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Bromine geochemistry of salar de Uyuni and deeper salt crusts, Central Altiplano, Bolivia

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Abstract

The salar of Uyuni, in the central Bolivian Altiplano, is probably the largest salt pan in the world (10000 km²). A 121 m deep well drilled in the central salar disclosed a complex evaporitic sequence of 12 salt crusts separated by 11 mud layers. In the lower half of the profile, thick halite beds alternate with thin mud layers. The mud layers thicken upwards and show clear lacustrine features. The thickness of the salt beds decreases markedly from the base upward.

The bromine content of the halite ranges from 1.3 to 10.4 mg/kg. The halite does not originate from the evaporation of the dilute inflow waters of the Altiplano, which would lead to Br content of tens of mg/kg. The presence of halite of very low Br content (2 mg/kg) in a gypsum diapir strongly suggests that most of the halite deposited at Uyuni originated from the leaching of ancient salt formations associated with the numerous gypsum diapirs of the Altiplano. The deep and thick halite beds were probably deposited in a playa lake, as suggested by their very low and fairly constant Br content (1.6–2.3 mg/kg) and by the abundance of detrital minerals. Thereafter, perennial salt lakes of increasing duration flooded the central Altiplano. Increasing amounts of dilute inflow waters of low Cl⁻/Br⁻ ratio and the exhaustion of diapiric halite lead to an increase of both the thickness of the lacustrine layers and of the bromine content of the salt crusts (5–10 mg/kg) deposited as the lakes dried up. Paleolake levels in the central Altiplano rose as those in the northern Altiplano (the Titicaca basin) were simultaneously falling. The progressive fluvial erosion of the threshold between the northern and the central Altiplano lowered the levels of the northern lakes and allowed more dilute waters of low Cl⁻/Br⁻ ratio to flood the central Altiplano. Therefore, both the thickness of lacustrine sediments and the bromine content of the salt crust increased to the present. The three upper crusts show a decrease in bromine content which may reflect a recent modification of the inflow regime to the last lakes.

The salt crust deposited by the last salt lake, 10000 years ago, shows a bromine distribution that unexpectedly increases with depth. As the lake dried, the salt crust was probably initially distributed over a wider area than the present flat crust, covering the topographic surface up to the level of the lake where halite reached saturation. The dissolution of the initial salt of low Br content from the margins of the lake to the center is probably responsible for the observed Br distribution in the surface salt, as in a playa. During the Holocene, a severe drought hit the Altiplano and drastically lowered the intracrustal brine table within the salt crust, leaving a thin layer of high-concentrated residual brine at the bottom of the crust. Bromine-rich halite replaced primary halite by a temperature-activated mechanism in the lower crust, further increasing the Br gradient with depth. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

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The salar of Uyuni is probably the most extensive salt pan in the world (10000 km²). It is located at an elevation of 3653 m in the central depression of the Bolivian Altiplano, a large closed basin surrounded by the Eastern and the Western Cordilleras of the Andes (Fig. 1). The origin of halite has been discussed in a preceeding paper (Risacher and Fritz, 1991a, cited hereafter as RF, which includes a set of 174 brine analysis). Several successive lakes are known to have occupied the Altiplano (Troll, 1927; Ahlfeld, 1972; Servant and Fontes, 1978; Lavenu et al., 1984). The present salt crust at Uyuni and the adjacent salar of Coipasa is a remnant of Paleolake Tauca, the last salt lake that covered the central Altiplano between 16000 and 10400 years B.P.



Fig. 1. Schematic map of the Altiplano showing major drainage basins and gypsum diapirs.

(Servant et al, 1995; Rouchy et al., 1996; Sylvestre, 1997). A chemical balance has disclosed a large excess of sodium and chloride with respect to the bittern solutes, lithium, potassium, magnesium and boron in Paleolake Tauca (RF). The estimated concentrations of Na⁺ (1.23 mmol/l) and Cl⁻ (1.26 mmol/l) are close to equimolarity. Therefore, we will refer throughout this paper to the NaCl concentration of the paleolake. Modern dilute and saline waters of the whole Altiplano have much lower Na⁺ and Cl⁻ contents with respect to Li⁺, K⁺, Mg⁺⁺, B. The NaCl excess in Paleolake Tauca is probably related to a salt input from ancient diapirs leached at an early stage of the basin history. Each lake, by redissolving a part of the halite deposited by its predecessor, inherited the initial anomaly. The excess halite was then transferred from lake to lake until the present.

Our former study (RF) rests exclusively on the average 5 m thick surficial crust. A 121 m deep borehole in the central salar disclosed a succession of twelve salt crusts separated by mud layers. Salts and muds were extensively sampled and intracrustal brines were pumped from each salt crust. However, salt was mostly disaggregated in the core sampler, which hindered reliable petrogaphic observations. This study first deals with the bromine geochemistry of Uyuni surficial crust with special attention to the major diagenetic events responsible for the very irregular bromine distribution in the salt. The surficial crust is the only one whose lateral extent and geochemistry is well known (Ericksen et al., 1978; Rettig et al., 1980; RF). The second part of this study describes the deep well with emphasis on the bromine geochemistry as a tracer of the origin of salts and processes of salt accumulation. The bromine contents are among the lowest reported in the world. The nearby salar of Coipasa (2500 km²; 3656 m) was also investigated down to 14 m. No deeper salt crusts were found at this location.

2. Methods

Bromide in surficial brines was determined by automated colorimetry (Balatre, 1936; Goldman and Byles, 1959) with an Technicon Auto-Analyser. This

method, however, did not work with deep brines because of their rather high organic matter content (Peron and Courtot-Coupez, 1978). The deep brines were analysed using ion chromatography. Ion chromatography was also used to determine Br⁻ in dilute waters.

Bromine in salt was analysed by automatic colorimetry. Halite was crushed and rinsed in ethanol to eliminate Br⁻ derived from fluid inclusions (Moretto, 1988). Then the salt was heated at 600°C for 12 h to destroy the organic matter. The crushing and heating operation was repeated three times. This procedure is essential, inasmuch as very low amounts of organic matter interfere with colorimetric measurements. Test samples of known Br content were added to check the conservation of Br. These tests show that there is no loss of Br during this procedure. Then, the salt was dissolved to a concentration slightly below 100 g/l, depending on the purity of the salt, and the solution filtered. A systematic addition of a bromide solution in the assembly line provided a constant background of about 0.5 mg/l Br⁻. Sodium chloride up to 100 g/l did not interfere with bromide detection. The precision of the method depends mainly on the irregularity of the baseline and is estimated at \pm 0.4 mg/kg Br in the salt. Each solution was also analysed for chloride to determine the proportion of pure halite in the bulk sample, and to correct the Br contents.

