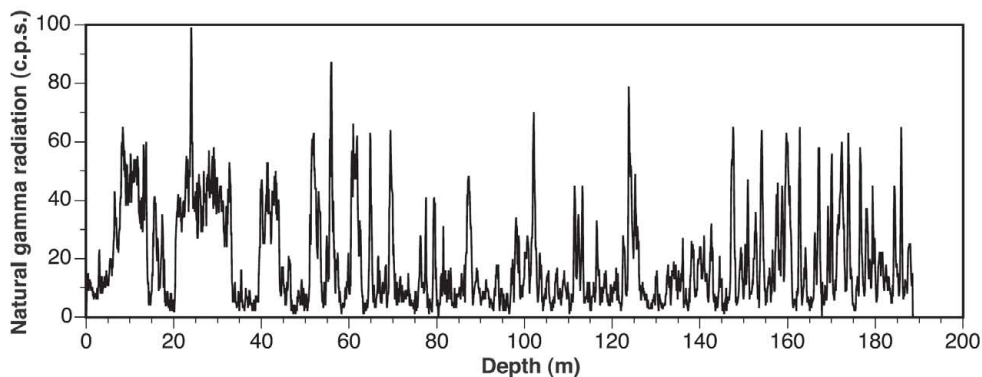


Figure 2. Log of natural gamma radiation (counts per second) in the Salar de Uyuni drill hole for the entire 188-m logged sequence.

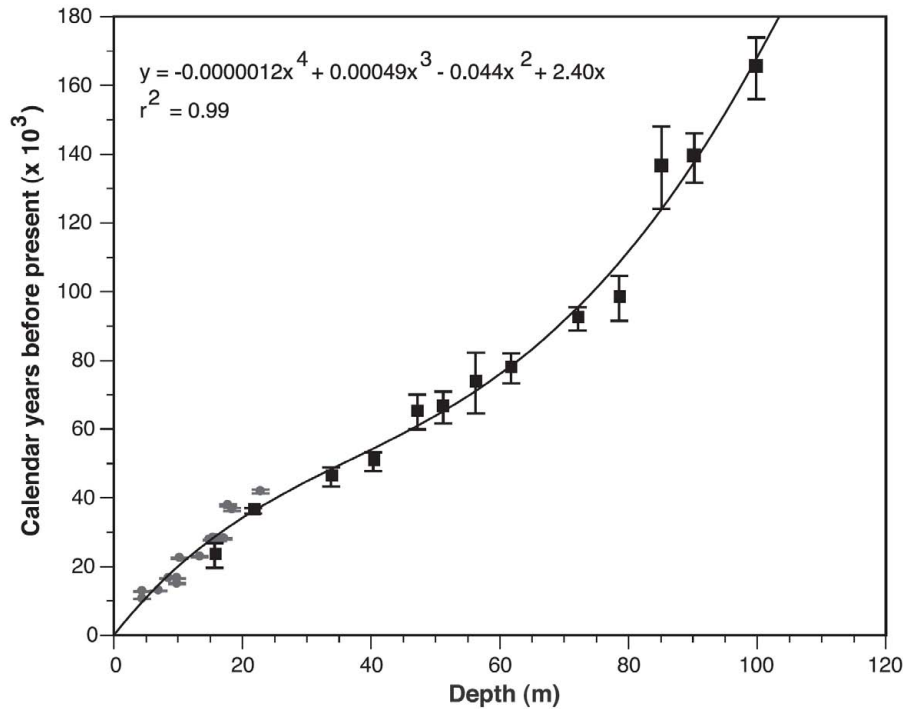


Figure 3. Relationship between core depth and calendar age as established by accelerator mass spectrometry ^{14}C analysis of organic carbon (gray circles) and U/Th series disequilibrium dating of salts using the isochron method (larger black squares). Error bars represent 1σ .

