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Dating of paleolakes in the central Altiplano of Bolivia

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Abstract

The deposits of the extensive paleolakes of the Bolivian Altiplano correspond to an alternation of lacustrine episodes and dry periods, a phenomenon commonly explained by climatic changes. The lack of precise dating of the deposits has prevented detailed reconstruction of the evolution of paleolakes that would allow a determination of the relative influence of interconnections between neighboring basins and local climatic conditions. Among the five paleolakes of the northern Altiplano (Titicaca basin) and the three of the central Altiplano (Poopó, Coipasa and Uyuni basins) only the two most recent paleolakes have been dated.

A 121 m long sediment core recovered from the Salar de Uyuni contained 11 lacustrine layers (L1–L11) separated by 12 salt crusts. Radiocarbon dating shows that the younger layers L1 and L2 are related to the Tauca lacustrine phase (12 000–16 000 cal yr BP) and layers L3 and L4 to the Minchin lacustrine phase (30 000–73 000 cal yr BP). Layer L5, located at 46 m below the surface, contains a volcanic ash with well-preserved biotites is here dated by the $^{40}Ar/^{39}Ar$ method. The measured age of 191 000 ± 5000 y is the first date ever obtained from a pre-Minchin paleolake (Lake Escara). This result combined with ^{14}C and U/Th data obtained on lakes Tauca and Minchin from various authors suggests that the duration of the lacustrine events increased regularly during the Pleistocene. In contrast, paleolake levels in the northern Altiplano decreased from the oldest known (Lake Mataro, 3950 m) to the present Titicaca level (3806 m). A progressive erosion of the threshold between the northern and central Altiplano may have allowed important volumes of water to overflow from the northern basin into the central Altiplano. The existence of large paleolakes in the central Altiplano was thus not only dependent on local climatic conditions but also on additional inputs from the north, where climatic conditions could have been quite different from those prevailing in the south.

Keywords: South America; Altiplano; Paleolakes; Radiometric dating; Paleoclimate

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1. Introduction

The Altiplano is an internally drained basin of ~200 000 km^2, that is located between the eastern and the western Cordillera of the Andes (Fig. 1). It lies above 3800 m, and is under the influence of an arid to semi-arid climate; annual precipitation drops from 700 mm in the north to less than 100 mm in the south; air temperature ranges from −20 at night in winter to 20°C during the day in summer. At present, the Altiplano contains an impressive set of evaporitic basins. The numerous, poorly drained intravolcanic basins of the southern Altiplano are occupied by playas, saline lakes and salt crusts. The central trough of the Altiplano is covered by two giant salt crusts: the Salar de Uyuni (10 000 km^2) and the Salar de Coipasa (2500 km^2). To the north, Lake Titicaca (8560 km^2) is

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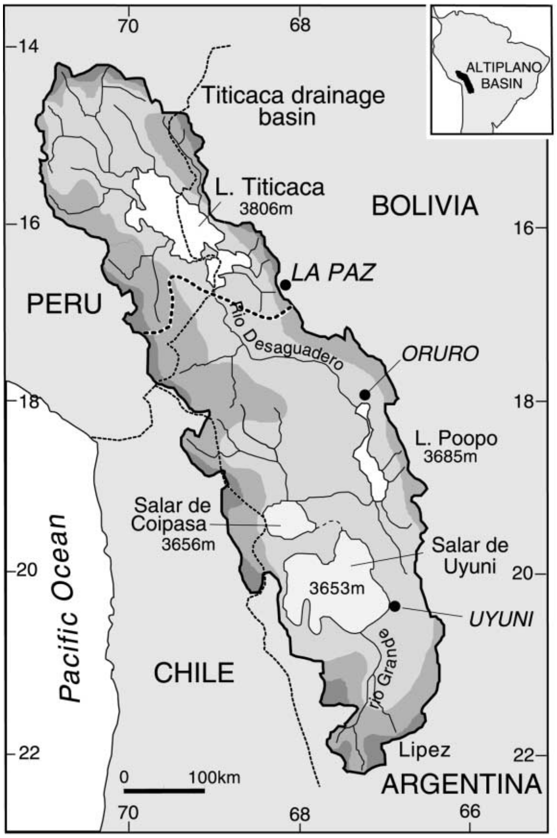

Fig. 1. Location of the Titicaca and central Altiplano drainage basins; the central Altiplano forms an endoreic basin, which includes Lake Poopo, Salar de Coipasa, Salar de Uyuni and smaller salt flats. The doted line is the actual limit between the Titicaca basin and the central Altiplano basin.

at an elevation of ~3806 m, and is 285 m deep; this makes it the lowest point on the Altiplano.

The Altiplano has been repeatedly covered by extensive paleolakes which have been studied for more than a century. These lakes were characterized by alternating episodes of expansion and desiccation that are commonly explained by climatic changes (changes of atmospheric circulation and deglaciation). Temporal interconnections between neighboring basins are rarely examined, mainly because of the lack of precise geochronological data (Servant and Fontes, 1978; Hastenrath and Kutzbach, 1985; Blodgett et al., 1997; Sylvestre et al., 1999).

Among the Andean paleolakes, Lake Ballivián in the northern Altiplano (Titicaca Basin) and Lake Minchin in the central Altiplano (Uyuni, Coipasa and Poopó basins were initially described (Minchin, 1882; Steinmann et al., 1904) but not dated. Lacustrine sediment outcrops and terraces can be observed in the northern and central Altiplano, whereas carbonate algal bioherms and salt crusts are only found in the central Altiplano. The first radiocarbon dating by Servant and Fontes (1978) of these paleolakes used shells in lacustrine outcrops from the central Altiplano. They identified two lacustrine episodes named Lake Tauca (12 000–10 000 ^{14}C yr BP; 14 100–11 400 cal yr BP) and Minchin (>32 200 cal yr BP). A former episode, corresponding to the Lake Escara, was observed in the central Altiplano, but was not dated. In the northern Altiplano, Servant and Fontes (1978) identified three undated lacustrine episodes, Titicaca–Tauca (at ca. 3815 m), Titicaca–Minchin (at ca. 3825 m) and Ballivián (at ca. 3860 m), which they tentatively correlated with those of the central Altiplano. Lavenu et al. (1984) described two pre-Ballivián paleolakes in the Titicaca Basin, and named them Cabana (at ca. 3900 m) and Mataro (at ca. 3950 m; Fig. 2).