3. The surficial salt crust at Uyuni and Coipasa

3.1. Bromine distribution in brine and salt

The crust is made of more or less friable halite layers of decimetric size, almost completely filled with a NaCl-rich intracrustal brine. In the dry season the brine table stands at 10–20 cm below the surface of the crust. Capillary evaporation of the subsurface brine cements the top centimeters of the crust creating a very hard and almost impermeable pavement. Most of the halite samples were disaggregated in the core sampler, which precludes a petrographic study of the halite crust. Therefore, we have focused our attention on the bromine content of halite, which can be determined on disaggregated samples and gives independent evidence of the environment of salt deposition.

Bromide concentration of the topmost brines, some centimeters below the surface, have already been published by Rettig et al. (1980). Table 1 gives bromide concentrations at various locations (Fig. 2) and depths in the intracrustal brine of Uyuni and Coipasa salars. Owing to the large number of analyses it is possible to draw the bromide iso-concentration curves at Uyuni (Fig. 3). These curves are very similar to those of lithium, potassium, magnesium and boron (see RF). High concentrations of bromide are found at the mouth of the Rio Grande River, exactly as for the other bittern solutes. This suggests that the strong increase of bromide concentration in this area is related, as for the other bittern solutes, to recent inputs by the Rio Grande River during the last 10000 years (RF).

Vertical bromine contents in halite at six locations at Uyuni and at two locations at Coipasa are given in Table 2. Fig. 4 shows vertical bromine contents of salt and brine in the surficial crust at Uyuni. These data can be used to provide a tentative estimation of the bromide concentration in Paleolake Tauca. Using this estimate the theoretical partition of bromine between salt and brine during the lake desiccation can then be modelled.

3.2. Bromide concentration in Paleolake Tauca

The estimated total amount of bromine in brine and salt in both the Uyuni and Coipasa surficial crusts are given in Table 3. Amounts in the highconcentrated southeastern area at Uyuni are also estimated. The precision of the estimate of the total mass of bromide in Uyuni brine $(\pm 15\%)$ is primarily related to the uncertainty in the porosity of the salt (RF). It is difficult to estimate the uncertainty in the mass of bromine in the Uyuni salt and in the whole salar of Coipasa. However, as can be seen in Table 3, bromide in Uyuni brine amounts to 76% of total bromine. Moreover, total bromine at Coipasa only amounts to 5% of that at Uyuni. Therefore, a large uncertainty on bromine tonnage in Uyuni salt and for the whole of Coipasa (e.g. \pm 50%) does not have a major effect on the uncertainty in the total bromine in the surficial crusts, which could reach about 25% in the extreme case.

Table 1			Table 1 (continued)				
Br (mg/l) a	and cl (g/l) conc	entration in brin	nes and waters ^a	Uyuni		Br	Cl
Uyuni		Br	Cl	UH	300	55	189
UA	10	. 48	190		500	56	189
	80	89	190		700	56	190
	. 200	83	191		- 900	58	188
	400	84	196	UI	15	47	190
	600	90	192		100	47	189
	800	101	185		1000	40	189
	1500	119	185	UJ	15	50	190
	1650	133	183		100	58	191
	1840	130	186		300	59	189
	2000	121	186		700	63	187
	2150	122	190	UK	10	65	191
	3690	83	186		. 100	96	192
	3840	82	185		200	87	190
	3990	81	184		400	85	187
	4750	70	190	UL	20	115	194
	4925	57	191		100	106	195 🦽
	5100	54	192		250	110	190
	5300	58	192	UM	17	44	189
	5750	66	192		100	54	191
	5950	66	191		400	63	187
	, 6165	63	192	UN	16	124	194
	6650	66	189		100	129	193
	7035	61	200		300	133	192
	7650	63	195	UO	9	74	191
	8050	65	195		100	94	190
	8800	62	195		500	109	190
	9400	65	195	UP	17	119	192
	10000	65	196		100	127	193
	11438	93	191		500	121	193
OR	0	257	201	UQ	17	58	190
	10	242	200		100	63	190
	100	358	210		450	62	192
	250	404	214		800	63	190
	400	404	215	UR	15	50	190
UC	5	198	194		100	54	190
	100	140	190		450	53	188
	250	133	192		800	49	187
τ III)	400	132	191	US	9	46	190
UD	10	204	197		100	53	192
	100	152	194		450	52	187
	250	130	193	7 100	800	58	186
107	400	120	191	UT	15	48	190
UE ·	5	142	195		100	49	189
	100	106	190		450	48	190
	250	104	190	¥ ** *	800	53	189
בח ז	400	104	189	UU	20	63	188
UF (30	21	190		350	53	190
UC	110	-30	190		700	52	188
00	15	29	190	UV	10	50	191
	95	29	191		100	51	190
TILI	270	24	190	1	500	52	191
UL	100	50	191	UW	22	164	200
	100	51	190		100	118	196

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and the second

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Uyuni		Br	Cl	Uyuni
IIX	90	183	105	
0A	300	180	195	01
UY	16	46	191	
	100	60	190	
1	300	76	189	Coipasa
	600	74	188	<u> </u>
UZ	12	68	191	CA
	100	80	191	CB
	450	84	192	CD
	800	88	190	C1
YA	17	69	192	C2
	100	72	191	C3
YB	11	36	190	C4
	100	47	190	C5
	500	63	189	
YC	12	32	191	TARCAMA
	100	38	189	
	600	44	188	IAR
YD	9	50	191	
	100	66	192	
	450	78	191	
	800	88	192	
YE	8	49	192	
	100	68	192	
	450	81	195	
VE	800	82	191	
IF	23	20	192	
VG	200	20	190	
10	100	50 27	191	
VH	100	363	207	
111	100	370	207	
	250	370	212	INFLOWS
YI	8	61	192	TITICACA
••	100	65	192	MAURI
	450	67	191	LAUCA
	800	74	191	RIO GRANI
YJ	17	53	193	
	100	65	194	^a The two
	400	69	189	identification
YK	1	58	191	centimeters
	100	68	192	
	400	73	190	
	700	76	189	RF est
YL	22	28	192	for a wate
	100	44	193	and Font
	400	46	191	observed
U1	12	87	196	1 4h 1-
	400	97	197	by the la
	800	101	193	than prev
U2	13	87	195	with our
	100	90	196	bromide of
	200	94	193	volume c
	300	97	190	

