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Late Quaternary Spatio-temporal Limnological Variations in the Altiplano of Bolivia and Peru[1]

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Between the western and eastern Andean cordilleras in Peru and Bolivia, there are three main lacustrine basins: Lake Titicaca, Lake Poopó, and the group of Coipasa-Uyuni. For the past few millennia, highly variable environmental conditions have been recorded in their sediments. Today a latitudinal meteorological gradient influences the lakes' status, leading to specific deposits and ostracod communities. Lake Titicaca in the north is oligohaline, whereas Lake Poopó further south is polyhaline. In the south, the Coipasa-Uyuni depression is characterized by a 12,000-km^2 surficial salt crust. During the Late Pleistocene (ca. 40,000 to 25,000 yr B.P.), the water depth and salinity in paleolake Poopó fluctuated widely and paleolake Titicaca was slightly larger than at present. Sedimentation was mostly biocarbonate in the shallower areas and it was detrital-organic in the deepest zones. During the Holocene, a dry period transformed Lake Poopó into a "salar" with evaporite precipitation. Lake Titicaca registered a large decline in water level (8100–3600 yr B.P.) initially inducing gypsum precipitation followed by short influxes of water, with an ostracod faunal composition similar to that of the modern brines of Lake Poopó. Lake Titicacas' present condition only appeared between 2200 and 1500 yr B.P. ©1995 University of Washington.

INTRODUCTION

The Altiplano is a 200,000-km^2 intermontane endorheic basin in the central Andes of Peru, Bolivia, and Argentine. The Peruvian–Bolivian section is a high plateau, lying between the Western and Eastern cordilleras. It contains a deep lake in the north (Lake Titicaca), a very shallow lake in the center (Lake Poopó), and dry salt lakes or "salares" (Uyuni and Coipasa) further south (Fig. 1). Since 1.8 myr ago, these water bodies have registered several maximum expansions linked with the termination of successive glaciations (Ahlfeld, 1972; Lavenu, 1992; Servant and Fontes, 1978; Servant *et al.*, 1994). The various lacustrine deposits are not superimposed, but rather inset within one another. Since 0.6 myr ago the neotectonic N–S extensional deformations have been weak and morphologic displacements do not exceed 2 m. From the oldest to the most recent, the corresponding enlarged lake surfaces are known as paleolakes Mataro, Cabana, Ballivian, Minchin, and Tauca (Figs. 2 and 3).

Paleolimnological data extending back to 40,000 yr B.P. and based on a ^{14}C radiochronology are presented here. Organic matter, and gastropod or ostracod shells were dated by accelerator mass spectrometry and the bulk sediment and stromatolites by a liquid scintillation procedure. Special emphasis is placed on the Holocene and Late Pleistocene records to underline and compare the high variability of these lacustrine ecosystems during the recent past.

METHODOLOGY

The paleoenvironmental interpretations are made with reference to qualitative changes in sediment records (Wirrmann *et al.*, 1988, 1992) and in ostracod assemblages (Mourguiart, 1992). Forty ostracod species have been collected from various modern lacustrine environments over the Altiplano from 40 different lakes and swamps. This large field investigation on modern ostracod faunas was necessary to specify their present tolerance limits and to cover the wide variation of present water bodies (from 0.3 to 80 g · liter^{-1} in salinity and from 0.2 to 80 m in depth). Sampling in lakes Titicaca and Poopó was conducted during dry and wet seasons, with a special focus on peculiar climatic events (e.g., the severe drought during 1982–1983).

Factor analysis of correspondences (FAC) or reciprocal averaging (Greenacre, 1984; Hill, 1973; Lebart *et al.*, 1984) has been used in this study for determining water depth and total dissolved salts (TDS) classes. A complete

