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Lake levels in the southern Bolivian Altiplano (19°–21° S.) during the Late Glacial based on diatom studies

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Abstract. This study is focused on the endorheic Uyuni-Coipasa Basin located in the southern Bolivian Altiplano. Stratigraphical and fossil diatom studies based on a detailed radiocarbon chronology revealed six phases in water-level changes and paleosalinity variations. At 15,430 ± 80 yr B.P., lacustrine conditions settled in the southern Bolivian Altiplano. A saline lake, characterized by benthic meso-metasaline species, reached ~ +4 m altitude above the present bottom of the basin. After 15,430 ± 80 yr B.P., the level rapidly rose to ~ +27 m, as suggested by a tychoplanktonic mesosaline flora. Between ~14,500 years and ~13,000 years, finely laminated sediments at ~ +32 m contained successively a dominance of epiphytic mesosaline to hypersaline species and tychoplanktonic oligosaline diatoms, indicating weak fluctuations in water-level and salinity. At 13,000 years, strong changes in the diatom flora occurred: epiphytic oligo-hypersaline diatoms were replaced by planktonic meso-polysaline species. They indicate a deep salt lake (the lake level reached ~ +100 m). After ~12,000 years, the lake level abruptly dropped, as suggested by fluviatile sediments with a benthic meso-polysaline diatom flora. The main lake was replaced by shallow saline ponds. A wet pulse occurred at ~11,400 years, characterized by low water level (~ +7 m) and high salinity. This lacustrine phase remained until 10,400 yr B.P. These data indicate changes in Precipitation minus Evaporation (P-E). Our regional interpretations are based on a comparison with the available data on the northern (Lake Titicaca) and southern (Lipez area) Bolivian Altiplano and on the northern Chilean Altiplano (Atacama Desert).

Key words: Bolivia, diatom, Late Glacial, paleohydrology, paleosalinity

Introduction

The Late Glacial (15,000–10,000 yr B.P.) was affected by a global warming associated with an increasing atmospheric concentration of greenhouse gases (Lorius *et al.*, 1990). This climatic change has been largely attributed to changes in solar radiation induced by variations in the earth's orbital parameters (Kutzbach and Guetter, 1986; COHMAP, 1988). A comparison between global climatic model simulations and paleoclimatic data are quite consistent in the northern tropics. Enhanced summer monsoons resulting from greater northern hemisphere summer insolation are compatible with high lake levels (Kutzbach and Street-Perrot, 1985). In the southern tropics, proxy data are needed to improve our understanding of climate changes and test model simulations.

Previous studies in the southern tropical Andes revealed a major lacustrine event (*Tauca Event*) during the late-glacial times. This was identified in lacustrine cores from Lake Titicaca in the northern Bolivian Altiplano (16° S) (Ybert, 1992; Wirrmann *et al.*, 1992), in lacustrine terraces on the margin of the Uyuni-Coipasa Basin in the southern Bolivian Altiplano (19°–21° S) (Servant and Fontes, 1978) and in the Atacama Desert (24° S) (Grosjean, 1994). Palynological studies (Ybert, 1992) suggest low salinity in Lake Titicaca, and diatom analyses (Servant-Vildary, 1978) high salinity in the Uyuni-Coipasa Basin. These later data are in agreement with a geochemical model (Risacher and Fritz, 1991) which indicates that this paleolake was deep and saline. More recent studies, achieved on several sites and based on a detailed radiocarbon chronology and previous diatom studies, established the regional stratigraphy between 15,000 and 10,000 yr B.P. (Servant *et al.*, 1995).

Of the various paleoclimatic indicators contained in sediments of closed basin lakes, diatoms are one of the most useful biological indicators to provide information on water-level and salinity changes. They have been used to produce both qualitative (Bradbury, 1991) and quantitative (Roux *et al.*, 1991; Fritz *et al.*, 1991) reconstructions of paleosalinity.

The present paper provides a detailed reconstruction of water-level and salinity of this lacustrine event. This reconstruction is based on fossil diatom studies from profiles cropping out on the margin of the two main basins in the southern Bolivian Altiplano.

Study area

The Bolivian Altiplano is a large basin of internal drainage at an altitude of approximately 3800 m (Fig. 1a). It is enclosed between the western and the eastern Cordilleras and extends from about 16° S to 22° S. The Lake Titicaca (3809 m) occupies the northern Altiplano and has a maximum depth of 285 m. The lake receives an average rainfall of 800 mm yr^{-1} (Roche *et al.*, 1992). Its outlet, the Rio Desaguadero (3804 m), flows south into the Lake Poopò (3686 m). Lake Poopò experiences drier climatic conditions, with mean annual rainfall being 390 mm yr^{-1}. Depending on the season and the year, lake depth varies from a few centimeters to 9 m during high run-off periods. Further south on the Altiplano are dry salt lakes or 'salares' Coipasa (3657 m) and Uyuni (3653 m). These two basins receive an average rainfall of 100 mm yr^{-1}. During the rainy season, the salars may be covered by