Table 1 (continued))			
Uyuni		Br	Cl	
U2	400	102	187	
	500	105	189	
	600	104	187	
Coipasa		Br	Cl	
CA	0	100	185	
	150	101	172	
CB	0	100	187	
	150	157	168	
C1	0	81	189	
C2	0	137	188	
C3	0	78	179	~
C4	0	100	187	
C5	0	72	186	
TARCAMAYA		Br	CÍ	
TAR	1 .	0.057	0.010	
	2	0.034	0.012	
	3	0.059	0.017	
	4	0.78	180	
	5	0.56	66.7	
	6	0.74	178	
	8	0.047	0.632	
	9	0.096	0.029	
	10	0.76	185	
	11	0.55	156	
	12	0.87	131	
	13	3.81	180	
	14	1.02	43.7	
	15	3.56	27.2	
INFLOWS		Br	Cl	
TITICACA		0.10	0.255	
MAURI		0.72	0.262	
LAUCA		0.63	0.331	
RIO GRANDE		0.81	1.58	

^aThe two letters of Uyuni and Coipasa samples are the well identification code (Fig. 2). The following number is the depth in centimeters

RF estimated the composition of Paleolake Tauca for a water level at 3720 m as reported by Servant and Fontes (1978). Recently, Bills et al. (1994) observed a high shoreline at 3780 m briefly occupied by the lake, that suggests larger lake fluctuations than previously estimated. In order to be consistent with our previous brine composition models, the bromide concentration will be estimated for a lake volume consistent with a water level at 3720 m. Some difficulties, already discussed in RF, arise in

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Fig. 2. Location of wells and samples in the salars of Uyuni and Coipasa. At Uyuni: open circles = drilled wells (not cored; brine samples only); solid circles = cored wells (brine and salt samples); large solid circle = the deep well. At Coipasa: open circles = surficial brine samples; solid circles = cored wells.

determining the bromide concentration of Paleolake Tauca. The lake was divided into three sub-lakes connected by narrow straits: Uvuni, Coipasa and Poopo. Lake Poopo was disconnected very early from the two others as they receded, so it will not be taken into account in the mass-balance calculations. Most of the dissolved salts in Lake Coipasa passed into the Uyuni basin as the lake dried up. Therefore, to obtain the bromide concentration of Paleolake Tauca, the total amount of bromine in salt and brine (Table 3), corrected for the effect of recent inputs, must be divided by the total volume of paleolakes Coipasa and Uyuni (1200 km³ for a water level at 3720 m). Recent inputs by the Rio Grande River may be very roughly estimated from the excess bromine in the southeastern area, at the mouth of the river (see below). They are small compared to the total amount of bromine in the whole salar. Recent input by the Lauca River into Coipasa was not taken into account, as it does not seem to have been conserved in the salar (see RF). The concentration thus obtained is then multiplied by a factor of 1.2 in order to account for a probable loss of salts durindesiccation, mostly by wind transport of salt efflores cences around the receding lake. This rather specula tive correction factor is based on several observations on receding salt lakes (Langbein, 1961 and discussion in RF). However, inasmuch as almost all solutes (except Ca and SO₄) are also multiplied by this factor, the ratio between solute concentration is not modified, especially Cl⁻/Br⁻ and Br⁻/Li⁺ which are used later. The bromide concentration in Paleolake Tauca (at 3720 m) may therefore be roughly estimated at 1.6 \pm 0.4 mg/l.

3.3. Theoretical distribution of bromine in halite

The distribution coefficient of Br, as defined by Boeke (1908) and Braitsch (1971) is:

$$\frac{\text{weight percent Br in the salt}}{\text{weight percent Br in the solution}}$$
(1)

$$q = D.(Br) / [Br^-]$$
⁽²⁾

where D is the density of the brine, (Br) the bromine content in halite (in mg/kg) and [Br⁻] the bromide concentration in the brine (in mg/l). Holser (1979)



Fig. 3. Average bromide iso-concentration curves of the intracrustal brine within the surficial crust at Uyuni (in mg/l).

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Br content in halite $(nnm)^a$				uie 2 (contin	uea)		
Ilunni		 D	<u>U</u> y	uni		Br	
		DI	U(3	400	4.8	
UA	0	2.0	UI	· I	0	2.6	
	40	2.4			50	2.3	
	80	2.3			100	2.4	
	200	2.6			200	2.4	
	275	2.4			300	2.5	
	300	7.8			400	2.7	
	350	7.1			500	3.7	
	400	9.2			600	5.1	
	450	4.3			700	5.9	
	500	4.8			800	7.5	
	550	4.4			850	7.8	
	600	4.7	· · · · ·	· .	900	18.9	•
	700	5.3			940	15.6	
	800	3.7			960	18.8	
	1430	4.1			985	2.5	
	1630	6.8	U2	2	0	2.8	
	1900	10.4			50	3.6	
	2050	7.1			100	2.8	
	2160	6.0			150	5.5	
	3570	1.8			200	10.5	
	3800	8.9			250	9.6	
	4050	6.9			300	15.0	
	4130	6.2			350	12.0	
	4780	23			400	12.0	
	4960	2.0			450	11.6	
	5140	43			500	20.8	
	5825	1.5			550	17.3	
	6100	13			600	97	
	6720	2.0			630	2.7 8.0	
	7110	2.0			050	0.0	
	7460	2.1	Co	inasa		Br	
	8040	1.5		<u></u>	··· p.,	101	
	8800	1.5	CA	1	0	5.0	
	0180	2.5	CE	5	0	6.9	
	10080	1.0			30	6.5	
	10640	1.5		9 -			
	10040	1./		"sample nun	bers as in Table 1.		
IIR	12100	1.0					
OD	0 0	11.9				· · · ·	
	100	0.5	rej	ports distri	bution coefficient	nts ranging from (0.053
	200	10.1	to	0.14, depe	ending on solution	on composition, cr	ystal-
	200	23.4	liz	ation rate	and temperature	As suggested by	1111-
	295	15.9		(1005)	it is botton to w	a a distribution of	onf:
1 117	400	18.7		an (1995),			
UF	3	2.4	C16	ent estimat	ed from Br conte	ents in recently pro	ecipi-
	25	2.3	tat	ed salt from	m the environme	nt of interest. The	salar
	CO	2.5	of	Coipasa is	s flooded most o	of the year by a N	VaCl-
	90	2.2	631	turated brin	e which nermit	the simultaneous	sam
	110	2.2	5a	ma of the	haine en 1 41-		34111-
UG	3	2.7	ph	ing of the	orme and the re	centry precipitated	salt.
	60	2.2	Ţ	ne average	distribution coe	fficient estimated	from
	100	2.3	sa	lt and brine	e samples CA-0 a	and CB-0 (Tables	1 and
	200	1.6	2)	is 0.072	There is a large	incertainty in this	value
	300	3.9	2)				1 .