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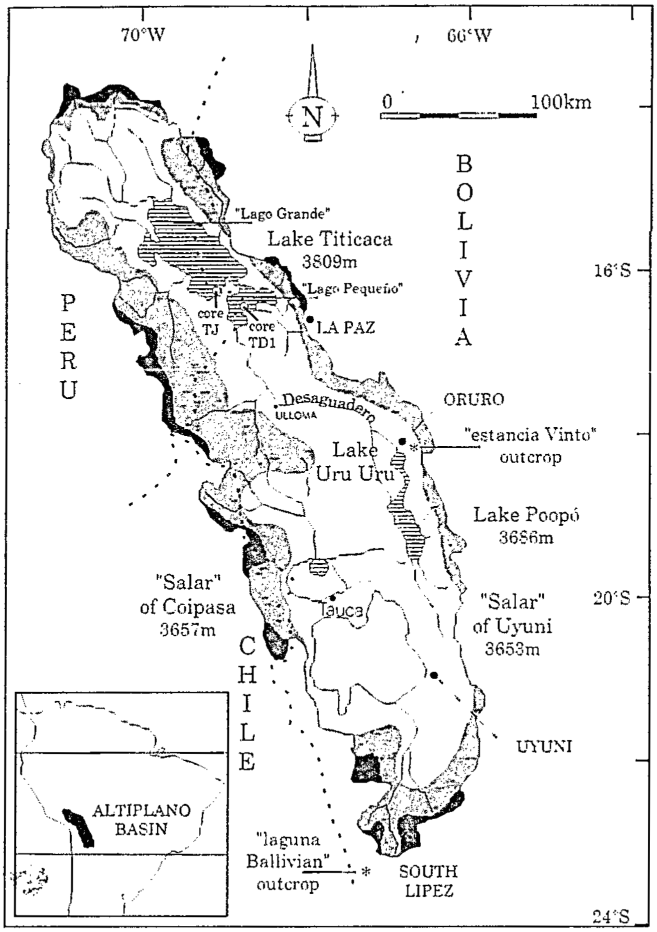

FIG. 1. Map of area showing sample location. (Dark gray) altitude > 5000 m; (gray) altitudes ranging between 4000 and 5000 m.

description of the statistical method is available in Servant-Vildary and Roux (1990). In the modern sedimentary surface samples, only 28 taxa from 9 genera were used for the statistical analysis, because the other living ostracods are poorly preserved (especially in the littoral area) or totally dissolved in the deep hypolimnetic sediment water interface (e.g., epiphytic species). The detailed listing of all the ostracod species used for building up the transfer function, their frequency of occurrence, and salinity indicator status is given in Mourguiart and Roux (1990) and in Mourguiart and Carbonel (1994). Water depth and salinity indicator values were assigned to each ostracod taxa of all the samples introduced in the FAC model (115 subsurface sedimentary samples). Different categories were determined according to the results of a first correspondence analysis by combining between five ranges of the water depth and five ranges for the TDS. A new FAC is thus collated: the data, including a species/classes matrix as active elements (28 rows or "species" and 11 columns or "modalities") and two matrices composed of the percentages of the 28 species distributed between the 115 modern samples and fossil samples as supplementary or passive elements (*sensu* Benzecri, 1973), are obtained as follows:

28 species	11 Classes	115 modern samples	X fossils

The union of these three tables is submitted to reciprocal averaging, but only the first table is considered active. The application of the FAC to the fossil data generates five factors that account for 83% of the global information (Table 1). Each class is defined by its coordinates on the factors, which are now considered as independent variables (Servant-Vildary and Roux, 1990). A regression analysis applied to these results allows establishment of a transfer function; its accuracy depends on the coefficient of multiple correlation (R). For the water depth, R is 0.98 (standard error of 0.81 m) and 0.86 for the TDS (standard error of 6.83 g $\cdot$ liter^{-1}). Considering the TDS, it seems that ostracods may be particularly responsive to the Mg/Ca ratio (Mourguiart and Carbonel, 1994).

STUDY AREA

Today a north–south meteorological gradient (Roche and Rocha, 1985; Sheriff, 1979) and a southward movement of water within the basin influence the water chemistry, biota, and sediment regime of the lakes. The hydrological balance depends on the rate of precipitation and evaporation, the latter being ca. 90% over the whole area (Carmouze and Aquize, 1981), whereas the average rainfall varies from 900 to $<$100 mm yr^{-1} from north to south. Lake Titicaca is oligohaline, while Lake Poopó is meso- to polyhaline, and the "salares" of Coipasa and Uyuni are dry and characterized by surficial salt crusts covering 1000 and 11,000 km^2 at altitudes of 3657 and 3653 m above sea level, respectively.