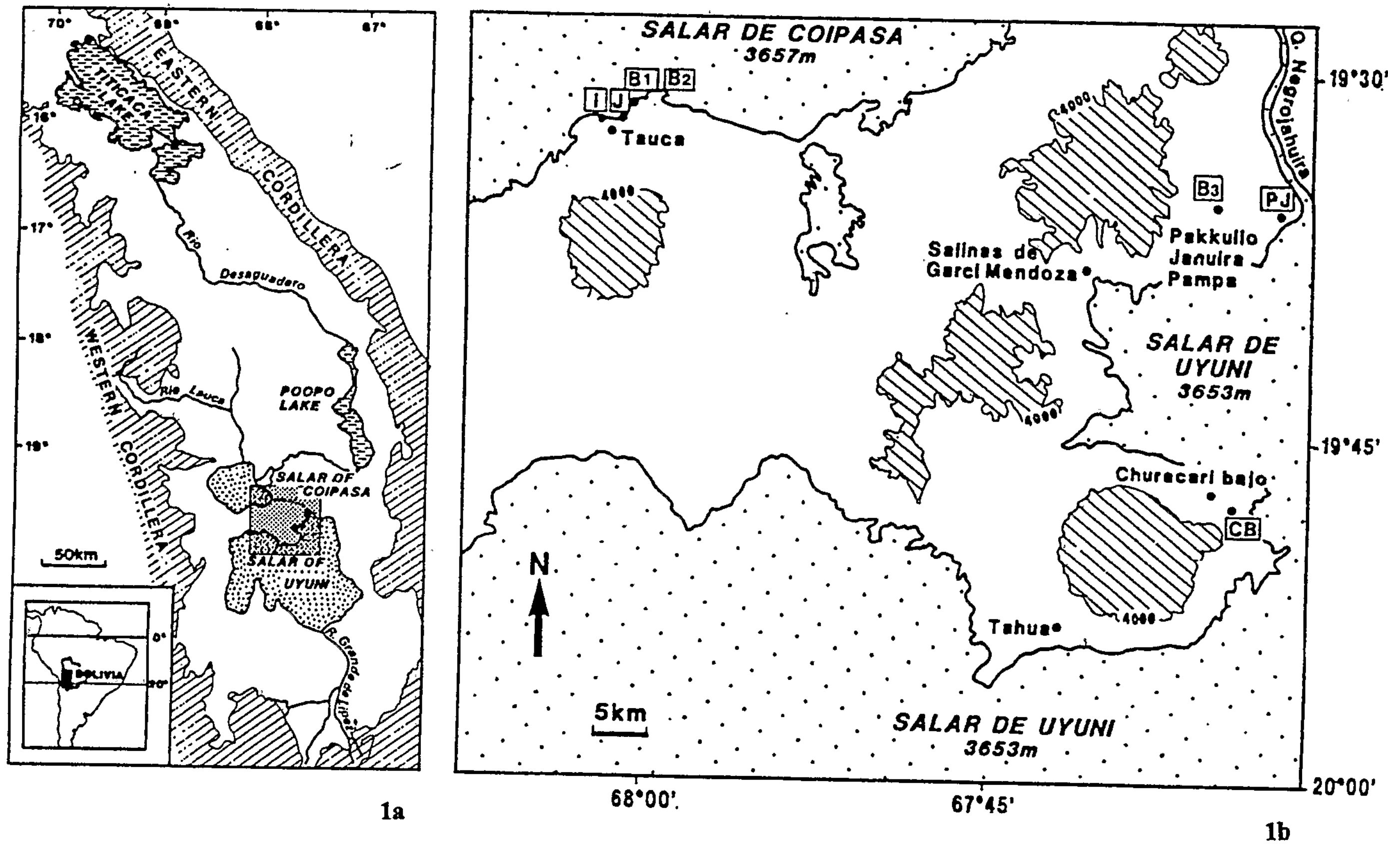


Fig. 1. (a) Bolivian Altiplano: Location of studied area; (b) Studied area (southern margin of the salar of Coipasa and northern margin of the salar of Uyuni): location of studies sites: **PJ**: Pakkollu Jahuira; **CB**: Churacari Bajo; **I** and **J**: Tauca.

brine to a depth of about 25 cm, but during the dry season the brine usually evaporates to expose the salt surface (Risacher, 1992). During periods of high water level, Lake Poopò may discharge into the salar of Coipasa (3657 m). But the salar of Uyuni is only fed by the Rio Grande of the Lipez, coming from the southermost part of the Bolivian Altiplano. Today, the north-south climatic gradient and the southward movement of water in the whole of the basin influence the water chemistry, biota and regime of the lakes. In Lake Titicaca, the total dissolved salt concentration varies from 0.9 g L^{-1} to 1.2 g L^{-1}. The waters are dominated by chloride, sulfate and sodium ions. In Lake Poopò, the mean concentration of total dissolved salts, dominated by Na–Cl (Carmouze *et al.*, 1978), varies between 10 and 40 g L^{-1}. The salars of Uyuni and Coipasa are occupied by a thick salt crust essentially made of porous halite, and during the rainy season, the salinity of the brine varies between 325 and 354 g L^{-1} (Risacher, 1992).

This study is focused on two areas near Tauca and Salinas de Garci Mendoza (Fig. 1b), respectively located on the southern margin of the salar of Coipasa and on the northern margin of the salar of Uyuni where Late Glacial deposits outcrop in several sites. In this area, water-level fluctuations could be controlled by the outlets of lakes Titicaca and Poopò. This will be taken into account for the interpretation of past lacustrine variations. Presently, the Uyuni-Coipasa Basin rely essentially on inputs of precipitation (Risacher, 1992).

Stratigraphy

Stratigraphical studies performed in these areas (Servant *et al.*, 1995) are based on a schematic cross-section of Upper Quaternary deposits (Fig. 2). Fossil diatoms were analysed on four outcrops: Churacari Bajo (**CB**), Pakkollu Jahuira (**PJ**), Tauca (**I** and **J**), and on algal bioherms (**B1-B2-B3**) located in the regional stratigraphy in Fig. 2. From the base to the top:

- the oldest deposit is a lacustrine formation (**M**, *Minchin event*) attributed to the Middle Last Glaciation (Servant and Fontes, 1978).
- the *Minchin* deposits are dissected by an erosion surface overlaid by fluviatile sands (**F1**).
- Further up, lacustrine deposits (**T**) and bioherms (**B**) extend on the slopes of the Uyuni-Coipasa Basin. The lacustrine deposits are divided into three stratigraphical units. Unit **I** is represented at 3657 m at the base of **PJ** section by a calcareous crust and clayey-silty sediments. Unit **II** is observed in **PJ** and **CB** outcrops. In **PJ** section, it is represented by clayey-silty sediments. In **CB** outcrop, it is largely developed (120 cm) and characterized by laminated sediments. Unit **III**, composed of homogeneous