due to imprecision in the measurements used to

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Fig. 4. Vertical bromine profiles in the surficial crust at Uyuni. Solid circles = Br content in the salt (mg/kg); solid squares = Br^- concentration in the brine (mg/l); dotted curves in UH and U2 diagrams are the theoretical Br content of the salt. The horizontal dotted line at the base of the profiles shows the contact between the salt and the underlying mud. The modeling of the Br content in the salt is based on three points: (1) Na⁺ is linearly related to the conservative component Li⁺ (analysis in RF) and therefore also linearly related to the concentration factor; (2) the removal of Na⁺ is mostly due to halite precipitation; (3) the mass of precipitated salt is assumed to be proportional to its thickness.

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Table 3

Br amounts in Uyuni and Coipasa salars (metric tons)

	Uyuni	Coipasa	
	WHOLE SALAR	SOUTH-EAST	
Brine	1,350,000	170,000	70,000
Halite	420,000	8000	20,000
Total .	1,770,000	178,000	90,000

calculated it and the assumption of instantaneous equilibrium. Moreover, the environmental conditions that prevailed during salt deposition at Uyuni were not necessarily the same than at Coipasa now. However, the uncertainty on the distribution coefficient is unimportant when comparing the shape of theoretical and actual Br profiles. In contrast, caution must be exercised when using it for mass-balance calculations.

A possible composition of the paleolake water is given by RF. Concentration of sodium chloride (NaCl), lithium, and bromide in Lake Tauca brine are estimated at 73 g/l, 10 mg/l and 1.6 mg/l, respectively (at 3720 m). As the brine evaporates, halite begins to precipitate at a concentration of about 300 g/l, which corresponds to a concentration factor of 4.1 (300:73). At this stage, lithium and bromide concentrations reach respectively, 41 mg/l and 6.6 mg/l. The first halite crystals have a bromine content of about 0.4 mg/kg. As desiccation goes on, halite precipitates massively and removes an increasing amount of bromide. Lithium can then be used as a good tracer as it is not involved in the precipitation of halite. The average concentration of lithium in Uyuni intracrustal brine is around 550 mg/l, which points to a concentration factor from the beginning of halite deposition to the present intracrustal brine of 13.4 (550:41). The bromine content of the precipitated halite is derived from Eq. (2):

$$(Br) = q/D.[Br^{-}] = q/D.F.(Br^{-})_{0}$$
 (3)

where F is the concentration factor (from 1 to 13.4) and $[Br^-]_0$ the concentration of bromide at the beginning of halite precipitation (6.6 mg/l). In this calculation, the concentration of bromide in the brine is not corrected for the small amount incorporated in the salt.

Eq. (3) is used to calculate the theoretical bromine distribution in halite at two sites, UH and U2 (Fig.

4). The shape of the predicted curve is very similar to those presented by Schulze (1960a) in the Zechstein series, by Raup (1966) in Utah and by Hite (1974) in Thailand. At the end of the desiccation, the theoretical bromide content in the residual brine and in the last deposited halite are respectively 88 mg/l and 5.3 mg/kg. The theoretical bromine content in the salt averages 1.2 mg/kg and differs dramatically from the measured one: 6.7 mg/kg Br, as an average for the whole salar. Bromine profiles in Fig. 4 clearly show a double disequilibrium. Bromide in the brine is out of equilibrium with bromine in the salt and the distribution of bromine in the salt has no relation with its predicted theoretical distribution based on a single stage desiccation. Some profiles, such as UH are almost completely reversed as compared to the theoretical one. Brine salt imbalance may be related to the rapid diffusion of bromide in the brine column which evens any concentration gradient. Moreover, the bromine content of a crystal growing in a saturated brine increases from nucleus to periphery. Only the outer part of the growing crystal is necessarily in equilibrium with the brine (see Kühn, 1968, p.450). Therefore, an analysis of the whole crystal may give an average bromine content somewhat lower than that expected from the final bromide concentration of the brine.

The halite crust at Uyuni can be apparently divided into three parts:

- 1. a homogeneous upper layer of constant bromine content;
- 2. a lower layer of high and irregular bromine content in the central area of the salar;
- 3. in the south-eastern area of the salar (well UB), at the mouth of the Rio Grande, bromide content in brine and salt that is much higher than in the rest of the salar.

3.4. Bromine in the upper crust (except UB area)

The thickness of the bromine-poor upper layer is variable, from one meter at U2 to four meters at UH. At UF, high bromine content in basal halite is not observed. The bromine content of the upper layer is strikingly constant both vertically and horizontally,

whatever may be the bromide concentration of the intracrustal brine.

Uniform vertical bromine content in salt are wellknown and may be accounted for by various processes: steady-state regime in coastal lagoons (Kühn, 1968; Hite, 1970), brine dilution by fresher inflows (Wardlaw and Schwerdtner, 1966; Kühn and Hsü, 1974), recycling of a whole halite layer by a major flooding event (Holser, 1966a; Decima, 1978; Kühn and Hsü, 1978; Fisher and Kreitler, 1983). Theoretical considerations may be found in Holser (1966a) and Tucker and Cann (1986). None of these processes is straightforwardly applicable to a receding salt lake in a closed basin. Cyclic salt pan deposition can also bring about a constant bromine content in the salt. However, there is little doubt that the salt crust is the remnant of a deep salt lake.

The mechanism that would best explain the uniform bromine content in the upper layer is the redistribution of primary deposited halite from the periphery to the center of the basin (Bonython, 1956; Schreiber, 1974; Decima, 1978). At present, the surface of the salar is perfectly flat. However, when the paleolake receded, bromine-poor halite began to precipitate at a level sustantially above the present salt crust (salting level), covering a wider topographic surface (Fig. 5). Lake volumes (V) as a function of depth (H) were determined from topographic maps:

For Uyuni:
$$V_{uyu} = 1.13 H_{uyu}^{3/2} + 4.38 H_{uyu} - 42.35$$
.