Lake Titicaca

Lake Titicaca, a high tropical Andean lake (3809 m altitude, 8562 km^2, 903 $\times$ 10^6 m^3; Wirrmann, 1992a) consists of two subbasins connected by the Tiquina strait (850 m wide and at least 21 m deep): (1) in the north, Lago Grande or Lake Chucuito, with a mean depth of 135 m (maximum 284 m) and (2) in the south, Lago Pequeño or Lake Huiñaimarca, with a mean depth of 9 m (maximum 41 m in the Chua trough).

The lake receives an average rainfall of 880 mm yr^{-1} (Roche *et al.*, 1992). The total dissolved salt concentration varies from 0.9 g $\cdot$ liter^{-1} in Lago Grande to 1.2 g $\cdot$ liter^{-1} in Lago Pequeño. The waters are dominated by chloride, sulfate, and sodium ions, with pH mean values ranging from 8.2 to 8.7. The annual turnover of the stocks of dissolved salts is very low in Lago Grande

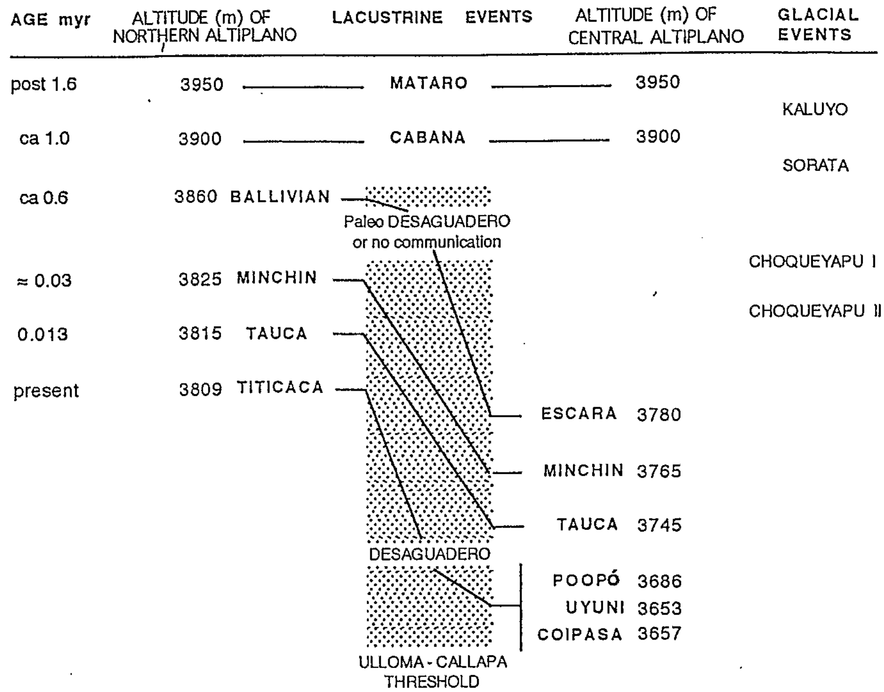

FIG. 2. Stratigraphy and spatial relationships between the northern and central Altiplano lacustrine episodes (modified after Lavenu *et al.*, 1984).