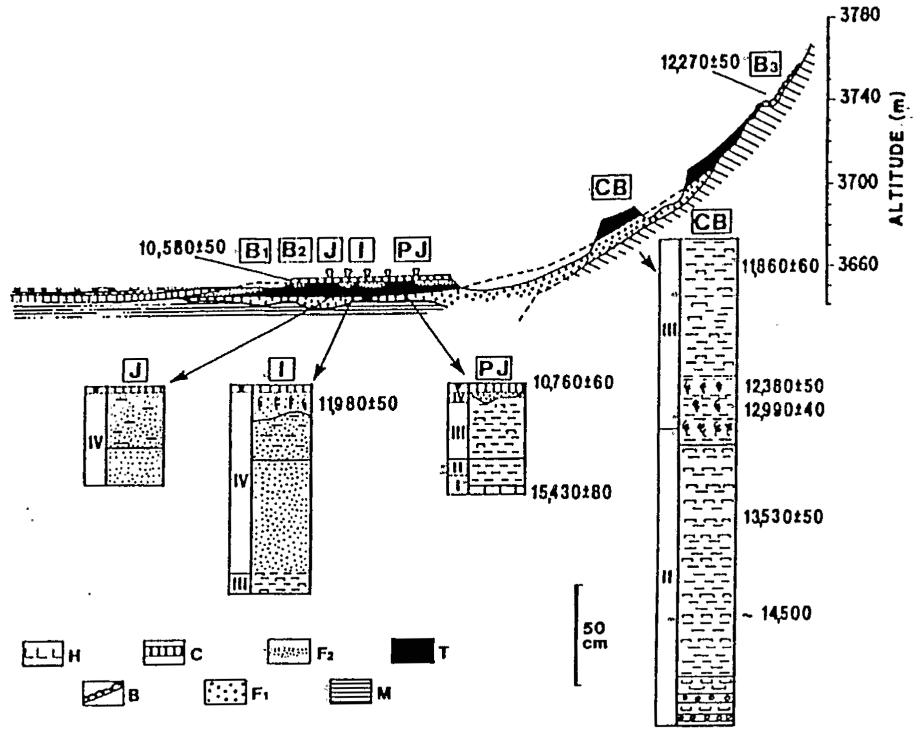


Fig. 2. Schematic cross-section of the Late Quaternary on the margin of the Uyuni-Coipasa basin. **M**: lacustrine formation *Minchin*; **F1**: fluviatile sands; **T**: lacustrine formation *Tauca* (**I-II-III**); **B**: algal bioherms; **F2**: fluviatile sands with clayey lens-shaped deposits (**IV**); **C**: calcareous crust with algal bioherms (**V**); **H**: holocene evaporite (salar). **PJ**: Pakkollu Jahuira; **CB**: Churacari Bajo; **I-.J.**: clayey lens shaped deposits; **B1-2-3**: algal bioherms.

diatomites, is widespread in several sites (**PJ**, **CB**, **I**) until about 3735m altitude. Algal bioherms (**B**) attributed to this phase reach 3760 m. These three units were studied on **PJ** at 3657 m, on **CB** at 3685 m and on algal bioherms (**B3**) at 3740 m from the margin of Uyuni Basin at 3740 m.

- Further up are fluviatile sands (**F2**) with interbedded clayey-silty lens-shaped deposits. Diatoms were studied on two outcrops (**I**, **J**) situated on the margin of the Coipasa Basin.
- A calcareous crust (**C**) with algal bioherms represents the most recent lacustrine deposit. This crust overlies the fluviatile sands (**F2**) and it is not observed above 3660 m. Diatoms were analysed on the algal bioherms (**B1-B2**).

Thirty-nine radiocarbon dates were performed on carbonate samples. They are discussed in Servant *et al.* (1995). One U-Th date performed on a bioherm sample is in agreement with a ^{14}C calibrated age (Causse *et al.*, 1995). Servant

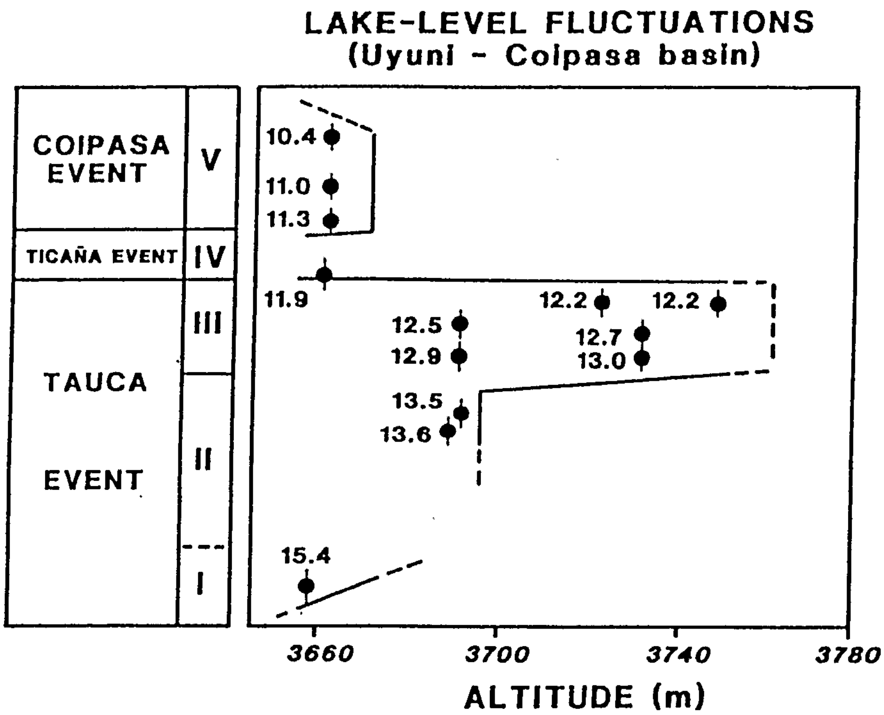


Fig. 3. Lake-level fluctuations in the Uyuni-Coipasa basin based on stratigraphical studies, radiocarbon chronology and previous diatom analyses (after Servant *et al.*, 1995).

et al. (1995) divided the Late Glacial into five paleohydrological phases (Fig. 3). Between 15,430 ± 80 yr B.P. and ~13,000 years, a transgressive lacustrine phase has been divided in two steps, the first one (I) recorded the transgression of the lake at 3657 m (~ +4 m) on the border of the salar; during the second step (II) the lake-level reached 3685 m (~ +32 m). Between ~13,000 years to ~12,000 years, the lake-level increased again and reached its maximum at 3760 m (~ +100 m) (III). These initial three lacustrine phases represent the *Tauca Event.* After ~12,000 years, the water table dropped ~100 m to at least 3657 m (IV, *Ticaña Event*). A new and moderate lacustrine phase (V, *Coipasa Event*) began at ~11,400 years and remained until at least ~10,400 years.