For Coipasa: $V_{coi} = 0.81 H_{coi}^{3/2} - 0.357 H_{coi} + 0.424$,

H is in m and V in km^3 . As shown in Fig. 5:

$$H_{\rm uvu} = H_{\rm coi} + 12.$$

Paleolake Tauca (Uyuni + Coipasa) at 3720 m had a volume of about 1200 km³ and a NaCl concentration of 73 g/l. Halite begins to precipitate at a concentration of 300 g/l NaCl, which corresponds to a concentration factor of 4.1, and a lake volume of 293 km³ ($V_{uyu} + V_{coi}$). It is easy to find H_{uyu} and H_{coi} corresponding to a total volume $V_{uyu} + V_{coi}$ of 293 km³: $H_{uyu} = 28$ m and $H_{coi} = 16$ m, which points to a salting level at 3670 m, 17 m above the present Uyuni crust (3653 m).

Thereafter, local rain may have rapidly dissolved and carried the bromine-poor halite from the upper edges of the salt crust to the lower parts where halite was reprecipitated. Such a process accounts quite well for both the vertical and the horizontal uniformity of the bromine content in the upper layer of the crust. Fig. 5 shows the theoretical bromine profile of the flattened crust after halite redeposition in the central area of the salar. There is a sharp contact between the two layers in this area. Such a feature has some similarity with the upper bromine profile at central Uyuni (well UA, Fig. 4).

3.5. Bromine in the lower part of the surface crust

High bromine content in the basal part of halite beds have been reported by Holser (1966a), Kühn (1968), Holser (1970), Hite and Japakasetr (1979) and Handford (1981). Such profiles are often related to Br--rich brines expelled from compacted underlying sediments. However, at Uyuni, sediments beneath the average 5 m thick surficial crust do not support a strong pressure. The difference between calculated and actual bromide concentration in the intracrustal brine (88 mg/l and 82 mg/l, respectively) is not significant owing to the uncertainty of these values (\pm 15%). In contrast, the gap between theoretical and measured bromine content in halite (1.2 mg/kg and 6.7 mg/kg, respectively) is likely to be significant. By using the highest distribution coefficient (q = 0.14) reported by Holser (1979), the theoretical bromine content of halite would still be only 2.2 mg/kg. A noticeable amount of bromide seems to have been removed from the intracrustal brine and incorporated into the lower part of the crust where bromine content increases sharply. Diagenetic Br--rich brines have precipitated brominerich halite within the lower crust.

Very severe droughts during the Holocene have been reported in the northern Altiplano by various authors (Wirrmann and Oliveira Almeida 1987; Wirrmann and Mourguiart, 1995; Abbott et al., 1997; Binford et al., 1997; Mourguiart et al., 1998). Lake Titicaca was at least 40 m lower during the drought period than its present level. It is likely that the central Altiplano was affected by the drought even more drastically and continuously than in the north

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Fig. 5. Cross-section through Uyuni and Coipasa basins showing the salting level of the last paleolake, the primary deposited crust moulding the topographic surface and the flattened secondary crust. For a modern analog see Bonython (1956, p. 81). The theoretical distribution of Br in the salt is shown at central Uyuni.

since aridity increases from north to south. Rainfall could have been almost nil for a long period, as in the nearby salar of Atacama (Chile) today. During the drought, the intracrustal brine at Uyuni slowly evaporated through the polygonal cracks and its level, presently at 10–20 cm below the surface, dropped much deeper within the crust, allowing the concentration of all bittern solutes (Mg⁺⁺, K⁺, Li⁺, B, Br⁻) to increase significantly.

Minor amounts of polyhalite $(K_2MgCa_2(SO_4)_4.2-$ H₂O) were detected by X-ray diffraction and scanning electron microscope at locations UH and U2 in the lower layer associated with bromine-rich halite (Risacher and Fritz, 1992). This mineral was also found in the south-eastern area at location UB where brines are highly concentrated in Mg⁺⁺, K⁺, Li⁺, B. Polyhalite generally forms by diagenetic alteration of anhydrite or gypsum in contact with bittern brines rich in potassium and magnesium (Schulze, 1960b; Holser, 1966b; Pierre and Fritz, 1984). According to the model of Harvie et al. (1984), UH and U2 brines are undersaturated with respect to polyhalite (Table 4). This confirms that brines much more concentrated in bittern solutes were once in contact with the lower halite layer in the central salar. The highest bromine content in halite at location UA, UH and U2 indicates the thickness of salt that was in contact with the concentrated brines (1-2 m). At UF the crust seems to have been completely dry. Very

roughly the brine volume in the upper crust was reduced by 80-90% during the drought, which corresponds to a concentration factor of 5–10 for the bittern solutes. The residual brine was of the Mg-Cl type with a bromide concentration of about 0.5–1 g/l. Magnesium concentration was in the range 50–100 g/l. Such a brine is similar to that observed today at the mouth of the Rio Grande River.

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The enrichment of bromine in the lower crust may be related to a temperature-activated replacement mechanism similar to that described by Schreiber and Walker (1992) to explain halite pseudomorphs after gypsum. According to the model of Spencer et al. (1990), the solubility of halite in pure water is

Table 4		
Polyhalite.	Saturation	index ^a

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	IAP ^b /K ^c	
UH-900	0.035	
U2-200	0.156	
300	0.188	
400	0.305	
500	0.323	
600	0.303	
UB-10	3.21	
100	1.07	ž

^aBrines are in contact with polyhalite.

^bIAP = Ionic Activity Product.

 ^{c}K = Solubility product. Brines analyses in RF.

almost constant between 0°C and 25°C. The variation is only 0.5%, which could even be within the range of uncertainty of the model. However, the variation of halite solubility with temperature is significantly enhanced as the magnesium concentration of the brine increases. With 70 g/l Mg, the halite solubility increases from 65 to 72.5 g/l (11%) in the range 0-25°C. Besides, a thin lens of hypersaline brine is more sensitive to environmental temperature changes than a thick brine body. Brine ponds are known to be heat-collectors (Hudec and Sonnenfeld, 1974). A temperature increase of the residual brine lens will induce a dissolution of primary bromine-poor halite in contact with the brine. In contrast, when the temperature decreases, bromine-rich halite will precipitate from the bromide-rich residual brine. Such a replacement mechanism may occur without major porosity change. The bromine content of the bulk halite will thus increase during one or several heating-cooling episodes.