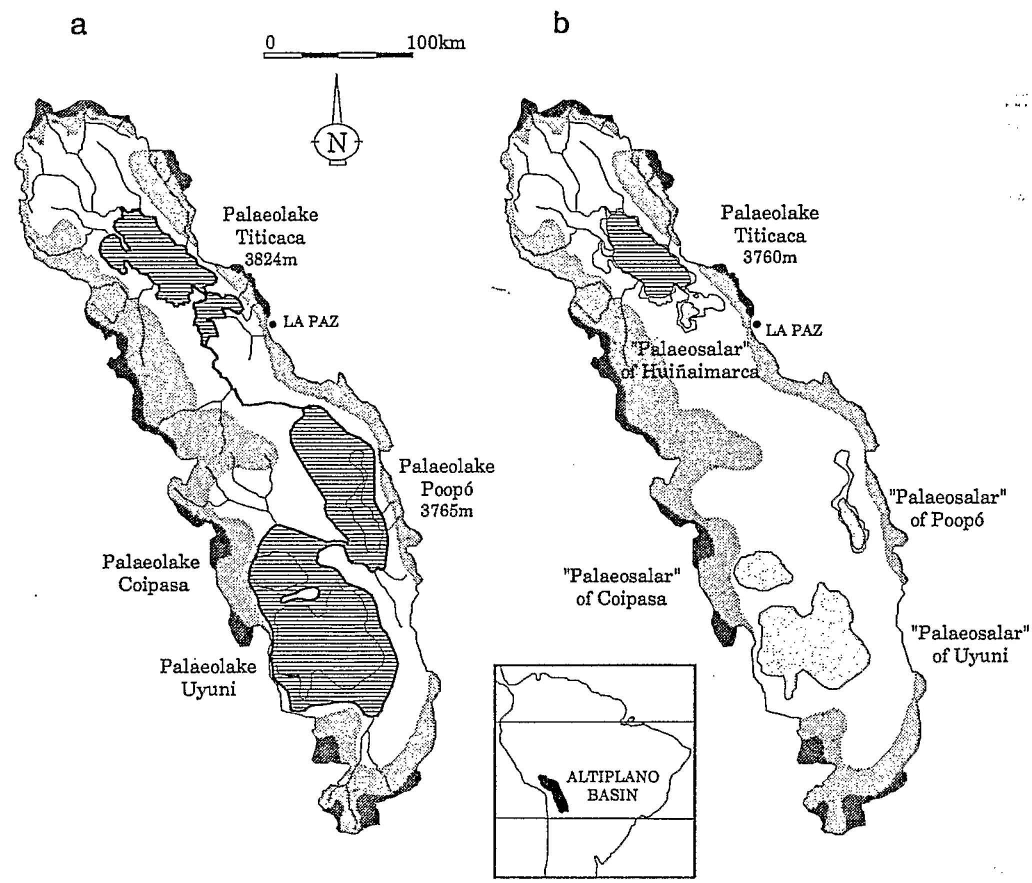

FIG. 3. Altiplanean palaeolakes extension (a) at 35,000 yr B.P. and (b) at 8000 yr B.P.

TABLE 1
Factor Analysis of Correspondence

Axis	Eigenvalues	Inertia %	Cumulative inertia
F1	0.97	22.15	22.15
F2	0.96	21.91	44.06
F3	0.65	14.86	58.92
F4	0.54	12.29	71.21
F5	0.52	11.84	83.05

(0.2% for Na, Mg, and Cl to 0.5% for Ca and HCO_3) but higher in Lago Pequeño (1.6% for Na and Cl, 2.6% for Mg, and to 7% for Ca and HCO_3; Carmouze *et al.*, 1978, 1981). Notable local influences (such as inflowing rivers and human disturbances) are limited to a few shallow areas relatively isolated from the main central water body of the lake (Northcote, 1992). Water clarities are greater in Lago Grande (Secchi disc mean values between 11.3 and 14.6 m) than in Lago Menor (mean values from 3.2 to 5.6 m), but great spatial and temporal variability is observed in both basins (Iltis *et al.*, 1992).

Based on an 80-y daily record, the lake level varies about 0.75 m annually, but interannual fluctuations are larger and lake-level variations occur with amplitudes of about 3.2 m around the reference level of 3809.9 m at Puno (Kunzel and Kessler, 1986; Lazzaro, 1981; Roche *et al.*, 1992). Within the period of record, lake oscillations are correlated with ENSO phenomena (Francou and Pizarro, 1985).

Bathymetry and local bottom relief control the distribution of the lacustrine macrophytes (Collot *et al.*, 1983; Iltis and Mourguiart, 1992). The sediments are mainly autochthonous and biogenic (organic matter derived from plankton decomposition, carbonated grains, shells, remains of macrophytes) in the shallower areas (to ca. 20 m depth); they are represented by fine detrital deposits in the central depression of Lago Grande and by coarser detrital facies along shores. Their distribution is also controlled by bathymetry (Boulangé *et al.*, 1981 and Fig. 4).