More recently, active research on the Altiplano has focused on sediments from Lake Titicaca (Wirrmann, 1987; Wirrmann et al., 1992; Mourguiart et al., 1992; Wirrmann and Mourguiart, 1995; Abbott et al., 1997; Binford et al., 1997; Mourguiart et al., 1997; Baker et al., 1998; Rowe et al., 1998; Seltzer et al., 1998; Mourguiart et al., 1998), on various carbonate algal bioherms in the central Altiplano (Rondeau, 1990; Causse et al., 1995; Rouchy et al., 1996; Grove et al., 1998) and on paleoclimatic reconstruction and modeling (Hastenrath and Kutzbach, 1985; Servant-Vildary, 1993; Bills et al., 1994; Servant et al., 1995; Sylvestre, 1997; Blodgett et al., 1997). The Salar de Uyuni has also been studied in detail (Rettig et al., 1980; Risacher and Fritz, 1991).

Lake Tauca is now subdivided into three lacustrine phases named Tauca (19 100–15 600 cal yr BP), Ticaña (15 600–13 400 cal yr BP) and Coipasa (13 400–12 300 cal yr BP) (Sylvestre, 1997; Sylvestre et al., 1999). In contrast, much less information is available on Lake Minchin. Neither the formation, nor the drying of this paleolake are precisely dated, but Servant and Fontes (1978) estimated the end of Lake Minchin at 32 200 cal yr BP by dating shells of lacustrine outcrops. Two generations of algal

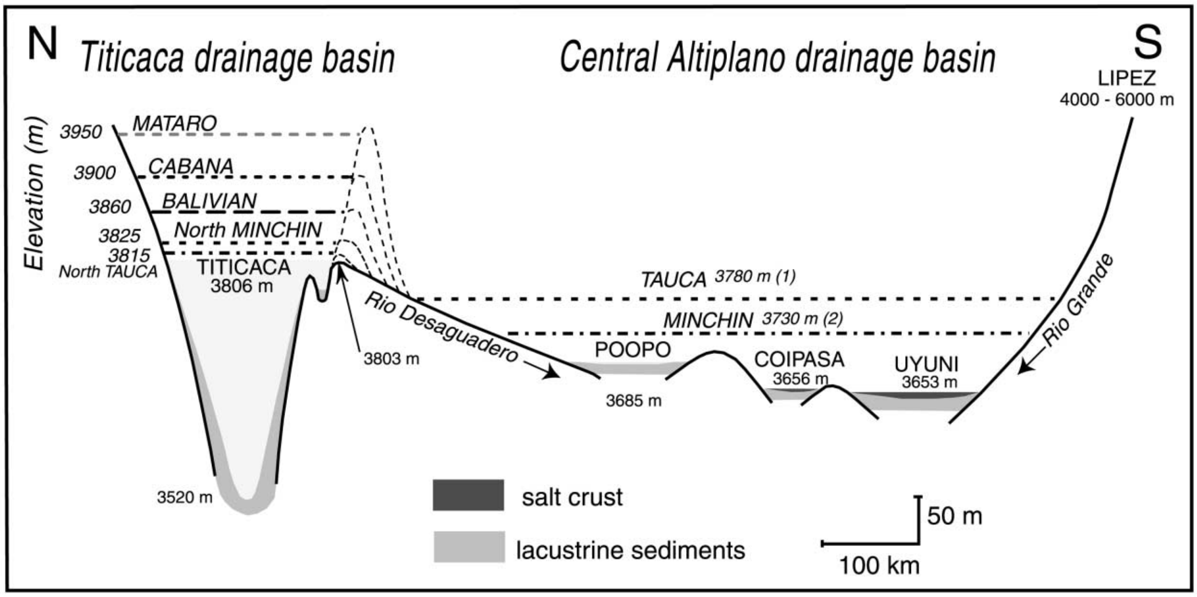

Fig. 2. NS schematic section of the Altiplano with the reconstruction of the paleolake levels in the northern and the central drainage basins. (1) from Rouchy et al. 1996; (2) from Bills et al. 1994. Hypothetical overflow levels for the three older paleolakes are shown as a doted line. Note the difference between vertical and horizontal scale.

bioherms related to Lake Minchin were dated by the U/Th technique at 34 000–44 000 and 68 000–72 000 yr BP. (Rondeau, 1990).

Table 1 reviews the prior chronological studies and includes our results. The latest lacustrine event (Coipasa) was separated from the Tauca event by Servant et al. (1995) and Sylvestre et al. (1999). It is possible that some Tauca datings in other studies are to be related to Coipasa (Servant and Fontes, 1978; Rondeau, 1990; Grove et al., 1998). However, the short Coipasa event could be considered as the last Tauca oscillation before complete desiccation. The correlation between Lake Escara and Lake Ballivián is hypothetical, as no dates are available for Lake Ballivián.

Datable material is scarce in the Bolivian Altiplano. Wood is considered to be the most reliable material for radiocarbon dating. Unfortunately, wood samples have not been found so far. Carbonate shells and probably also Characeae, are the best available material for radiocarbon dating. However, shells may be reworked (Sylvestre et al., 1999). Disseminated organic matter in sediments may be used with lower but still reasonable confidence. Finally, calcareous crusts and algal bioherms are the least useful material due to their frequent recrystallisation. Datable samples are generally selected after close petrographic inspection.

In closed lakes, contamination by old carbon in fossil water can lead to older ages (reservoir effect). Thus, it is not easy to extrapolate measurements on present lakes to the past. Moreover, $^{14}C/^{12}C$ ratios in living organisms depend on the ratio in the lakewater, which could be different than the atmospheric ratio. In order to estimate the error in ^{14}C ages, Sylvestre et al. (1999) compared ^{14}C and U/Th ages of the same samples. They found a good agreement during time of high lake levels and a divergence as high as 1000 yr for the lowstand Coipasa event.