Methods

Diatom samples were treated with 10% HCl and 30% H_2O_2 to remove carbonates and organic matter, respectively. A small quantity of the sample (0.4 mL) was evaporated onto coverslips and subsequently mounted onto a glass slide with Naphrax. Diatoms were identified using a Nachet NS 400 microscope (1000 × magnification with Nomarski optics, n.a. = 1.32). A minimum of 500 diatom valves were identified and counted along parallel transects from each sample. Systematic and ecological interpretations are based on a variety of literature sources, including Krammer and Lange-Bertalot (1986–1991), Germain (1981), Hendey (1964), Bourrelly and Manguin (1952), Frenguelli (1929, 1936). To complete our ecological interpretations, we used data from modern samples collected in small basins in southernmost Bolivian Altiplano (Servant-Vildary and Roux, 1990) and from small saline ponds around the Uyuni salar (Sylvestre, unpublished data). Dominant taxa were selected to show the succession of diatom communities and to illustrate major ecological changes along the outcrops (Figs. 4 and 5).

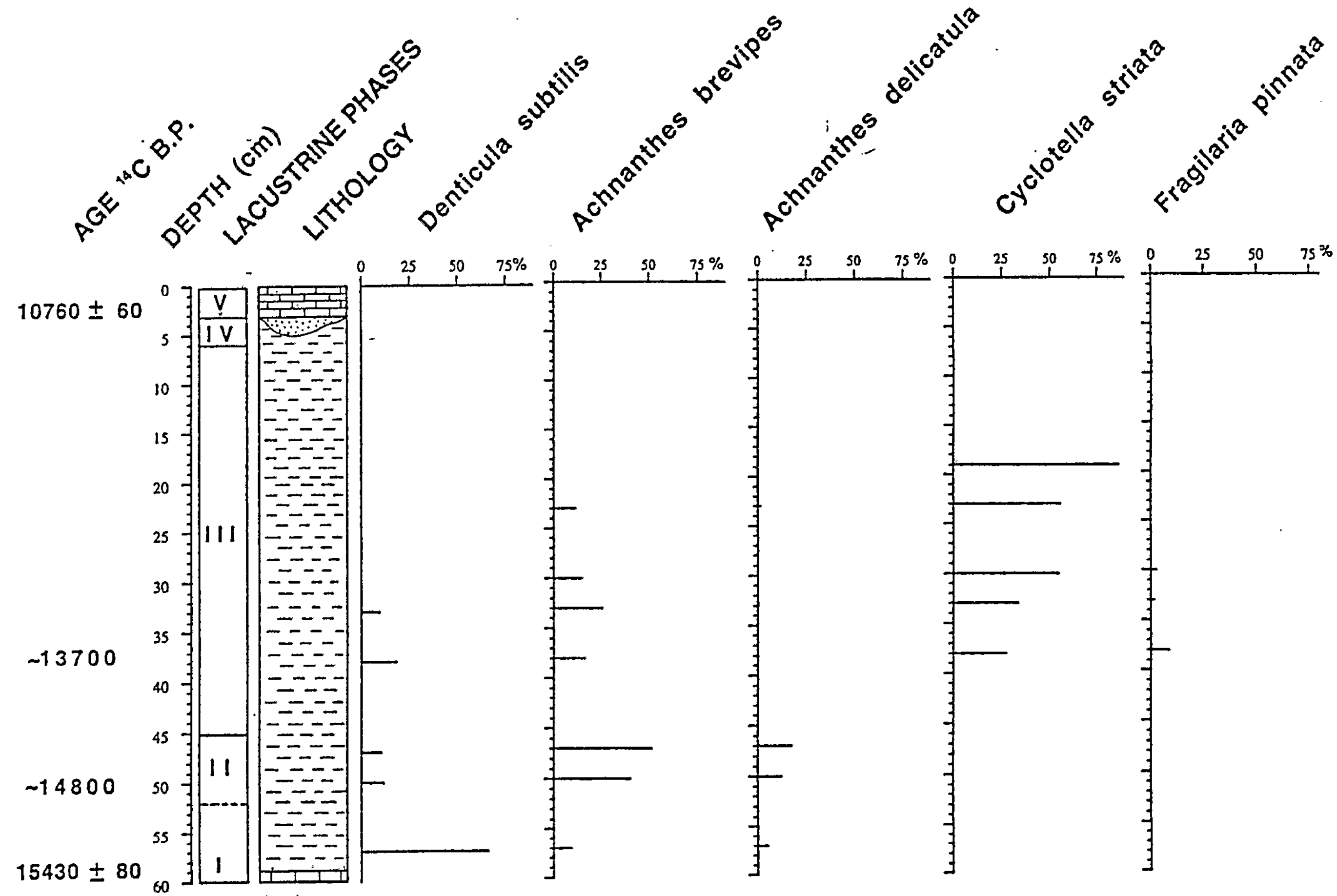
Several patterns for classifying diatoms according to salinity have been developed. Many diatomists commonly used the halobian system of Hustedt (1957), based on the system proposed by Kolbe (1927), in which diatoms are classified according to Na-Cl affinities. Gasse *et al.* (1987) modified this system for applications to athalassic environments; in it, diatoms are classified into seven major classes taking into account species preference and tolerance with regard to Total Dissolved Solid (TDS). In this paper, we used this classification (Table 1).

Results

Pakkollu Jahuira (**PJ**) (Fig. 4)

Fossil diatoms were studied in the **PJ** outcrop located in the north-western margin of Uyuni Basin at 3657 m, ~ +4 m above the present bottom (Fig. 1). This outcroup is 58 cm deep. A thin calcareous crust essentially composed of aragonite marks the base of the section. A radiocarbon date gave an age of 15,430 ± 80 yr B.P. (Beta 73088, aragonite). Between 58 cm to 6 cm, sediments are composed of homogeneous clayey silts. At 6 cm, an interbedded thin layer of fluviatile sands is attributed to the *Ticaña Event* (~11,900 years). Further up, at 3 cm, a thin calcareous crust gave an age of 10,760 ± 50 B.P., correlated to the *Coipasa Event* (OBDY 927, calcareous crust).