The ostracod distribution in Lago Pequeño is strongly correlated with sediment composition and macrophyte distribution (the euphotic zone reaching to the bottom over most of its extension except in Chua trough) and, therefore, with water depth (Mourguiart, 1992). Six major ecozones are found (Fig. 5). Near the shoreline (<2m), assemblage A1 is dominated by two benthic species (*Ilyocypris gibba* Ramdohr and *Cyprinotus* sp.) and two epiphytic species (*Chlamydotheca incisa* Claus and *Herpetocypris reptans* Baird). The latter two species are very common in the belt known as "totora fringe," composed of *Schoenoplectus tatora*, in association with some benthic species such as *Candonopsis* sp., *Darwinula* aff. *incae* Delachaux 1928, and *Limnocythere titicaca* Lerner-Seggev 1973 (assemblage A2). Between 3.5 and 7.5 m, ostracod association A3 is characterized by *Cypridopsis vidua* Müller percentages exceeding 90%. The two combinations, A4 and A5, between 7.5 and 10 m and between 10 and 14 m, respectively, contain numerous species of the genus *Limnocythere*, associated with an increasing percentage of *Candonopsis* sp. in relation to increasing water depth. *Amphicypris nobilis* Sars 1902 and *D.* aff. *incae* are also present. The only species living in the deepest part of the lake is *Candonopsis* sp. (A6).

In Lago Grande, the ostracod communities are the same but the depth distributions are expanded: from 3.5 to 15 m for assemblage A3, 15 to 25 m for A4, 25 to 40 m for A5, and >40 m for assemblage A6.

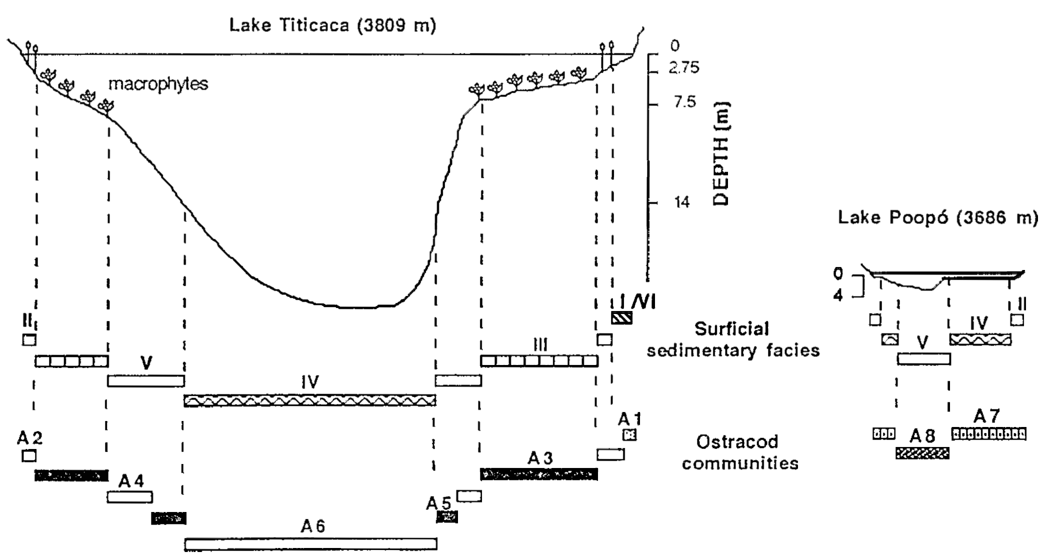

FIG. 4. Modern schematic distribution of sedimentary facies and ostracod assemblages in cases of high water levels for lakes Titicaca and Poopó. Surficial sedimentary facies (after Boulangé *et al.*, 1978, 1981) (I) detrital; (II) organic; (III) carbonate detrital; (IV) carbonate; (V) carbonate organic-detrital; (VI) organic-detrital.