Seventy ages are available for the Tauca event and 14 for Minchin. With the exception of the youngest U/Th date of Rondeau (1990) on algal bioherms, all dates of the Tauca event are quite consistent and point to an age of 12 000–16 000 yr BP. in both the central and the northern Altiplano with the highest stand around 16 000 yr BP. The end of Minchin seems to be fairly well dated around 30 000 yr BP. Older Minchin ages are U/Th ages of algal bioherms. The

Table 1
Compilation of radiometric ages

Central Altiplano					Northern Altiplano				
Paleolake	Material (number)	Method	Age in yr BP	Ref.	Paleolake	Material	Method	Age in yr BP	Ref.
Coipasa 3660 m	Calcareous crust (9)	^{14}C	8,500–9,500	Servant et al. (1995) and Sylvestre et al. (1999)					
Tauca 3780 m	Shells (3)	^{14}C	12 400–14 500	Servant and Fontes (1978)	Tauca 3815 m	Shells (2)	^{14}C	12 200–16 500	Mourguiart et al. (1997)
	Calcareous crust (5)	^{14}C	11 600–14 500	Servant and Fontes (1978)			^{14}C	13 200 (Highstand)	Sylvestre et al. (1999)
	Algal bioherms (5)	U/Th	7200–14 800	Rondeau (1990)					
	Algal bioherms (21)	^{14}C	8100–17 200	Rondeau (1990)					
	Shells (2)	^{14}C	16 800 (Highstand)	Bills et al. (1994)					
	Algal bioherm (1)	U/Th	16 650 (Highstand)	Causse et al. (1995)					
	Organic matter (4)	^{14}C	11 600–16 700	Grove et al. (1998)					
	Shells (12)	^{14}C	13 000–15 600	Servant et al. (1995) and Sylvestre et al. (1999)					
	Characeas (10)	^{14}C	14 000–16 400	Servant et al. (1995) and Sylvestre et al. (1999)					
	Algal bioherms (2)	^{14}C	14 500	Servant et al. (1995) and Sylvestre et al. (1999)					
	Carbonate (1)	^{14}C	14 300	This study					
	Organic matter (2)	^{14}C	13 000–16 100	This study					
	Shells (2)	^{14}C	before 32 200	Servant and Fontes (1978)					
	Algal bioherms (6)	U/Th	34 400–72 600	Rondeau (1990)					
Minchin 3730 m	Algal bioherms (4)	U/Th	40 000	Causse et al. (1995)	Minchin 3825–3860 m	Shells (3)	^{14}C	Before 31 100	Mourguiart et al. (1997)
	Carbonate (1)	^{14}C	Before 34 400	This study					
	Organic matter (1)	^{14}C	36 000	This study					
Escara	Ashes, biotites	Ar/Ar	191 000	This study	Ballivian 3860 m			?	Servant and Fontes (1978) and Lavenu et al. (1984)
?					Cabana 3900 m			?	Lavenu et al. (1984)
?					Mataro 3950 m			?	Lavenu et al. (1984)

oldest ages reported for Minchin are about 68 000–73 000 yr BP. According to Rondeau, 1990, they would correspond to the first bioherm generation. Radiocarbon and U/Th chronology based on distinct samples show a good overall agreement.

In this paper we present the subsurface stratigraphy in the central part of the Salar de Uyuni observed in a 121 m deep borehole. A volcanic ash embedded in the core provides a unique opportunity to furnish direct time constraints on a pre-Minchin paleolake. The age of this layer allows us to discuss more precisely the duration of the main episodes of dry and humid periods during the last 200 000 yrs in the central Altiplano, and to evaluate the influence of the northern Altiplano on the hydrology of the central Altiplano. Here we show that the thicknesses of the successive central Altiplano paleolake deposits seem highly dependent on the direct connection with the northern basin. This point is crucial for paleoclimate reconstructions in the Altiplano region.

2. Methods

2.1. Drilling procedure

The borehole was drilled 10 km north of Incahuasi Island in May–June 1986 (UTM 19KFT42957170) with a Craelius Pixie®51 short-hole core drilling machine. The superficial brine of the salar was used as injection fluid to drill the salt crusts. The mud layers were sufficiently plastic to be cored dry, which avoided contamination of the mud by the injection fluid. Core diameter ranged from 2 to 4 cm, according to the diameter of the core sampler. The hole was progressively cased down to 70 m. At 121 m, the drilling stopped in a salt layer, but the bottom of the basin is probably much deeper. Samples for radiocarbon dating where dried to avoid bacterial or fungi growth and sealed in plastic bags.

2.2. Semi-quantitative determination of mineral fraction

X-ray diffraction shows that calcite, aragonite, gypsum, halite and volcanic detrital material (silicates) makes up the bulk of the salt crusts and mud layers. A known weight of dried sample was washed in a known volume of distilled water. Li, Cl and Ca were analysed in the rinse water. A dried sample contains salts precipitated from the interstitial brine retained in openings of the salt/sediment. Li is assumed to be present only in precipitated salts from the interstitial brine. Cl is assumed to come from halite and precipitated salts and Ca from gypsum and salts. The amount of Ca resulting from the dissolution of calcium carbonate is neglected. At each sample location, interstitial brine concentrations of Li, Cl and Ca and total salinity are interpolated from 53 analyses of interstitial brines pumped in the salt crusts or squeezed in mud sediments. The amounts (in %) of halite and gypsum are given by:

$$(\text{halite}\%) = \frac{[\text{Cl}]_{\text{wash}} - [\text{Cl}]_{\text{brine}} \times [\text{Li}]_{\text{wash}}/[\text{Li}]_{\text{brine}}}{1000 \times m/v - [\text{TDS}]_{\text{brine}} \times [\text{Li}]_{\text{wash}}/[\text{Li}]_{\text{brine}}} \times 5.85$$

$$(\text{gypsum}\%) = \frac{[\text{Ca}]_{\text{wash}} - [\text{Ca}]_{\text{brine}} \times [\text{Li}]_{\text{wash}}/[\text{Li}]_{\text{brine}}}{1000 \times m/v - [\text{TDS}]_{\text{brine}} \times [\text{Li}]_{\text{wash}}/[\text{Li}]_{\text{brine}}} \times 17.21$$

Where $[\ ]_{\text{wash}}$ is the concentration in mmol/l in the rinse water, $[\ ]_{\text{brine}}$ is the concentration in mmol/l in the interstitial brine, m is the amount in grams of dried sample (0.5 g for halite and 0.1 g for gypsum), and v is the volume in ml of distilled washing water (25 ml for halite and 50 ml for gypsum)

Volcanic detrital material is determined gravimetrically after washing successively the dried sample with H_2O_2 (110 vol), dilute HCL, and distilled water. Calcite is determined by calcimetry of the dried bulk sample. The results in % must be corrected for the amounts of precipitated salts from the interstitial brine. Bulk percents must be divided by:

$$1 - [\text{TDS}_{\text{brine}} \times ([\text{Li}]_{\text{wash}}/[\text{Li}]_{\text{brine}}) \times ((v/m)/1000)$$

where TDS is total dissolved solids.