Once the drought was over, the crust was refilled with very dilute waters from direct rainfall and runoff, which must have dissolved some halite. The volume to be refiled was about 14 km³. A simple calculation shows that an average increase of porosity of about 7% would result in the salt crust. However, the question arises whether the dissolution evenly affected the whole crust. At present, deep and narrow pits, locally named "ojos" (eyes), are observed in the eastern area of the salar. They are located at the boundaries of desiccation polygons. Their diameter ranges from some centimeters to decimeters. Such features have been described by Hunt et al. (1966) in Death Valley, Stoertz and Ericksen (1974) in Chile and Busson and Perthuisot (1977) in Tunisia. Ericksen et al. (1978) and RF suggested a possible dissolution of Uyuni crust by more dilute and ascending brines. An alternate hypothesis contemplates a local dissolution process during the refilling of the crust by surficial dilute waters. At the end of the drought, direct rainfall on the dry crust and runoffs may have infiltrated through the boundaries of polygonal cracks and locally dissolved the halite crust.

3.6. Bromine in the south-eastern crust

The concentrations of all bittern solutes $(Mg^{++}, K^+, Li^+, B, Br^-)$ in the Uyuni brine display the

same trend in the south-eastern salar, just downstream the Rio Grande delta. They increase sharply within a reduced volume of brine (RF and this paper, Fig. 3). The horizontal concentration gradient of bromide is 40 mg/1/km, to be compared with the average gradient in the central salar: 2 mg/1/km. RF tentatively estimated the amounts of Mg⁺⁺, K⁺, Li⁺, B brought into the salar from the Rio Grande River since Paleolake Tauca dried up 10000 years ago. These estimated amounts agree fairly well with the measured amounts stored at present in the southeastern area. In this area, the intracrustal brine completely fills the crust and continuously evaporates, even in the dry season, in contrast with the central salar where the brine at 10-20 cm below a surficial compact pavement, almost does not evaporate. Continuous flow by the Rio Grande produces permanent evaporation of the intracrustal brine downstream the river mouth, which induces a local evaporativepumping mechanism (Hsü and Siegenthaler, 1969) and allows bittern solutes to accumulate in a reduce volume of the total brine (RF). The input of bromide from the Rio Grande from the end of the drought 4000 years ago up to present is estimated to be 200,000 tons (annual discharge: 60×10^6 m³, RF; Br⁻ concentration: 0,81 mg/l, Table 2). It is reasonable to use this time span inasmuch as most of the crust was dry during the drought. Bromide reserves in the south-eastern crust amount to 178,000 tons (Table 3) in good agreement with the recent Rio Grande inputs. An important outcome, at south-eastern Uyuni, is that the infiltration rate of the intracrustal brine within the underlying sediments and its lateral movement towards the center of the salar have to be extremely low.

4. The deep well

4.1. Stratigraphy

The deep well (UA) was drilled in the central area of the salar (location in Fig. 2). Twelve salt crusts, including the surficial one, alternate with eleven mud layers (Fig. 6). The salt crusts and the mud layers are respectively numbered from top to bottom, S1–S12 and M1–M11. Most deep crusts are very similar to

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Fig. 6. The deep well (UA). S1-S12 = salt crusts; M1-M11 = parting muds; all depths in centimeters. Solid circles = Br content in halite (mg/kg); open circles = average Br content of the crust; solid squares = Br^- concentration in the brine (mg/l); open squares in the brine profile = average Br⁻ concentration in the brine; the dotted curve connecting small open squares is the theoretical Br content of halite in equilibrium with the brine (mg/kg). The horizontal bar at the base of the salt profile shows the variation of the theoretical Br content in salt in equilibrium with the intracrustal brine by using the whole range of distribution coefficients reported by Holser (1979). The range is similar for the other open squares.

the surficial one (S1) described in RF. They are made of porous, layered halite, with little gypsum and are filled with an NaCl-rich interstitial brine. The deepest and thickest salt crusts (S10-S12) contain only 60-85% halite. The remaining fractions are gypsum (8-27%) and detrital minerals (3-13%). The thinner salt crusts S9 to S1 show a progressive increase in halite abundance from S9 to S6 (80–90%) and a simultaneous decrease in detrital minerals. Halite content of the upper salt crusts (S5-S1) ranges from 90% to 100% with an average detrital minerals content of only 1%. The friable halite layers were mostly broken up in the core sampler, so it was not possible to measure the porosity of the crusts. However, it was as easy to pump the deep brines as the surficial ones, which suggests that the porosity does not change drastically with depth. This is quite a contrast with most salt pan settings documented elsewhere. The mud layers are essentially made of volcanic detrital minerals, calcium carbonate (calcite and aragonite) and gypsum. Fine laminations and Artemia faecal pellets in layers M1-M8 indicate that these are lacustrine sediments. Mud layer M5 contains a volcanic ash layer dated with Ar^{40}/Ar^{39} technique at 195000 years BP (Fornari et al., 1999). Layer M10 was not sampled and layer M11 does not show clear lacustrine features. The contact between salt crusts and mud layers is sharp. Salt and mud units are clearly separated. This suggests that at least salt crusts S1-S9 are the remnant of perennial salt lakes. As for crusts S10-S12 some question arises as to their origin, inasmuch as no lacustrine features

were observed in mud layers M9 and M11. It is very likely that these salt crusts were partially redissolved when a new lacustrine episode began (see discussion in RF).

4.2. Bromine distribution in salts and brines

Fig. 6 shows the bromine content of salts and brines in the twelve crusts (analyses in Tables 1 and 2). Bromine contents of the salt range from 1.3 to 10.4 mg/kg. This is much lower than typical bromine contents in halite from marine environments (above 75 mg/kg; Holser, 1966a; Herrmann et al., 1973; Raup and Hite, 1978; McCaffrey et al., 1987). Similarly low bromine contents in halite have been reported only in a few places: in the Great Basin (Holser, 1970), at Luke Salt Body, Arizona (Eaton et al., 1972), at Lower Elk Point, Canada (Holser et al., 1972) and in the Nippewalla Group, Kansas (Holdoway, 1978). A discussion of the origin of salt according to its bromine content may be found in Hardie (1984). The average bromine content of salts and brines of each crust is also presented, along with the theoretical bromine content of halite in equilibrium with the intracrustal brine calculated with a distribution coefficient of 0.072. Average contents are useful for comparing salt beds (Raup et al., 1970). Bromine content in halite is almost constant in the deepest crusts (S12-S7) at Uyuni. Then bromine content increases upwards from crusts S7-S4 and decreases from S3 to S1. Except for the deepest brine, the average bromide concentration in brines show the same trends as the average bromine content in halite. The difference between theoretical and actual average bromine content of halite is constant at 2 mg/kg in the deep crusts S7-S11. In the upper crusts S6-S1, the observed concentrations of Br agree closely with the predicted; however, the dispersion and the low number of samples make the difference not so significative as for the lowest crusts. As already mentioned, the average bromine content of the salt may be somewhat lower than that expected from the final bromide concentration of the brine.