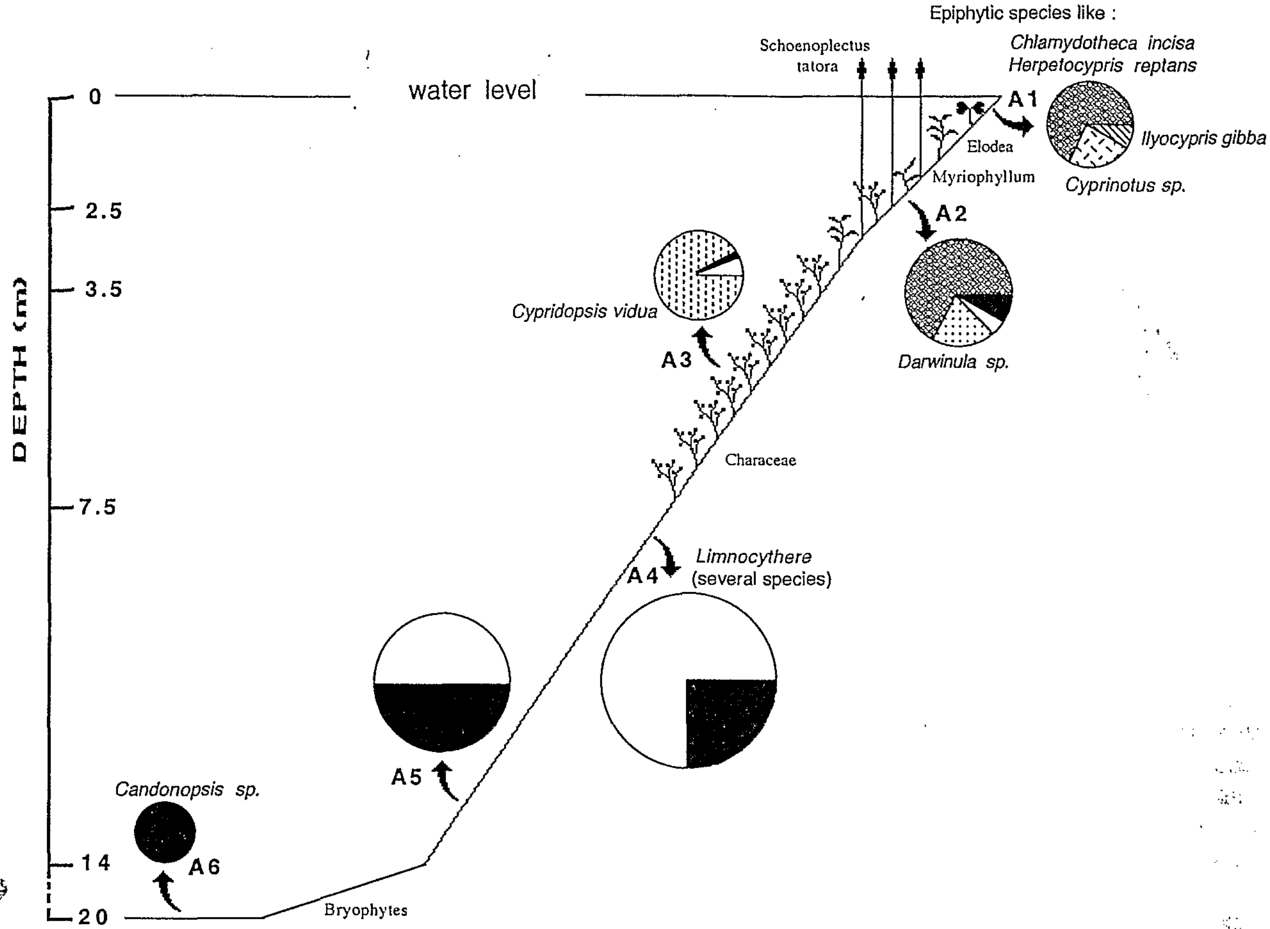

FIG. 5. Ostracod assemblages versus macrophyte distribution in the Lago Pequeño. The size of the circles is proportional to the density of the valves.