3. Stratigraphy

Eleven soft mud layers (L1–L11) alternate with twelve hard salt crusts (S1–S12) (Fig. 3). The mud layers consist essentially of calcium carbonate (calcite or aragonite), gypsum, and volcanic detrital material. Clay minerals are scarce. *Artemia* faecal

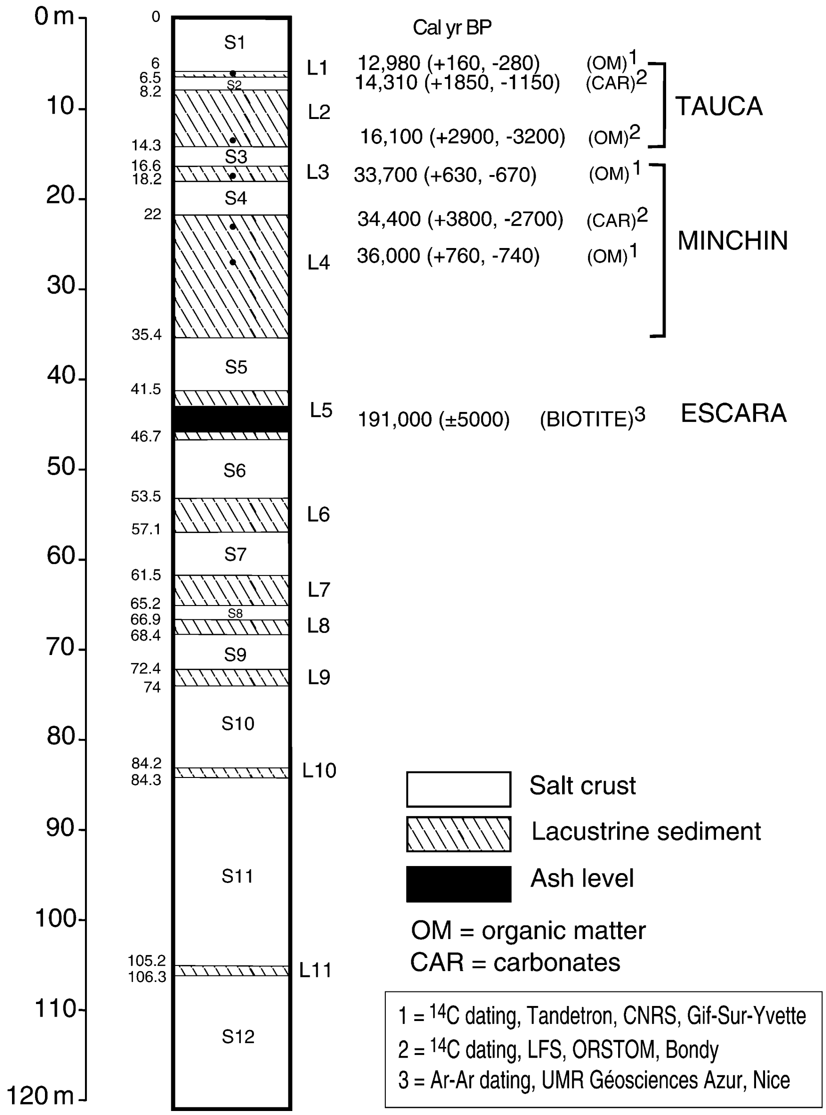

Fig. 3. Log of the borehole showing the stratigraphic units and the position of the dated samples in the central Salar de Uyuni evaporitic sequence.

pellets are present in mud layers L1–L9. At 46 m, mud layer L5 contains a 3 m thick volcanic ash with well-preserved biotites; the presence of unfragmented pristine acicular amphibole crystals indicates that the ash has not been reworked, although the biotite flakes are more altered in the upper part of the layer. The porosity of the mud layers varies between 30 and 50% and does not decrease with depth, suggesting that the sediments have not undergone significant compaction. The salt crusts consist mainly of halite with a minor amount of gypsum. Their porosity (15–30%) is lower than that of the mud layers. The entire profile contains an interstitial brine, except the upper 5–10 cm during the dry season. Semi-quantitative estimates of the mineral fractions are shown in Fig. 4.