4.3. Tentative interpretation of Br profiles

The interpretation of Br profiles in the deep well is based on a reasonable working hypothesis: both

vertical and horizontal brine movements are restricted due to entrapment by the crusts and sediments. Lateral flow in the central trough of a closed-basin is obviously limited due to the lack of hydraulic gradients. In addition, restricted infiltration is a basic condition for a saline lake to form: the lower the infiltration, and the higher the salinity of the brine. Mass-balance calculations assuming a steady-state regime for the conservative solutes Li⁺ (data in RF) and Br⁻ lead to an infiltration rate of 5 m in 100000 years for the surface brine (in crust S1). However, steady-state conditions do not seem to exist, at least in the south-eastern area of the salar where dissolved salts provided by the Rio Grande are stored at the river mouth. Therefore, vertical infiltration of the brine column is likely to be neglectible.

In contrast, diffusion of solutes is an important diagenetic process in the brine column. Bulk sedimentary diffusion coefficients in pore brine are not known. They are probably higher in the salt than in the mud, inasmuch as salt crusts have a higher permeability and a lower tortuosity than fine-grained muds. For a very gross estimate we will use the value of 5×10^{-6} cm²/s estimated by Ullman (1995) for Br⁻ in porebrines of sediments underlying an halite crust in playa lake Frome (South Australia). This coefficient is probably somewhat too high because of the lower temperatures at Uyuni. The maximum value of the flux of bromide downwards between S6 and S3 would then be 58 mg/cm^2 in 10000 years. This gross estimation shows that the Br⁻ concentration of the upper intracrustal brines (S2–S5) has been significantly reduced since they were formed. The constant Br⁻ concentration in the 53 m thick brine column in lower crusts S6-S11 may be due to lower initial variations in Br⁻ concentrations and to a longer time of diffusion that occurred mostly in salt crusts. The thicker mud layers of the upper profile may reduce the diffusive flux of solutes. Therefore, diffusion has smoothed the initial Br⁻ profile maintaining the initial trends.

The bromine in the salt has also undergone diagenetic changes, as suggested by the large variability of Br contents in the upper crusts S6-S1. As in the surface crust, the salt and the brine are not in equilibrium perhaps due to the same circumstances that lead to disequilibrium in the surface salt. There is no

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Fig. 7. Index map of Tarcamaya gypsum diapir showing the location of the springs.

relation between the Br contents in the salt and in the brine of a single crust. However, the average bromine content of the salt crusts shows a correlation with the bromide concentration of the intracrustal brines (Fig. 6), which suggests that the initial bromine profile has not been completely obscured during diagenesis. The average Br profile in the salt may still reflect the initial trends at the time of deposition and may then be tentatively used to investigate the origin of the salt.

The evaporation of the main modern dilute waters of the Altiplano (Lake Titicaca, Lauca, Mauri and Rio Grande rivers, Fig. 1, Table 1), up to halite saturation, leads to bromine contents in salt ranging from 4 to 30 mg/kg at the very beginning of the precipitation. It is therefore obvious that the halite of all crusts did not originate from the mere evaporation of dilute waters of the Altiplano. Numerous gypsum diapirs, of Tertiary and Cretaceous age, outcrop in the Altiplano (Fig. 1; Ahlfeld, 1972, Rouchy et al., 1993). Almost pure NaCl brines, several of them saturated with respect to halite, spring out from the Tarcamaya diapir (Fig. 7; Br⁻ and Cl⁻ concentrations in Table 1). The Cl⁻/Br⁻ ratio of the spring waters decreases as the salinity decreases, which indicates a mixing with dilute waters of lower Cl⁻/Br⁻ ratio. The highest Cl⁻/Br⁻ ratio of the most concentrated brines leads to a bromine content of the dissolving halite of 2 mg/kg, which definitely points to a non-marine origin of the diapiric halite. Reprecipitated halite from the most concentrated Tarcamaya brines has a bromine content of about 0.05 mg/kg. The mixing of such brines with dilute waters of the Altiplano leads, after evaporation, to a bromine content in salt ranging from 0.05 to 10s of mg/kg. Therefore, the bromine profile results from varying amounts of the three main sources of bromine and halite: the two end-members, diapirs and meteoric inflows, and the recycling of earlier halite crusts (Fig. 8). Halite and bromine do not have the same origin. Halite is mainly derived from the leaching of ancient salt diapirs and bromine was brought in the basin by meteoric dilute waters. The diapiric origin of halite has already been suspected by RF in view of the large excess of sodium chloride relative to the bittern solutes in the salar of Uyuni (S1), as compared to their proportion in all modern waters of the Altiplano. At present only gypsum is present in most diapirs. All the salt has been recycled to the Uyuni crusts. Ancient salts were also detected below the volcanic structures in the southern Altiplano (Risacher and Fritz, 1991b).

The low and fairly constant bromine content in lower salts S7–S12 can be accounted for by several processes:

 deposition in a stable and hypersaline lake where halite precipitation is compensated by saline inflows, so as to maintain a steady-state regime;



Fig. 8. Cl/Br ratio of waters and salts of the Altiplano (Br, Cl in mg/l in waters and in mg/kg in salts). T = Titicaca; R = Rio Grande; L = Lauca; M = Mauri.

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- 2. precipitation in a receeding deep salt lake, a process analogous to that envisioned for the surface crust where the calculated Br content in halite is almost constant in the lower part of the profiles;
- 3. deposition in a playa lake by periodic flooding events.

Precipitation in a drying lake is at odds with the high detrital content of the salt which suggests a high-energy environment. The upper crusts deposited by deep lakes are almost devoid of detrital minerals. Continuous deposition in a stable lake would require large volume of dilute water of low Cl^-/Br^- ratio to balance the evaporation. Br content in halite would be higher than the very low values presently observed. In contrast, a playa lake fed by periodic and saline inflows fits with all observations: thick salt beds interbedded with thin mud layers, the lack of lacustrine features in the deepest mud layers, the abundance of detrital minerals and the constant bromine distribution in the salt. The leaching of ancient salt diapirs provided most of the halite.