Results

Chronology

The U-series ages indicate that the upper 100 m of the core spans approximately the past 170,000 years (Table 1). A date of 276,000 ($\pm 21,000$) yr on salt at 116 m is near the limit of the U-series method and indicates that accumulation rates de-

clined sharply below 100 m. As a result, we focus here on the uppermost 100 m. Our two uppermost U-series dates overlap with the radiocarbon chronology (Figure 3). The youngest of these U-series ages ($23,000 \pm 3,600$ yr, 15.65 m) is less than the bracketing radiocarbon ages (Table 1), but has a relatively large error, which arises from uncertainties in the detrital ^{230}Th correction. Thus, the radiocarbon chronology in this zone is more likely correct. The U-series age estimate at 21.65

Table 1. Radiocarbon ages determined by accelerator mass spectrometry (AMS) on the total organic carbon of the mud and U-series disequilibrium dating of the salts using the isochron method

Sample number	Sample depth (m)	$\delta^{13}\text{C}\%$ PDB	Radiocarbon age ($\pm 1\sigma$) ^{14}C yr B.P.	Calibrated age ($\pm 2\sigma$) cal yr B.P.	Sample depth (m)	U/Th age ($\pm 1\sigma$) (yr)
11511	6.91	-16.0	$10,980 \pm 55$	12,659 (12,993) 13,162	15.65	$23,200 \pm 3,600$
10884	8.47	-13.9	$13,800 \pm 100$	16,067 (16,560) 17,091	21.65	$36,200 \pm 800$
11509	9.77	-13.9	$13,840 \pm 65$	16,142 (16,606) 17,109	33.75	$46,100 \pm 2,800$
10885	10.20	-13.6	$18,920 \pm 250$	21,575 (22,452) 23,406	40.30	$50,500 \pm 2,700$
10886	13.35	-13.4	$19,250 \pm 190$	22,027 (22,832) 23,730	47.2	$64,900 \pm 5,100$
10887	15.14	-13.5	$23,600 \pm 190$	27,750	51.15	$66,300 \pm 4,700$
10888	15.72	-13.4	$24,100 \pm 200$	28,200	56.25	$73,400 \pm 8,800$
10889	16.22	-13.3	$24,000 \pm 800$	28,210	61.75	$77,700 \pm 4,400$
10890	17.09	-13.4	$23,900 \pm 190$	28,100	72.10	$92,100 \pm 3,500$
10891	17.70	-15.9	$32,600 \pm 410$	37,830	78.55	$98,000 \pm 6,500$
10892	18.37	-15.5	$31,500 \pm 480$	36,630	85.10	$136,000 \pm 12,000$
10893	22.78	-17.6	$36,300 \pm 590$	41,840	90.20	$138,900 \pm 7,200$
					99.80	$165,000 \pm 9,000$
					116.50	$276,000 \pm 21,000$

Radiocarbon ages were calibrated using Calib 4.3 (Stuiver et al., 1998) for ages $< 20,000$ ^{14}C yr B.P. and the equation of Bard et al. (1998) for older dates. Ages derived with Calib 4.3 show the calibrated age in parentheses and the 2σ range.

m ($36,200 \pm 800$ yr) is also less than adjacent radiocarbon ages. This sample had a low detrital content and hence is better constrained, which suggests that the adjoining radiocarbon ages may be too old, because of reworking of old carbon or because of a reservoir effect that is not accounted for. Despite these discrepancies, overall there is remarkably good agreement between the two dating methods, and given our emphasis here on millennial trends and the long-term record, we feel that the chronology is robust.

Our U-series ages cast doubt on a single Ar–Ar date of $191,000 \pm 5000$ yr reported at a volcanic ash at 46 m below the Salar surface in a previous study (Fornari et al., 2001). This ash was not recovered in our drilling, because of the loss of fine sediments in this interval caused by fluid circulation. However, the two cores are from approximately the same location on the Salar and have nearly identical stratigraphies. Our U/Th chronology places the interval at 46 m, which likely contained the ash, at about 59,000 yr. Although sources of error in the Ar–Ar age estimate are not readily apparent, the well-constrained U-series ages suggests that the Ar–Ar date is incorrect or alternatively not indicative of the age of deposition of the tephra.

Stratigraphy

We distinguish three major depositional environments in the Salar de Uyuni core based on sedimentary structures (Figure 4). Strata characterized as “perennial lake” are mud units from lakes that ranged from shallow to deep and relatively fresh to saline (based on diatom analysis; see below). The mud units vary from massive to laminated and in grain size and concentrations of carbonates (calcite, as mud and as rod-shaped fecal pellets), gypsum crystals, sulfides, organic mate-

rial, and ostracode and siliceous remains. Strata characterized as “shallow perennial saline lake” and “salt pan” are salt units that are distinguished based on salt textures. The bedded salts are dominantly halite, with laminae and thin beds of gypsum crystals and carbonate mud and pellets. Halite layers commonly contain well-preserved “chevron” textures outlined by fluid inclusion-banded crystals, as well as sorted crystal plates, rafts, and hoppers, all diagnostic of precipitation in a shallow perennial saline lake (Smoot and Lowenstein, 1991). Other halite units are nonbedded massive cements typical of saline pan deposits, such as present-day Salar de Uyuni, where extensive recycling by dilute floodwaters destroys primary halite and produces porous crusts that are later cemented.