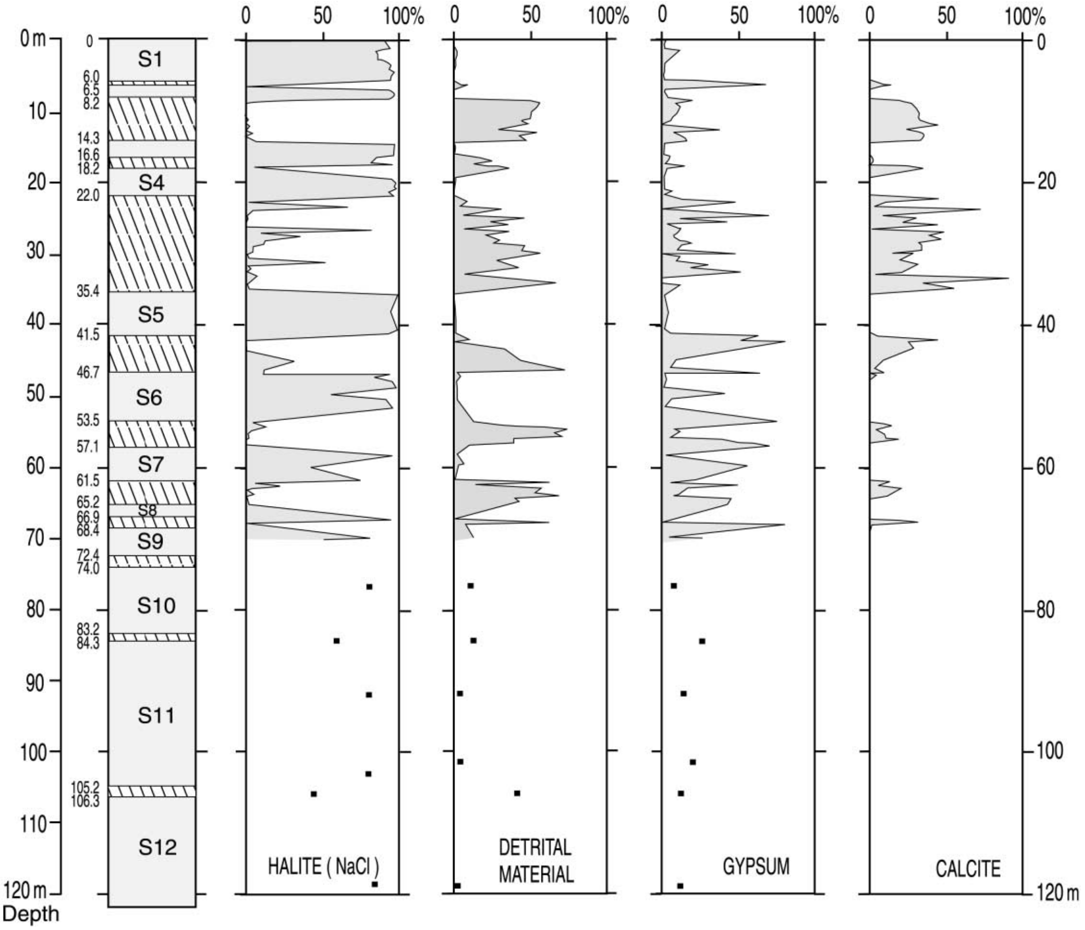

Fig. 4. Semi-quantitative mineral contents (in %) in the evaporitic sequence from the drill hole in the central Salar de Uyuni.

4. ^{14}C results

Six ^{14}C analyses were performed on two carbonate samples and four organic matter samples from the upper mud layers L1–L4 (Fig. 3, Table 2). Three analyses were done by liquid scintillation counting (Geochronology Laboratory, Orstom, Bondy, France, 1987) and three other analyses with a tandem accelerator mass spectrometer (Tandetron, CNRS, Gif-Sur-Yvette, France, 1991). Carbonates were observed by scanning electron microscopy (SEM) to check for detrital fragments and diagenetic overgrowths. Even if such features were not observed, an authigenic origin cannot be definitely ensured. Organic material is more reliable, although the ^{14}C/^{12}C ratios in organisms depend on the ratio that existed in the lakewater, which could have been different from the atmospheric ratio. This reservoir effect is more important in small lakes than in large lakes such as Lake Tauca and Lake Minchin. By comparing U/Th and ^{14}C ages, Sylvestre et al. (1999) showed that radiocarbon ages are valid during times of high lake level.

Radiocarbon ages were calibrated to calendar ages with the CALIB program (Stuiver and Reimer, 1993; Stuiver et al., 1998). Prior to 20 000 yr BP, ages were corrected with the polynomial of Bard (1998); Bard et al. (1998). From bottom to top, the ages range from 36 940 ± 750 to 12 980 (+160, −280) cal yr BP, with a good apparent internal agreement.

Table 2
Radiocarbon ages of sediments from Salar de Uyuni

Sample No.	Method	Material	Depth (cm)	Measured age (^{14}C yr BP)	Measured error (^{14}C yr BP)	Calibrated age (cal yr BP)	Calibrated error (cal yr BP)
UA-630	LSC[a]	Carbonates	630	12 340	+ 1240 − 1080	14 310	+ 1850 − 1150
UA-630	TAMS[b]	Organic matter	630	10 940	+ 150 − 150	12 980	+ 160 − 280
UA-1410	LSC	Organic Matter	1410	13 370	+ 2930 − 2160	16 100	+ 2900 − 3200
UA-1800	TAMS	Organic Matter	1800	28 840	+ 580 − 580	33 700	+ 630 − 670
UA-2240	LSC	Carbonates	2240	29 500	+ 3520 − 2450	34 400	+ 3800 − 2700
UA-2700	TAMS	Organic matter	2700	30 940	+ 680 − 680	36 000	+ 760 − 740

[a] LSC = Liquid scintillation counting, ORSTOM, Bondy, France, 1987.
[b] TAMS = Tamdem accelerated mass spectrometry, CNRS, Gif sur Yvette, France, 1991.

5. ^{40}Ar/^{39}Ar results

The volcanic ash level contains mainly biotite, sodic plagioclase, quartz, hornblende and magnetite. Typical crystal sizes are less than 1.5 mm. Biotite grains used for dating were observed by binocular microscope and SEM; they have typical hexagonal, euhedral or subeuhedral shapes with occasionally rounded edges. Composition determined by EDS analysis shows a K_2O content of 8.4 ± 0.5 wt%; Fe_2O_3T (from 15.6 to 21 wt%) and MgO (from 12.6 to 15.8 wt%) contents display a greater range of variation, but the Mg number (Mg/Mg + Fe) is around 0.56; all these values are in the range of biotites produced by a calc-alkaline magma, which is consistent with the geotectonic environment. Although they were in salt-rich solutions from their time of deposition to the present, they do not appear to alter. Some of the biotites contain inclusions of apatite, which can explain the $^{37}Ar_{Ca}$ values measured during dating experiments (see below).

For biotite preparation, the samples were gently crushed and sieved; then 800–500 and 500–300 micron size biotites were concentrated using bromoform. Grains for laser heating and high frequency furnace experiments (29.3 mg) were handpicked under a binocular microscope.