A total of 43 diatom taxa were recorded in the section. At the base (57–59 cm), diatom assemblages are characterized by the dominance (69 per cent) of a benthic species, *Denticula subtilis*, living in mesosaline to metasaline water (13–45 g L^{-1}). *Denticula subtilis* is frequently observed in brackish-water (Krammer and Lange-Bertalot, 1988) and in marine estuaries (Poulin *et al.*, 1987). Between 50 cm (*ca.* 14,800 yr B.P.) and 45 cm, the flora is domi-



... depth (cm) and age (^{14}C) B.P. axes of Pakkollu Jahuira outcrop showing diatom taxa selected as

Fig. 4. Lithology and percentage diagram along depth (cm) and age (^{14}C) B.P. axes of Pakkollu Jahuira outcrop showing diatom taxa selected as characteristic of the successive assemblages.

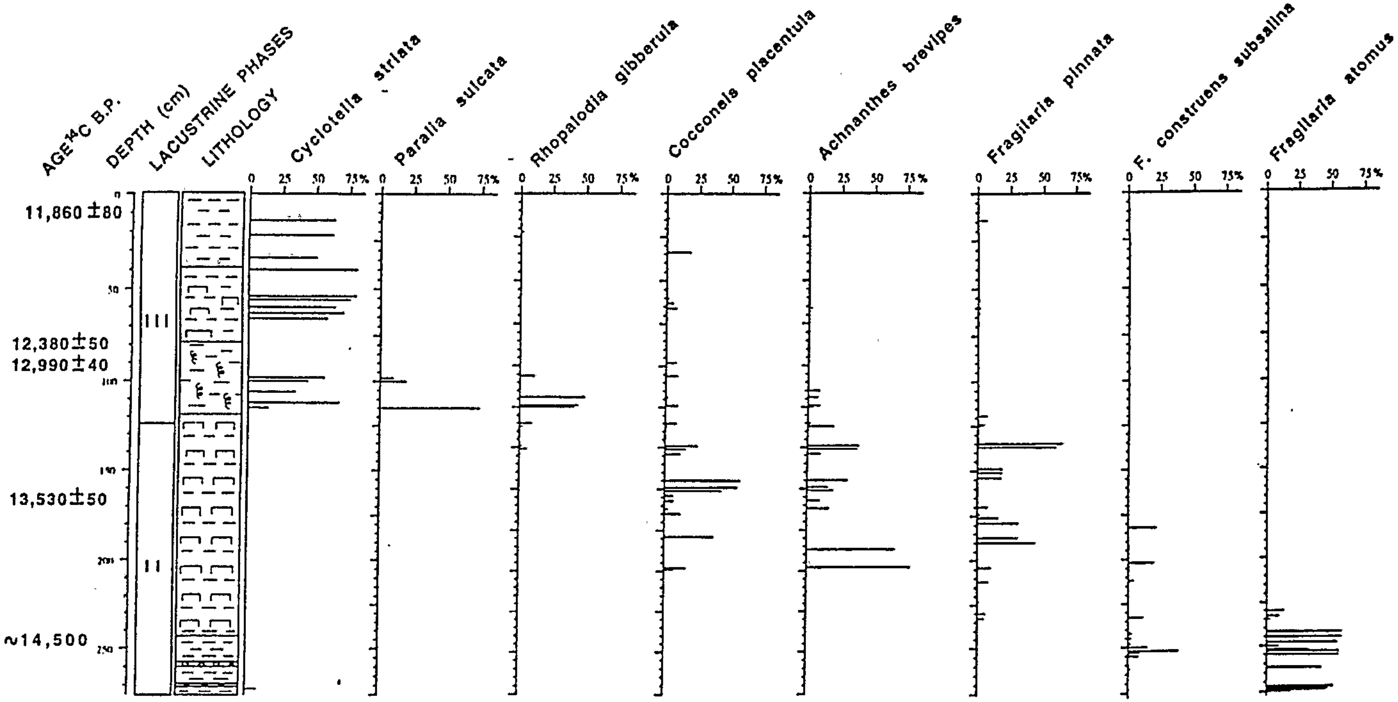
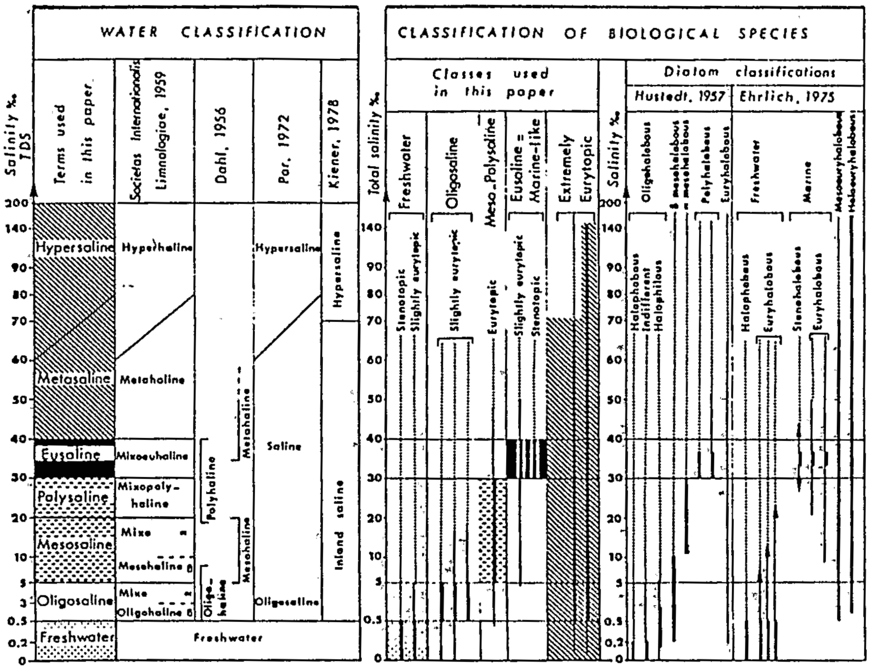


Fig. 5. Lithology and percentage diagram along depth (cm) and age (^{14}C B.P.) axes of Churacari Bajo outcrop showing diatom taxa selected as characteristic of the successive assemblages.