The downhole natural gamma log from the cased drill hole provides the most complete record of the Salar de Uyuni stratigraphy, because sediment recovery in drilling was only about 85% complete. The gamma record differentiates mud units, which contain abundant radiogenic K, U, and Th, from salts, which are largely nonradioactive (Figure 2). When plotted on an age scale (Figure 4), it is apparent that the uppermost mud units are more persistent than those lower in the sequence. Furthermore, salt textures suggest that most of the salts above 70 m were deposited in shallow perennial saline lakes, whereas below this, the salts are characteristic of salt pan environments.

Diatom stratigraphy

The diatom assemblage of the Salar de Uyuni core is diverse (Figure 5), and preservation is highly variable. In the uppermost major mud unit (9.75–18.42 m), diatoms are not preserved in some samples, but those samples containing diatoms are dominated by planktic species (Figure 6a), with moder-

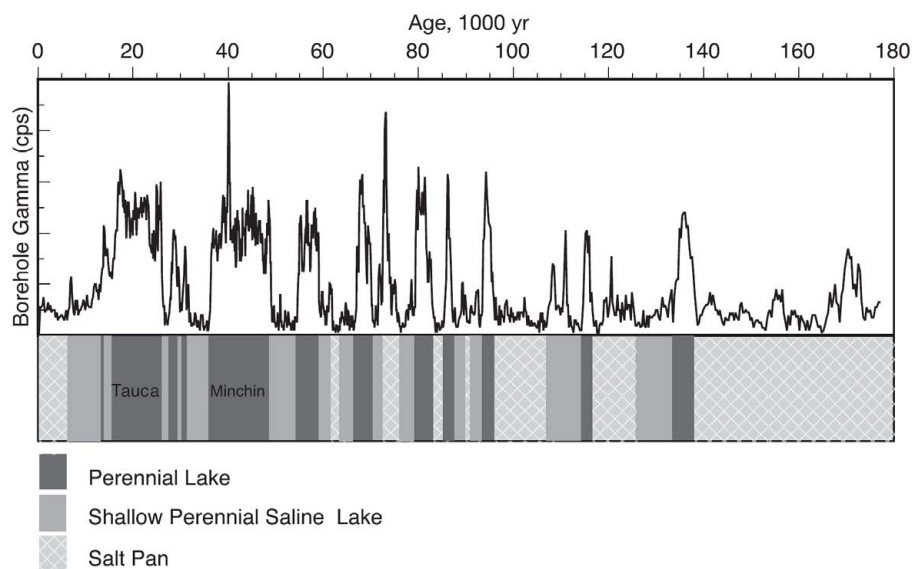


Figure 4. Generalized stratigraphy of the upper 100 m of the Salar de Uyuni core displayed versus calendar age. See text for additional details.