The samples were irradiated in the 5C position of the McMaster University nuclear reactor (Hamilton, Canada). The samples were irradiated for 1.5 h with cadmiun shielding, together with the Bern 4B biotite (17.25 Ma, Hall et al., 1984 and subsequent analyses in Nice and Toronto) as a neutron flux monitor. ^{40}Ar/^{39}Ar age determinations were performed at the Université de Nice — Sophia-Antipolis. Experimental techniques are described in detail by Ruffet et al. (1991) for the laser heating and by Féraud et al. (1982) for the high-frequency furnace heating procedures. The bulk sample analysis was performed with a mass spectrometer composed of a 120° M.A.S.S.E. tube, a Baur–Signer GS 98 source and a Balzers electron multiplier. For laser heating experiments, the gas extraction was carried out by a Coherent Innova 70–4 continuous laser. The mass spectrometer is a VG 3600 working with a Daly detector system. The typical blank values of the extraction and purification laser system range from 9 to 5×10^{-13} ccSTP for ^{40}Ar, 8 to 1×10^{-14} ccSTP for ^{39}Ar, 2 to 1×10^{-13} ccSTP for ^{37}Ar, and 7 to 3×10^{-14} ccSTP for ^{36}Ar, measured every second or third step. For the fusion steps, argon isotopes were typically on the order of 200 and 5000 times over the blank level, for ^{40}Ar and ^{39}Ar, respectively. The criteria for defining a plateau age were the following: (1) it should contain at least 70% of released ^{39}Ar, (2) there should be at least three successive steps in the plateau, and (3) the integrated

Table 3
Ar dating analytical data. (^{40}Ar = radiogenic ^{40}Ar. $^{37}\mathrm{Ar_{Ca}}/^{39}\mathrm{Ar_K}$: produced by Ca and K neutron interference. Correction factors for interfering isotopes were $(^{39}\mathrm{Ar}/^{37}\mathrm{Ar})_{\mathrm{Ca}} = 7.06 \times 10^{-4}$, $(^{36}\mathrm{Ar}/^{37}\mathrm{Ar})_{\mathrm{Ca}} = 2.79 \times 10^{-4}$, $(^{40}\mathrm{Ar}/^{39}\mathrm{Ar})_{\mathrm{K}} = 1.15 \times 10^{-3}$)

Step	Atmospheric contamination (%)	^{39}Ar (%)	$^{37}\mathrm{Ar_{Ca}}/^{39}\mathrm{Ar_K}$	$^{40}\mathrm{Ar}^{*}/^{39}\mathrm{Ar_K}$	Age (Ma)
Laser fusion procedure: one or two steps of degasing before fusion					
v985 = 1 biotite grain (0.10 mg)					
1	–	0.18	15.017	–	–
2	99.83	0.19	0.002	0.433	0.296 ± 13.851
Fuse	80.45	99.63	0.038	0.261	0.179 ± 0.031
				(integrated age: 0.139 ± 0.050)	
v986 = 1 grain (0.15 mg)					
1	99.27	1.72	1.837	1.834	1.256 ± 2.998
Fuse	82.93	98.28	0.085	0.313	0.214 ± 0.041
				(integrated age: 0.232 ± 0.065)	
v1033 = 3 grains (0.25 mg)					
1	99.37	0.51	9.961	1.904	1.294 ± 5.079
Fuse	95.44	99.49	0.090	0.285	0.193 ± 0.033
				(integrated age: 0.199 ± 0.042)	
v1034 = 3 grains (0.35 mg)					
1	–	0.40	0.000	–	–
2	–	4.85	0.978	–	–
Fuse	90.70	94.75	0.058	0.254	0.172 ± 0.016
v1055 = 3 grains (0.48 mg)					
1	–	0.97	1.987	–	–
2	99.37	9.11	0.200	0.085	0.058 ± 0.099
Fuse	84.38	89.91	0.046	0.275	0.187 ± 0.011
				(integrated age: 0.161 ± 0.017)	
v1056 = 3 grains (0.63 mg)					
1	97.95	1.91	0.000	1.412	0.960 ± 0.449
2	95.23	11.69	0.000	0.316	0.215 ± 0.054
Fuse	80.92	86.40	0.067	0.262	0.178 ± 0.009
				(integrated age: 0.197 ± 0.013)	
v1057 = 3 grains (0.47 mg)					
1	99.47	2.47	0.000	0.578	0.393 ± 0.535
2	96.33	15.18	0.000	0.330	0.224 ± 0.070
Fuse	75.83	82.35	0.041	0.311	0.211 ± 0.011
				(integrated age: 0.218 ± 0.019)	

M1236 = High frequency furnace step-heating experiment; bulk sample 29.32 mg

Step T°C	Atmospheric contamination (%)	^{39}Ar (%)	$^{40}\mathrm{Ar}^{*}/^{39}\mathrm{Ar_K}$	Age (Ma)
400	96.83	0.00	77.581	51.977 ± 56.447
500	99.27	0.25	2.701	1.835 ± 1.549
550	–	0.19	–	–
600	–	0.19	–	–
650	–	0.34	–	–
700	99.30	1.94	0.236	0.161 ± 0.142
750	97.48	4.47	0.263	0.179 ± 0.044
800	96.09	6.04	0.298	0.202 ± 0.029
850	95.29	8.38	0.345	0.234 ± 0.032
900	94.01	8.18	0.269	0.183 ± 0.020
950	93.56	6.72	0.302	0.205 ± 0.024
1000	92.87	9.23	0.336	0.229 ± 0.021
1050	82.22	14.69	0.290	0.197 ± 0.010
1100	65.90	32.32	0.287	0.195 ± 0.004
1150	67.23	5.04	0.279	0.189 ± 0.011
1200	81.94	1.82	0.262	0.178 ± 0.026
1300	–	0.17	–	–
1350	93.87	0.04	6.726	4.566 ± 1.423
			(integrated age: 0.139 ± 0.007)	