The upper 50 m of the profile are clearly marked by thicker mud layers and higher bromine content in the salt. Stable saline lakes of increasing duration have occupied the central Altiplano. More dilute inflow waters of low Cl^-/Br^- ratio were feeding



Fig. 9. Lithium and bromide concentration profiles in intracrustal brines at central Uyuni (in mg/l).

Table	5
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CL/Br and Cl/Li ratio in major inflow waters of the Altiplano (concentrations in mg/l)

	Cl/Br	Cl/Li	
Titicaca	2550	735	
Mauri	364	265	
Lauca	525	414	
Rio Grande	1950	395	

the basin. Conversely, the volume of leaching saline waters, enriched in bromine-poor diapiric halite, was decreasing. However, if the paleolakes would have been exclusively fed by dilute waters, similar to the modern ones, then the bromine content of the salt should be of several tens of mg/kg. This is obviously not the case. It is likely that large amount of sodium chloride dissolved in paleolake waters stems for the re-solution of bromine-poor halite from the underlying crust, as sampled from the diapiric brines.

The reduction of bromine in the upper three salt crusts could be due to a reduction of inflows in the last paleolakes M3-M1. Most of the halite of crusts S3-S1 would then come from the recycling of the underlying salt crust. However, according to Bills et al. (1994), the most recent paleolake reached the highest elevation at 3780 m, which implies an increase of inflows. Lithium, an other conservative component, shows an opposite trend in central Uyuni (Fig. 9). Its concentration increases regularly from S5 to S1. A variation of the main inflow regime in the central Altiplano may explain the divergence. Table 5 gives the Cl^{-}/Br^{-} and Li^{+}/Cl^{-} ratio of the main dilute waters of the Altiplano. An increase of salt inputs by the Rio Grande river is the simplest way to account for the decrease of Br- and the increase of Li⁺. An increase of Titicaca salt inputs would lead to a decrease of both bromide and lithium.

5. Concluding remarks

Bromine contents of halite in salt crusts of the central Altiplano are among the lowest reported in the world. Most of the halite originated in the leaching of older non-marine salt formations. Salt recycling has often been reported (Neev and Emery,

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1967; Bradbury, 1971; Krinsley, 1972; Eaton et al., 1972; Schreiber and Schreiber, 1977; Antsiferov, 1979; Lindsey et al., 1981; Matray and Fontes, 1990). A review of such occurrences may be found in Sonnenfeld (1984).

The deep salts of Uyuni were probably deposited in a playa lake environment and maintained by saline inflows. Halite originated in ancient gypsum and salt diapirs scattered in the drainage basin. Thereafter, stable salt lakes of increasing duration successively flooded the basin. The Cl^{-}/Br^{-} ratio of the lakewater becomes more influenced by dilute waters of low Cl⁻/Br⁻ ratio. Each salt lake re-dissolved a part of the salt crust deposited by its predecessor. The last lake deposited a primary crust 17 m above the present flat crust, covering a wider area. Halite was rapidly redistributed from the edges to the center of the basin. Such a process is also likely to apply to each ancient lake. A drastic drought that hit the Altiplano after the lake dried up is responsible for a strong evaporative concentration of the residual brine. The concentration of bittern solutes increased in 80-90%. Bromine-rich halite replaced primary halite by a temperature-activated mechanism in the lower crust. These two diagenetic processes result in a striking inverse vertical bromine profile in the salt crust. It is interesting to note that an apparently simple process such as the drying-up of a salt lake, only 10000 years ago, may give so irregular a distribution of bromine in the salt. It is therefore no surprise if most bromine profiles related to more complex depositional processes, and in much older salt formations, are often very difficult to explain.

The central Altiplano was receiving increasing amounts of water from one wet period to the next. The lake levels were probably rising from one lacustrine phase to another. The highest level was attained by the last paleolake (Bills et al., 1994). However, Lavenu et al. (1984) have shown that in the northern basin the levels of the five paleolakes, so far detected in lacustrine outcrops, were markedly decreasing from past to now. Paleolake levels were respectively, from the oldest to the most recent one, at 140, 90, 50, 15 and 5 m above the present Lake Titicaca level (3808 m). Although no precise correlation between northern and central lacustrine phases can be made because of the lack of appropriate stratigraphic dates, there seems to be an antipathetic relation between

the northern and the central lacustrine history. The threshold between the central Altiplano and the Atlantic basin is at 3810 m of elevation in the eastern Cordillera. It is not undergoing active erosion. Therefore, the presence of lake levels at much higher elevations in the northern Titicaca basin implies the existence of an ancient high threshold between the northern and the central Altiplano. Today the threshold between the Titicaca and Poopo basin is at 5 m below Lake Titicaca level (Boulange and Aquize Jaen, 1981). In past times the threshold was at a much higher elevation allowing deep lakes to occupy the wet northern basin and isolating the arid central Altiplano. The levels of the northern lakes were controlled by the threshold and some overflow may have occurred. With time, active erosion by the overflowing river progressively lowered the threshold and the lake levels in the north, allowing more water to enter the central basin. The increasing water supply of low Cl⁻/Br⁻ ratio, associated with the exhaustion of diapiric halite of high Cl/Br ratio, induced the establishment of deeper, longer and more dilute lakes with waters of decreasing Cl⁻/Br⁻ ratio. Therefore, both the thickness of the lacustrine layers and the bromine content of the salt were increasing. The control of paleolake levels in both the northern and the central Altiplano by overflow of the northern lakes is an important drawback for paleoclimatologic studies in the Bolivian Altiplano.

The reduction of bromine in the upper three salt crusts could be due to a modification of the inflow regime to the lakes. A distinction must be made between the origin of water and the origin of salts. Today, the Rio Grande water is 3-4 times more concentrated than the Titicaca water. A net precipitation increase on the Titicaca basin would dilute the lakewater and bring large volume of water in the central Altiplano. Most of the water of the new lake in the central Altiplano would originate from the Titicaca basin but most of the dissolveld salts from the Rio Grande basin. Alternatively, a strong precipitation increase during the last three lacustrine episodes, maintaining the same north-south gradient over the whole Altiplano, could have leached the arid south and brought in the central lake large amounts of salts dissolved in little water, while most of the inflow water would still have come from the north.

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