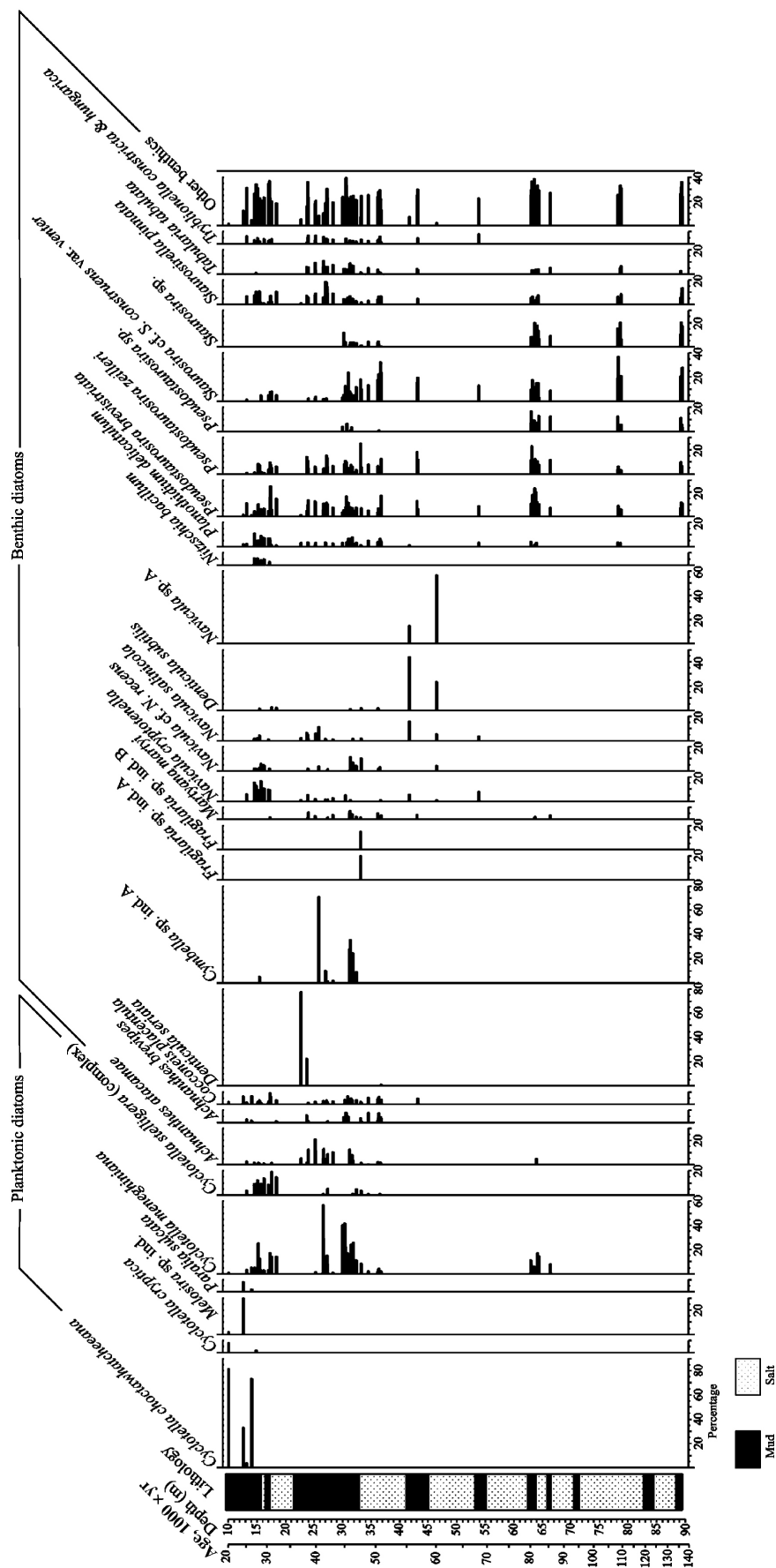


Figure 5. Stratigraphy (percent abundance) of the common (>5%) diatom taxa in the upper 100 m of the Salar de Uyuni core. Samples were taken from all mud units and from lenses of mud within some of the salt units. Note that some of the mud units, particularly below 65 m, were barren of diatoms (see Figure 6).