Table 1. Classification of athalassic environments (Gasse *et al.*, 1987).



nated by an epiphytic species, *Achnanthes brevipes* (54 per cent), which often lives in mesosaline to eusaline water. Hustedt (1938) considers this species as a mesohalobe (3–16 g L^{-1}). Presently, *A. brevipes* is observed in small Na–Cl saline ponds around the Uyuni basin (34 g L^{-1}). Ben Khelifa (1989) describes this species in higher abundance in Na–Cl dominated saline lakes. At 37 cm (*ca.* 13,700 yr B.P.), a planktonic, meso-polysaline species, *Cyclotella striata* appears. It dominates the assemblage (75 to 80 per cent). *Cyclotella striata* is a common marine and brackish-water species often abundant in the spring estuarine plankton (Hendey, 1964), living in salinities between 3 and 16 g L^{-1} (Servant-Vildary, 1978). In Choctawhatchee Bay (Florida), *Cyclotella striata* was found during the spring as salinities increased to >20 g L^{-1} and decreased during the winter when salinities and temperature are lower (Prasad *et al.*, 1990). Near the top of the section (0–17 cm), diatom frustules are highly dissolved.

Churacari Bajo (CB) (Fig. 5)

This section is located on the border of Uyuni Basin in front of outcrop **PJ** at 3685 m, +32 m above the present bottom (Fig. 1). It is 275 cm deep and presents 4 lithological units. From the base to 240 cm, it is composed of homogeneous clayey-silty sediment rich in diatoms with two sandy-gravelly layers at 260 and 270 cm. Between 240 and 120 cm, the sediment is finely laminated. The thickness of the individual laminae varies between a few tenths of a millimeter to several millimeters. Each lamination is composed of clays, silts, ostracods and diatoms. Between 120 and 80 cm, sediments are composed of a mixture of mollusc shells, characeae debris, ostracods, diatoms, clays and silts, characterizing synsedimentary reworkings (Servant *et al.*, 1995). The uppermost 120 cm are composed of homogeneous clayey-silty sediments rich in diatoms. Radiocarbon dates gave ages of 13,530 ± 50 yr B.P. (OBDY 879, carbonate) at 156 cm, 12,990 ± 40 yr B.P. (OBDY 916, characeae) and 12,380 ± 50 yr B.P. (OBDY 919, mollusc shells) at 92 cm, 11,860 ± 60 yr B.P. (OBDY 969, carbonate) at 9 cm. Assuming constant sedimentation rates between 92 and 156 cm, we estimated the beginning of the laminated deposits at ~14,500 yr B.P.

Fifty-one samples were analysed for diatoms and 173 species were identified. From 280 to 230 cm, the diatom assemblages are characterized by a dominance of *Fragilaria atomus* and *Fragilaria construens* var. *subsalina*, comprising 50 to 80 per cent of the assemblage. *Fragilaria atomus* is considered a brackish-water species and is abundant today in the Baltic Sea (Lange-Bertalot, personal communication), in which salinities are < 10 g L^{-1} (Kullenberg, 1981). *Fragilaria construens* var. *subsalina* is considered as halophile by Hustedt (1938), mesohalobe by Bourrelly and Manguin (1952), and presently lives on the margin of Uyuni salar in Na–SO_4–Cl water where the salinity is 6 g L^{-1}.

Between 230 and 120 cm, four dominant species characterized the diatom flora contained in the finely laminated sediment: *Achnanthes brevipes*, *Cocconeis placentula* var. *euglypta*, *Rhopalodia gibberula* and *Fragilaria pinnata*. The base of the lamination (225–223.1 cm) is characterized by a dominance (69–81 per cent) of *Achnanthes brevipes*. Further up, between 212.4 and 154.5 cm, *Cocconeis placentula* var. *euglypta* and *Fragilaria pinnata* are alternately dominant. *Achnanthes brevipes* reappears between 151 and 148.6 cm, followed by *Fragilaria pinnata* between 137.4 and 134.8 cm. *Rhopalodia gibberula* characterizes the upper part at 125.2 cm, 124.5 cm and 119 cm. *Achnanthes brevipes*, *Cocconeis placentula* var. *euglypta* and *Rhopalodia gibberula* are benthic and/or epiphytic, living in shallow waters and/or in the littoral zone. Only *Fragilaria pinnata* is a tychoplanktonic species. These four species have been observed in samples collected in small ponds around the salt crust of Uyuni salar. *Cocconeis placentula* var. *euglypta* and *Fragilaria pinnata* lives in Na–SO_4–Cl water where salinities are respectively 0.9 and 1.1 g L^{-1}. Generally, *Cocconeis placentula* var. *euglypta* is considered as euryhaline (Bourrelly and Manguin, 1952). In lakes of the Northern Great Plains (North America), where the inferred salinity optimum is 8.87 g L^{-1}, the salinity tolerances of this species lies between 4.20 and 18.69 g L^{-1} (Fritz *et al.*, 1993). Noël (1984) found this species in brines of Bras del Port (Spain) where salinities are 64 to 86 g L^{-1}. *Fragilaria pinnata* is considered as oligohalobe (Hustedt,1957), but it occasionally may survive over slight variations in osmotic pressure (Cholnoky, 1968). In small salt lakes, located in the south of the studied area, the salinity tolerance was between 1.4 and 14.3 g L^{-1} (Servant-Vildary and Roux, 1990). *Rhopalodia gibberula* and *Achnanthes brevipes* presently live on the border of the salar of Uyuni in NaCl water where salinities are 5 and 34 g L^{-1} respectively. *Rhopalodia gibberula* is considered as euryhaline (Iltis, 1972), and *Achnanthes brevipes* as mesohalobe (Hustedt, 1938).

At 120 cm, the diatom assemblages abruptly change. The laminae disappear and are replaced by homogeneous clayey-silty sediments. The marine species *Paralia sulcata* characterized the 115 cm level where it reachs 76.5 per cent. After 112 cm, the assemblage is dominated by planktonic forms, such as *Cyclotella* species (70 per cent). *Cyclotella* frustules are mostly dissolved, but they present different states of dissolution that allow us to attribute the *Cyclotella* frustules to *Cyclotella striata*. The dissolution process may have occurred after the sedimentation. Algal bioherms, covering slopes from 3730 to 3760 m (~100 m above the outcrop), contain assemblages dominated by the same *Cyclotella*. *Cyclotella striata* is considered as mesohalobe by Hustedt (1938) and it is observed in marine estuarine and brackish water (Iltis, 1972).