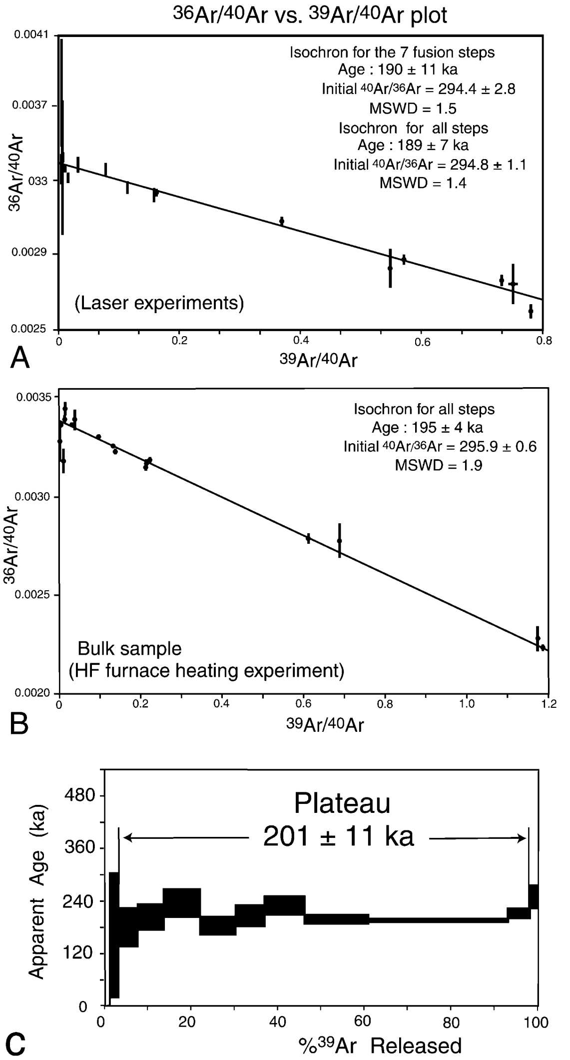

Fig. 5. (A) ^{36}Ar/^{40}Ar vs. ^{40}Ar/^{39}Ar correlation plot for single and small clusters of biotite grains (laser experiments). (B) ^{36}Ar/^{40}Ar vs. ^{40}Ar/^{39}Ar correlation plot for biotite bulk sample (hight frequency furnace experiment). (C) ^{40}Ar/^{39}Ar age spectra for biotite bulk sample; the plateau includes steps from 750 to 1150°C, with a temperature increment of 50°C, accounting for 95% of the total ^{39}Ar released.

age of the plateau should agree with each apparent age of the plateau within two sigma (2σ). All errors are quoted at the 1σ level and do not include the errors on the age of the monitor. The error on the ^{40}Ar*/^{39}Ar$_K$ ratio of the monitor is included in the plateau age error bar calculation. Laser heating experiments were performed with one or two steps at low temperature (about 500°C maximum) before fusion, to release part of the atmospheric contamination, and alteration products. Two experiments were performed on one single grain (v985, v986), and five other experiments on three, in order to increase the quantity of argon measured (Table 3).

For all the laser experiments, the fusion steps, that represent more than 80% of the ^{39}Ar released, display ages ranging from 172 ± 16 to 211 ± 11 ka that are concordant at the 2σ level. The corresponding weighted mean age is 188 ± 5 ka. The ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar correlation plots display similar ages of 189 ± 7 ka (initial ^{40}Ar/^{36}Ar ratio = 294.8 ± 1.1 of atmospheric composition, MSWD = 1.4), and 190 ± 11 ka (initial ^{40}Ar/^{36}Ar ratio = 294.4 ± 2.8, MSWD = 1.5), for all steps and the seven fusion steps, respectively, (Fig. 5).

The bulk sample step-heating experiment provides a plateau age of 201 ± 11 ka on 95% of the total ^{39}Ar released (9 steps, temperature 750–1100°C), concordant with an isochron age of 195 ± 4 ka (initial ^{40}Ar/^{36}Ar ratio = 295.9 ± 0.6 of atmospheric composition, MSWD = 1.9) (Fig. 5).

As shown in Fig. 6, all of the measured ages are concordant at the 2σ level. This shows that the population of investigated biotites is homogeneous (concordant data on single grain, groups of three grains and populations of grains), and belong to the same eruption or cycle of eruptions. This also confirms that the investigated ash layer is not reworked. The weighted mean of the plateau age and the seven laser fusion ages is 191 ± 5 ka, concordant with the corresponding isochron age of the bulk sample and laser data (194 ± 4 ka) (not shown in figure). It represents the best estimate of the age of the ash layer.

6. Discussion

Despite the poor quality of the mud samples, the ^{14}C ages obtained on different types of materials and by two different methods are fairly consistent. The data on both the carbonate and the organic matter of mud layer L1 agree closely. Even with large uncertainties, the ages allow a correlation between the upper mud layers and the lacustrine episodes reconstructed from sediment outcrops and algal bioherms.

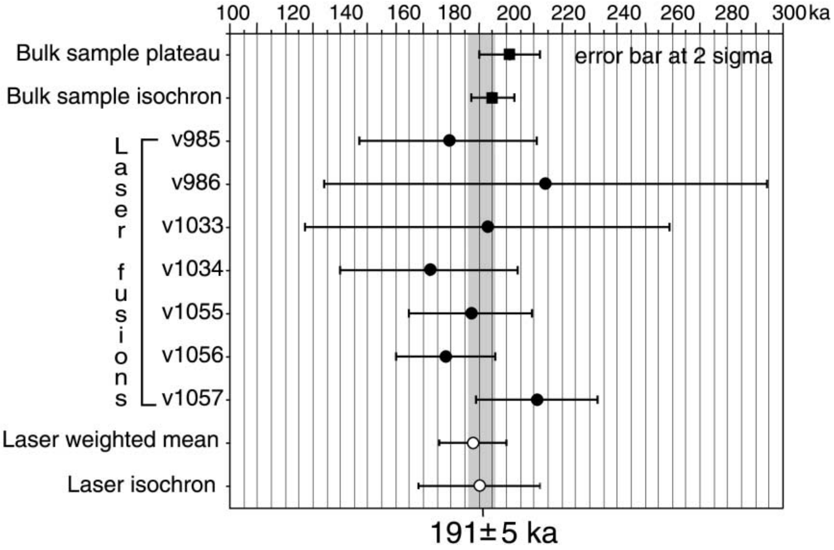

Fig. 6. Summary plot of the measured ages on biotite (error bar at the 2σ confidence level) and best estimated age of the ash layer.

Mud layers L1 and L2 probably correspond to Lake Tauca and mud layers L3 and L4 to Lake Minchin. Unfortunately it has not been possible to date the basal contact of mud layer L4 (3540 cm), which probably corresponds to the beginning of Lake Minchin.

The ^{40}Ar/^{39}Ar age of layer L5 (191 000 ± 5000 yr BP) is consistent with those of the overlying mud layers. It represents the first date of a pre-Minchin paleolake in the central Altiplano. The Escara Formation of the central Altiplano was previously related to the paleolake immediately prior to Minchin (Servant and Fontes, 1978). So, although several lacustrine episodes have flooded the central Altiplano prior to Lake Minchin, as observed in the stratigaphic record in the Salar de Uyuni (Fig. 3), the layer L5 at 191 000 yr BP. corresponds to Lake Escara. In the northern Altiplano, Lake Ballivián is assumed to be immediately prior to Minchin (Servant and Fontes, 1978) and would be contemporaneous to Escara.