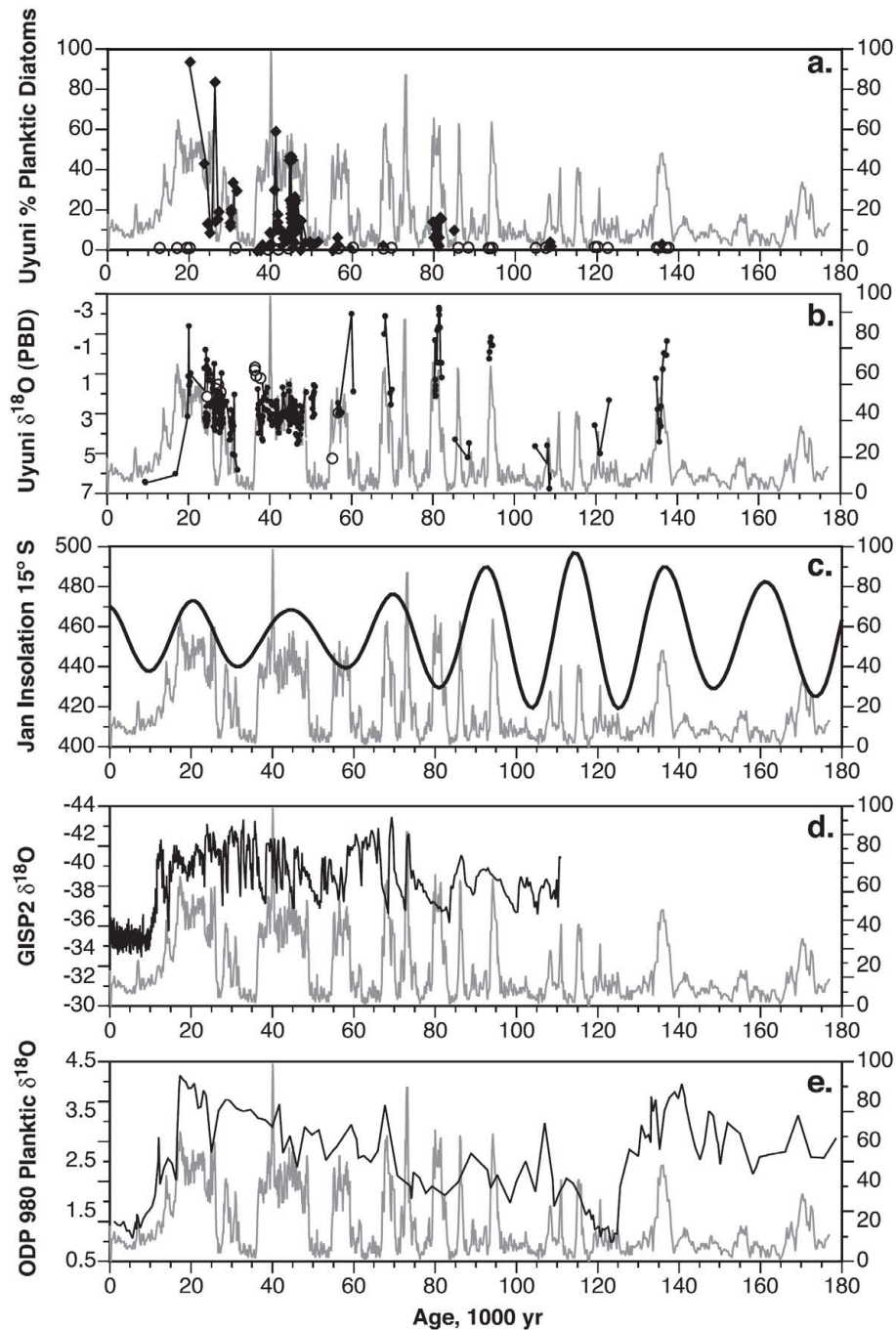


Figure 6. Changes in natural gamma radiation (gray line) in the upper 100 m of the Salar de Uyuni core (right-hand vertical axis), displayed versus calendar age, compared with biotic and geochemical measurements in the mud units and with other paleoclimatic time series. (a) Percentage of planktic (free-floating) diatoms in lacustrine muds (solid diamonds); the remainder of the diatoms are benthic (shallow-water) taxa. Samples without any preserved diatoms are indicated by open circles. (b) $\delta^{18}\text{O}$ of authigenic carbonate in the mud units; open circles are measurements on lithified crusts, (c) calculated January insolation at 15°S (Berger, 1978), (d) GISP2 $\delta^{18}\text{O}$ of the ice (Grootes and Stuiver, 1997), and (e) $\delta^{18}\text{O}$ of planktic foraminifera in North Atlantic site ODP980 (McManus et al., 1999).

ate (20–40%) percentages of benthic taxa. The saline species, *Cyclotella choctawatcheana*, is dominant in several samples in this unit, and *Cyclotella meneghiniana* and *C. stelligera*, which tolerate a range of salinities, dominate the other samples. The second youngest major mud unit (22.6–33.38 m) has high percentages of planktic species (primarily *C. meneghin-*

iana) in most levels, together with a mixture of benthic diatoms, some salinity indifferent and others characteristic of saline waters (Sylvestre et al., 2001). *Denticula seriata* dominates the uppermost samples in this section, which suggests increased salinity just prior to precipitation of the overlying salts. The third major mud unit (41.6–46.5 m) is distinct, be-

cause of the high percentages of *Denticula subtilis*, *Navicula salinicola*, and *Navicula* sp. A, which together suggest shallow moderately saline waters. A mixture of generalist benthic taxa, particularly in the genera *Pseudostaurosira*, *Staurosira*, and *Staurosirella*, dominate the diatom-bearing mud units below 50 m. Many of these species are common in freshwater springs at the margin of the contemporary Salar (Sylvestre et al., 2001). Planktic diatoms are generally rare (<4%) in these lowermost sections, with the exception of some layers between 62.95 and 66.31 m, where they attain up to 20%. In general, diatom preservation is much poorer below 40 m than above, and many of the lower mud units are barren of diatoms.