*Tauca (***I** *and* **J***)*

The study of *Ticaña Event* (**IV**) is focused on diatoms contained in clayey-silty, lens-shaped deposits interbedded in fluviatile sands (**F2**) located at 3657 m in two different sites (**I**, **J**) on the border of the Coipasa Basin. One radiocarbon date (11,980 ± 50, OBDY 1290) on non-reworked Gasteropod shells contained in lens shaped-deposits has been achieved. This ^{14}C age is reliable because 1) there is a good consistency with the local stratigraphy (Servant *et al.*, 1995); 2) an X-ray diffraction (XRD) on the gasteropod shells show that they are composed of 80 per cent aragonite. The proximity to the most recent radiocarbon ages achieved on the lacustrine deposits **T** suggests that this drop of the lake occurred abruptly.

The *Coipasa Event* (V) is represented by a calcareous crust (C) widely expanded around the basin at 3660 m and by algal bioherms on it. This event has been dated on several sites; ages lie between 11,390 ± 50 yr B.P. (OBDY 925, calcareous microcrystalline crusts) and 10,450 ± 160 yr B.P. (Orsay 42, calcareous microcrystalline crusts).

These two events are characterized by *Denticula subtilis*, comprising 90 per cent in the assemblage. Diatom frustules contained in samples are not in a good state of preservation. They are higher dissolved and we assume that the death associations are modified accordingly.

Paleohydrological changes from Uyuni-Coipasa basin

Table 2 shows the synthetic reconstruction of the paleohydrological changes from the Uyuni-Coipasa Basin. The lake level is estimated for each phase by the altitude of the lacustrine deposits.

The Tauca Event (I-II-III): ~15,500–12,000 yr B.P.

Lacustrine conditions in the Uyuni-Coipasa Basin began at least at about 15,500 years. At 15,430 ± 80 yr B.P. (**Ia**), a shallow saline lake developed in the basin.The diatom assemblages indicate a range of salinity between 13 to 45 g L^{-1}. The lake level was ~ +4 m above the present bottom of the salar.

After 15,430 ± 80 yr B.P., the lake level increased and reached ~27 m (**Ib**). At 3657 m, planktonic meso-polysaline (20 g L^{-1}) Na–Cl species *Cyclotella striata* indicated deep, saline water-body conditions. At 3682 m, the deposits contain tychoplanktonic mesosaline (6–10 g L^{-1}) Na–SO_4–Cl species, such as *Fragilaria atomus* and *Fragilaria construens* var. *subsalina*.

Between ~14,500 years and ~13,000 years, the sedimentation in **CB** outcrop is characterized by finely laminated deposits (**II**). They successively contain a dominance of epiphytic meso-hypersaline diatoms and tychoplanktonic oligosaline diatoms living in an Na–Cl to Na–SO_4–Cl dominated lake. The water-level was at ~ +32 m and it was subject to weak water-level and salinity fluctuations. These suggest short variations between precipitation and evaporation over time.

At ~13,000 years, strong sedimentological and ecological changes appeared. The laminated sediments were replaced by homogeneous clayey-silty sediments and the epiphytic flora by a planktonic meso-polysaline species (**III**), implying a salinity of 20 g L^{-1}. At 3740 m altitude, algal bioherms contain the same diatom flora. At this time, the lake reaches its maximum extension (~80000 km^2). This implies a deep salt lake (~ +100 m).

Table 2. Synthetic reconstruction of paleohydrological changes in the Uyuni-Coipasa basin.

Age ^{14}C B.P.	Lacustrine phases	Dominant diatoms Ecology: habitat and salinity (g L^{-1})	Lake level fluctuations (m)
10,450 ± 160		*Denticula subtilis*	
	V	Benthic	~ +7
11,390 ± 50		13–45	
		Denticula subtilis	
11,980 ± 50	**IV**	Benthic	~ +4
		13–45	
ca. 12,000		*Cyclotella striata*	
	III	Planktonic	~ +100
		<20	
13,030 ± 80		*Rhopalodia gibberula*	
		Benthic	
		5	
		C.placentula euglypta	
		Epiphytic	
		0,9–86	
	II	*Fragilaria pinnata*	~ +32
		Tychoplanktonic	
		0,83–14,3	
		Achnanthes brevipes	
		Epiphytic	
		3–34	
ca. 14,500		*Fragilaria atomus*	
	I b	*F. construens subsalina*	~ +27
		Tychoplanktonic	
		6–10	
	I a	*Denticula subtilis*	
		Benthic	~ +4
15,430 ± 80		13–45	

The Ticaña Event (IV): ~12,000–11,400 yr B.P.

After ~12,000 years, the lake level abruptly dropped ~100 m. This abrupt drop is documented by the erosion of **III** deposits and by the deposition of fluviatile sands (**IV**) at 3657 m altitude on the margin of the basin. The lens-shaped deposits interbedded in the fluviatile sand contained the benthic meso-metasaline species *Denticula subtilis*. This lenticular sedimentation suggests shallow residual saline ponds remained around the main basin.

The Coipasa Event (V): ~11,400–10,400 yr B.P.

At 11,390 ± 50 yr B.P., a new moderate lacustrine phase (V) appeared. This is recorded by a calcareous crust supporting algal bioherms which contained the same diatom assemblages as those identified during the phases **I** and **IV**. This presumes no modification of the ionic composition of the water during low water-level events.

Discussion and conclusion

The paleoecological records derived from diatom analyses in the Uyuni-Coipasa Basin may be compared with available data from the northern Altiplano. In Lake Titicaca, a palynological study (Ybert, 1992) performed on two cores (TD and TD1) taken at 19 m water depth, and diatom studies on TD1 (Servant-Vildary, unpublished data), show the major trends in the evolution of lacustrine fluctuations during the last 20,000 years B.P.

The beginning of lacustrine conditions occurred at ~15,500 years B.P. in the Uyuni-Coipasa Basin. In Lake Titicaca (core TD1), the dominance of *Isoëtes* taxa and pollen of wetland plants which presently live in the littoral zone between 20 cm and 2 m depth indicate a low water-level. No diatoms were observed. Very thin deposits (10 cm) between 18,185 ± 180 yr B.P. and an estimated age at ~14–15,000 years B.P. suggest a hiatus of sedimentation (Servant *et al.*, 1995). Then, the level of Lake Titicaca was lower than its outlet and could not discharge into the southern basins. Thus, the increasing lake level in the Uyuni-Coipasa Basin was essentially due to water inputs from local precipitation. The high salinity values (13–45 g L^{-1}) may be explained partly by the accumulation of total dissolved salt derived from rivers and partly by the dissolution of former salt crusts deposited during previous lacustrine phases. During the phase **Ib**, diatoms indicate a decrease of salinity, related to the increase of the lake level, implying large fresh- water inputs into the basin.