The thicknesses of Tauca and Minchin lacustrine muds in the Uyuni borehole are 660 and 1500 cm, and the Tauca duration was about 3100 yrs. According to other studies reported in Table 1, Lake Tauca duration was somewhat longer about 4000 yrs. Considering the oldest known age of 72 000 yr obtained on Lake Minchin by Rondeau, 1990, Lake Minchin duration was at least (and probably longer than) 44 500 yr. Therefore, we estimate sedimentation rates on the order of 1.6–2 mm/yr for Lake Tauca and probably less than 0.4 mm/yr for Lake Minchin. This large difference cannot be the result of the compaction of Lake Minchin layers, because the porosity does not decrease with depth. On the other hand, a closer inspection of the mud layer composition (Fig. 4) shows that Tauca main layer L2 has a rather uniform content of volcanic detrital material and calcite, and almost no halite, whereas Minchin main layer L4 shows very irregular content of all components. Therefore, sedimentation rates were less variable during Lake Tauca than during Lake Minchin where the high halite contents at 2330, 2650, 2750 and 3100 cm may point to dry periods of relatively long duration. Thus, layer L4 may not reflect continuous sedimentation, which is partially confirmed by the detection of two generations of Lake Minchin algal bioherms (Rondeau, 1990. Lake Minchin was probably subdivided into several lacustrine episodes interrupted by dry periods. In such a case, the average sedimentation rate is significantly lower than the true sedimentation rate of the lake phases.

The upper salt crusts were deposited by drying saline lakes. A good analog of the Salar de Uyuni is Searles Lake in California (Smith, 1979) where trona layers alternate with mud layers and a large number of ages allowed an estimation of the deposition rate of the salt between 150 and 250 mm/yr. Busson (1980) suggested a 150 mm/yr deposition rate for halite in Kara-Bogaz Lake (Caspian Sea) and in Zuni Salt Lake (USA). In contrast, the sedimentation rate of soluble salts in playa (ephemeral lakes) deposits may be lower. Eugster (1970) found a 3 mm/yr rate for trona accumulation in Magadi Lake (Kenya). A detailed discussion is given in Sonnenfeld (1984). Nevertheless, it must be emphasized that the thickness of the salt crusts has relatively little significance because a large part of the salt may have been redissolved by freshwater inputs of the subsequent lake. Some crusts may have even almost completely redissolved, as suggested by the sedimentological record of Minchin layer L4. Moreover, the top contact of each salt crust corresponds to a sedimentation gap of unknown duration (about 12 000 yr for the present surface of the salar). Therefore, the time elapsed during the dry period between two lacustrine phases may be very variable. Salt crusts S2 (within Tauca) and S4 (within Minchin) probably represent a short time lapse, whereas S3, between Minchin and Tauca, corresponds roughly to a period of 17 000 yr. S5 probably represents a large gap because the oldest known Minchin age is only 72 000 yr as compared to the 191 000 yr age of Lake Escara.

The thickness of the mud layers increases regularly from L11–L4. However, as previously suggested, layer L4 probably corresponds to several lacustrine episodes, similar to L3/L2 or L2/L1 for Lake Tauca. In this case, Tauca layer L2 would be the thickest conformable lacustrine layer and the trend of increasing thickness of lacustrine units would apply to the entire profile. We may reasonably assume that the thickness of conformable lacustrine layers approximately reflects the duration of the lake that deposited them. Therefore, the duration of existence of the paleolakes in the central Altiplano increased regularly with time during the Pleistocene. This could be correlated to an increase of inflow, which in turn could have induced an elevation of lake levels. An increase of inflow is confirmed by the geochemistry of bromide of the salt crusts (Risacher and Fritz, 2000). Dating of shoreline deposits supports this hypothesis for Minchin and Tauca lacustrine episodes. Rouchy et al. (1996) reported elevations of 3660–3705 m for early Lake Minchin, which corresponds to a water depth of 40–90 m, and a possible maximum elevation of 3730 m for late Lake Minchin, which corresponds to a water depth of about 100 m. Lastly, Lake Tauca reached the highest stand observed in the central Altiplano at 3780 m (Bills et al., 1994), which is equivalent to a water depth of 135–142 m. According to mud layer thickness, lakes Tauca and Minchin received more water than the seven observed paleolakes prior to 191 000 yr BP. Therefore, it seems likely that a significant change in the hydrology of the Altiplano occurred in the last 200 000 yr.

The striking point is that the opposite trend is observed in the northern Altiplano (Titicaca basin, Fig. 2), where the paleolake levels decrease from the oldest known (Mataro, 3950 m) to the most recent phase (Titicaca–Tauca, 3815 m). Their levels may have been controlled by the threshold between the northern and the southern basins, at the outlet of Lake Titicaca into the Desaguadero river, or further to the south. The lowering of the threshold by erosion, clearly demonstrated by the higher levels of older northern paleolakes, could also have increased the amount of inflow to the central Altiplano during the Pleistocene. Such a process is an important drawback for paleoclimatic reconstructions based on the paleolimnology of the Altiplano, because the extent of the central paleolakes might not have depended solely on the local climate, but also on additional inputs from the north, where climatic conditions could have been quite different from those prevailing in the south.

7. Conclusions

1. Biotite from an ash bed sampled from a 121 m deep borehole in the Salar de Uyuni display a $^{40}Ar/^{39}Ar$ age of 191 000 ± 5000 yr BP, which represents the first date from a pre-Minchin paleolake in the Bolivian Altiplano.
2. The stratigraphic record of the Salar de Uyuni deposits shows a regular increase in the thickness of the mud layers with time. This result combined with the biotite age, ^{14}C, and U/Th data obtained on lakes Tauca and Minchin strongly suggests that the duration of the lacustrine events in the central Altiplano increased regularly during the Pleistocene.
3. An inverse trend is observed in the Titicaca basin where the paleolake levels decreased from past to now. This suggests that the evolution of the central

Altiplano paleolakes is at least partly controlled by the overflow of the Titicaca basin, favored by the erosion of the threshold between northern and southern basins, and not only by the local paleoclimatic evolution

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