Isotopes

Stable-oxygen-isotopic ratios ($\delta^{18}O$) of lacustrine carbonates range from about -3 to $+7\text{‰}$ (PDB) (Figure 6b). The oldest muds of the uppermost mud unit ($\sim 32,000$ yr) have $\delta^{18}O$ of $+6\text{‰}$, then values decrease to $\sim 0\text{‰}$ just after the LGM, and then rapidly increase to $>6\text{‰}$ coincident with evaporative drawdown of the lake. This isotopic "cycle" is driven primarily by changes in the isotopic composition of source precipitation, the post-LGM portion of which is observed in the Sajama ice core (Thompson et al., 1998), and secondarily by changing water balance of the filling-then-desiccating paleolake. In lower mud units, mud recovery was often incomplete, and therefore we cannot generate a continuous reconstruction of the isotopic evolution of lake waters within an individual mud unit. Many of the earlier mud units have more depleted isotopic values than do the two uppermost units.

Discussion

The most distinctive feature of the Salar de Uyuni stratigraphy is that the mud units are longer in duration in the upper part of the sequence than below. The two uppermost major mud units have been identified with paleolakes Tauca (26,000–15,000 cal yr B.P.) and Minchin (46,000–36,000 yr) (Baker et al., 2001a), which are associated with dated paleoshorelines (Bills et al., 1994; Servant et al., 1995 and Sylvestre et al., 1999). Our new extended record indicates that these were also the two longest lacustrine intervals in the entire dated sequence. Fossil-diatom analysis of the muds (Figure 5 and Figure 6) suggests that paleolake Tauca was the deepest of the paleolakes, as indicated by intervals with the highest percentages of planktic diatoms and the dominance of *Cyclotella choctawatcheeana*, a planktic diatom characteristic of deep mesosaline (>10 g L⁻¹) lakes and brackish marine systems (Fritz et al., 1993 and Prasad, 1990). The highest outcropping paleoshorelines in the basin demonstrate that paleolake Tauca reached 140 m above the modern Salar (Bills et al., 1994). Stable-oxygen-isotopic values of carbonates in the Tauca unit (Figure 6b) are surprisingly low for a closed-basin saline lake, a result of input of high amounts of

isotopically depleted precipitation and inflow. Modern precipitation near the Salar averages -16‰ (SMOW) (Baker, unpublished data), and 20th-century snowfall on the nearby Sajama volcano averaged -17.5‰ (SMOW) (Thompson et al., 1998). However, during the LGM, when the Altiplano was wetter than today (Baker et al., 2001a and Baker et al., 2001b), the $\delta^{18}O$ of precipitation was considerably more depleted, averaging -22‰ in the Sajama ice core (Thompson et al., 1998). Thus, precipitation and local inflow to paleolake Tauca would have been $\sim 4\text{‰}$ lower than modern values. In the LGM, waters of Lake Titicaca were also more depleted due to more depleted values in precipitation and a greatly increased throughflow. We calculated previously that lake waters were about -13‰ , which is 9‰ more negative than today (Cross et al., 2001). At that time, outflow from Lake Titicaca was many times its modern value and likely contributed a large fraction of the input that sustained the deep paleolake in the Uyuni basin.

The diatom composition of paleolake Minchin muds suggests that lake depths varied from moderate, with high proportions of the planktic *Cyclotella meneghiniana* and *C. stelligera*, to shallow, with a diverse flora of benthic species. Isotopic analyses of authigenic carbonates of paleolake Minchin show fluctuations of up to 4‰ due to variations in the isotopic concentration of source precipitation and/or hydrologic mass balance.