At ~14,500–13,000 years B.P., lake level continues to increase in the southern Altiplano. Finely laminated sediments in Uyuni-Coipasa Basin indicate a water-table at ~ +30–35 m higher than today's level. In Lake Titicaca, an increase of algal taxa (*Botryococcus* and *Pediastrum*) is dated a little before 13,180 ± 130 yr B.P. (core TD1). These algae represent 60 per cent of the palynomorph assemblage. In comparison with their present day distribution, the lake level could still not reach its outlet and the water-level in the southern basins increased without any discharge from the northern part of the Altiplano. On the margin of the Uyuni-Coipasa Basin, the diatom assemblages suggest high salinity with weak fluctuations. Estimations of salinity based only on data from the literature is difficult. However, during increasing lake level (tychoplanktonic species), we assume a range of salinity between 0.83 and 14.3 g L^{-1} (Servant-Vildary and Roux, 1990). The salinity may have reached 86 g L^{-1} during water table stabilization (epiphytic and/or benthic species).

At ~13,000 years B.P. in the Uyuni-Coipasa Basin, the water-level abruptly increased to reach ~ +100 m depth above the present bottom. In Lake Titicaca, the algal taxa (*Pediastrum* and *Botryococcus*) also reached maximum percentages (>90 per cent). The present day distribution of these taxa show that they are dominant in water depths between 4 m to >10 m. Diatom assemblages observed in the same core are characterized by a dominance of the planktonic species *Cyclotella andina.* This species presently lives between 5 and 25 m water depth (Miskane, 1992) and is very abundant between 3.5 and 80 m (Servant-Vildary, 1992). An undated lacustrine terrace located at few metres above the present day level is attributed to this phase (Servant and Fontes, 1978). These observations suggest that the lake level was high and water overflowed to the southern basins. The abrupt and strong increase in lake level in the Uyuni-Coipasa Basin at ~13,000 years B.P. may be explained by a large discharge to the basin from Lake Titicaca. Nevertheless, the dominance of *Cyclotella andina* and *Isoëtes* taxa indicates freshwater conditions in Lake Titicaca, whereas *Cyclotella striata* indicates a mesosaline lake in the Uyuni-Coipasa Basin. This suggests that the northern Altiplano was more humid than the southern Altiplano of today.

At about 11,900 years B.P., a sudden dry event occurred in the Uyuni-Coipasa Basin. In Lake Titicaca, a disappearance of planktonic diatoms and a decrease in other algae occurred just after 13,000 years B.P. These data indicate that the decrease in water-level began at about this time. Thus, the strong drop of the water-level in Uyuni-Coipasa Basin could have been amplified by the interruption of the discharge from Lake Titicaca.

At ~11,400 years B.P., lacustrine conditions returned briefly, lasting until 10,400 yr B.P. We assume that the lake dried after 10,400 yr B.P. because Lake Titicaca was low before 9,620 ± 90 yr B.P.

The data available on the southernmost part of the Bolivian Altiplano (south Lipez 23° S) (Servant-Vildary and Mello e Sousa, 1993) and on the northern Chilean Altiplano (24° S) (Messerli *et al.*, 1993; Grosjean, 1994; Grosjean and Schotterer, 1995) show that lacustrine fluctuations are similar between ~15,500 years B.P. to ~13,000 years B.P. in the south Bolivian Altiplano (Uyuni-Coipasa Basin and south Lipez) and in the Atacama desert.

In the Laguna Leija (north Chilean Altiplano), the beginning of lacustrine conditions occurred at the same time as the Uyuni-Coipasa basin at ~15,500 years B.P. and the level continued to increase until ~13,000 years B.P. But, after ~13,000 years B.P., the lake stayed at the same level, at ~ +25 m higher than today's level, whereas in the Uyuni-Coipasa Basin the range of the increase of the lake level is generally higher. The sudden dry event between ~12,000 and 11,400 years B.P. had not yet become evident in the Lipez area and in the Atacama desert, but lake levels remained high until 10,400 yr B.P. and dried prior to 8,500 yr B.P.

To lead to the formation of high lake levels, higher precipitation rates than today are assumed (Hastenrath and Kutzbach, 1985; Grosjean, 1994; Servant *et al.*, 1995). Glacial fluctuations deduced from moraine stratigraphy and water budget models corroborate this interpretation. On the Peruvian-Bolivian Andes, Servant *et al.* (1995) and Seltzer (1990) provided evidence for three major advances at M1b, M2 and M3, respectively, dated a little after 15,500 yr B.P., a little after 13,900 yr B.P. and at 11,000 yr B.P. These three major glacial advances are associated with increasing lake level phases I, II, III and V, respectively. They show that the lacustrine phases cannot be explained by glacier melt waters, but by an increase of Precipitation minus Evaporation (P-E). Two water and energy budget models have been achieved on the south Bolivian Altiplano (Hastenrath and Kutzbach, 1985) and on the northern Chilean Altiplano (Grosjean, 1994). In the south Bolivian Altiplano, precipitation of 300 mm/yr above the modern average annual value (200 mm/yr) has been estimated for a lake at 3740 m. In the northern Chilean Altiplano, precipitation rates of 400–>500 mm/yr have been predicted for the maximum late-glacial water level.

In summary, lake level fluctuations recorded in the Uyuni-Coipasa Basin, when compared with paleohydrological data available on the Bolivian and north Chilean Altiplano, show that during the earlier Late Glacial, precipitation rates were higher than today in the southern basins. From ~13,000 yr B.P. in the south Lipez and in the north Chilean Altiplano, the lake apparently stayed at the same level until 10,400 yr B.P., whereas in the Uyuni-Coipasa Basin lake level fluctuations were largely influenced by the north Bolivian Altiplano. However, these fluctuations revealed a maximum of precipitation at ~13–12,000 years B.P. and a drier phase between ~12,000 and ~11,400 years B.P.

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