Prior to $\sim 50,000$ yr, the hydrology of the Uyuni basin seems to have been fundamentally different. The thinner mud units and dominance of halite indicate that relatively fresh perennial lakes were short-lived and less frequent. In contrast to the upper part of the core, petrographic textures and fabrics of the salts indicate that many were deposited in predominantly dry salt pans rather than shallow hypersaline lakes. Similarly, the dominance of benthic diatoms in the lower mud units (Figure 5 and Figure 6) suggests that older paleolakes were relatively shallow. On the other hand, the $\delta^{18}O$ of carbonate muds in many of the older lacustrine units is surprisingly low (Figure 6b), especially given the diatom-based inference of shallow waters. It is possible that the water temperature was much higher in these shallow lakes at the time of carbonate formation, but the approximately 15°C warmer conditions required seem improbable. A more likely explanation is that overflow from Lake Titicaca to the Salar de Uyuni was reduced or absent prior to $\sim 50,000$ yr. In that case, shallow paleolakes would have formed during sustained wet periods entirely from direct precipitation and local runoff (with more negative isotopic values than Lake Titicaca overflow).

Two mechanisms can account for a reduction or absence of overflow from Lake Titicaca to the central Altiplano in the earlier part of the record. One explanation is regional climatic change, and there is limited evidence to suggest a major reduction in effective moisture in the central Altiplano prior to 50,000 yr. At the Salar de Atacama (23°S), efflorescent halite crusts and cements indicative of hyperarid conditions dominate from 325,000 to 53,000 yr, whereas bedded salts characteristic of shallow saline lakes are more common afterward

(Bobst et al., 2001 and Lowenstein et al., 2003). In addition, seismic reflection stratigraphy from Lake Titicaca indicates that lake levels were at least 240 m lower than today sometime >50,000 yr (D'Agostino et al., 2002). A second explanation for the pattern of less persistent and generally shallower lacustrine phases is geomorphic or tectonic alteration of basin hydrology, including the possibility that this period pre-dates complete downcutting of the Rio Desaguadero (Servant and Fontes, 1978). Lacustrine deposits in the upper Rio Desaguadero valley, just south of Lake Titicaca, have been radiocarbon-dated at ca. 40,000 cal yr B.P. (Rigsby, unpublished data) and have an elevation about 50 m above modern lake level. One explanation for these dated deposits is that the outlet for Lake Titicaca was south of its present location and higher in elevation at that time. In any case, this timing postdates the observed shift in Salar hydrology, which suggests that geomorphic change may not be the major driver.

Among the mud units from 140,000 to 50,000 yr, that from ~85,000 to 80,000 yr has moderate percentages of planktic diatoms (5–20%), as well as depleted values of $\delta^{18}\text{O}$, which suggest that precipitation may have been somewhat higher than in mud units immediately pre- and postdating this. In contrast, the period from about 125,000 to 105,000 yr has relatively enriched oxygen isotopic values, and diatoms are poorly preserved, which indicates enhanced silica dissolution likely related to elevated salinity. Where preserved, the diatoms are all benthic species. Together these data suggest low lake levels and reduced precipitation relative to other mud units and indicate that MIS 5d and 5e were relatively dry. Salt deposition characterized the majority of MIS6, particularly between 140,000 and 170,000 yr, which indicates that the climate was dry. Thus, the wet LGM is apparently not representative of all prior glacial stages in the central Altiplano.

Regardless of the cause of the directional change in the hydrology of the Salar prior to 50,000 yr, switches between muds and salts certainly reflect an alternation between times of increased and reduced effective moisture (Blodgett et al., 1997; Hastenrath and Kutzbach, 1985 and Kessler, 1984). During the past 50,000 years, wet periods in the Altiplano were in phase with summer (January) insolation maxima (Baker et al., 2001a) produced by the Earth's precessional cycle (Figure 6c), probably because high insolation enhanced the South American summer monsoon. Our extended record suggests that during earlier times, wet intervals and insolation were not as tightly coupled, although lacustrine phases were associated with most insolation maxima (Figure 6c). We hypothesized previously that wet intervals on the Altiplano also were associated with cold periods in the North Atlantic region, possibly because of the impact of tropical sea-surface temperature gradients on moisture advection into the continent (Baker et al., 2001a and Baker et al., 2001b). Based on our expanded time series from the Salar, the wetter periods of the past 70,000 years occurred during times of cold North Atlantic temperatures (Figs. 6d, 6e), but prior to that time the relationship is not as coherent. Thus, the data suggest that the relationship between moisture balance in the South American Altiplano and major forcing factors may have changed with time.

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