The typical assemblages of Lake Titicaca include the species: *Limnocythere* sp. A1, *L.* sp. S1, *L. titicaca* Lemer-Seggev, *Candonopsis* sp. C1, *Darwinula* aff. *incae* Delachaux, *Amphicypris* aff. *nobilis* Sars, and *Cyprinotus* sp. CN1.

Lake Poopó

About 350 km farther south, and receiving water from Lake Titicaca via the Desaguadero River, Lake Poopó (3686 m, 2530 km^2, 2569 $\times$ 10^6 m^3 at high water) experiences drier climatic conditions, with the mean annual rainfall being 390 mm (Mariaca, 1985).

Depending on the season and the year, the lake depth varies from a few centimeters (as in 1982–1983, a 2-yr drought period) to 9 m in high runoff periods: therefore, this basin is subject to severe interannual variations in water chemistry and lake level. During periods of high water level, the mean concentration of total dissolved salts dominated by NaCl (Carmouze *et al.*, 1978), varies between 10 and 40 g $\cdot$ liter^{-1}. A north-south gradient in concentration has sometimes been observed. The lake does not stratify, and during drought it can turn into a "salar."

Figure 4 summarizes the present-day conditions: the ostracod distribution depends on the lake's status. When Lake Poopó is high and mesohaline, two species are found and can be considered typical of this lake: *Cypridopsis* sp. (abundant on plant stems) and *Limnocythere* sp. aff. *L. bradburyi* Forester (assemblages A7 and A8). When the lake is low, the water is polyhaline and only the second species is encountered.

RESULTS

The Late Pleistocene

During the Minchin lacustrine event (Late Pleistocene, prior to 21,000 yr B.P.; Ahlfeld, 1972; Servant and Fontes, 1978, 1984), all present lakes were larger and connected to each other by straits. The resulting paleolake was formed by two water bodies separated by the Ulloma threshold (Figs. 2 and 3). The enlarged water surfaces were unequal; the northern one, developed over Lake

Titicaca, being much smaller than the southern one, covering the Poopó and Coipasa-Uyuni basins.

No sediments have been recovered from Lake Titicaca for this epoch. The oldest age estimated is 24,000 yr B.P. for the base of core TD1 (Wirrman *et al.*, 1992; see also Fig. 9). Nevertheless, according to geomorphic evidence, such as the occurrence of a lacustrine terrace 15 m above the present shoreline, Lake Titicaca was characterized by a higher water level. This episode is attributed to paleolake Minchin based on the analogy of the spatial relations of ablation surfaces and terraces in the central Altiplano.

In the central Altiplano, stromatolitic deposits delimit lacustrine shorelines and beach deposits which indicate enlarged lake surfaces. The highest water level was established over 3765 m (the higher altitude of the stromatolites from the islands in Uyuni Salar) and makes a mega-lake, known as Minchin, with a maximum depth in its center of at least 105 m. Its maximum area is estimated to be at least 60,000 km^2. A lacustrine sedimentological record, obtained in an excavation at the foot of stromatolites in the shape of 3-m-high conical columns, was obtained on the shoreline of this paleolake at "Estancia Vinto," 8 km southeast of Oruro (Figs. 1 and 6).

The 320-cm-long lithologic column is characterized by alternation of coarse lacustrine sediments and sands, including gastropod and/or ostracod and/or diatoms, with a gypsum layer (level 190–218 cm) in the middle of the profile (Figs. 6 and 8). The base of the section has a mean age of 37,000 yr B.P. [37,060 ± 1120 for *L. titicaca* in level 225–229 cm (Beta Analytic 38780/ETH 6905) and 36,820 ± 1200 for *Littoridina andecola* d'Orbigny in level 314–316 cm (Beta Analytic 38781/ETH 6906)].

Based on our sedimentological and micropaleontological analysis, the deposits from the Estancia Vinto outcrop can be attributed to seven episodes (A, B, C, D, E, F, and G), each characterized by specific paleoenvironmental conditions (Figs. 7 and 8). There are no ostracods in parts A (corresponding probably to the littoral area), D (gypsum level), and F (brief emersion stage ?). The ostracod assemblage from segment B indicates that the paleosalinities varied from freshwater conditions (presence of *Limnocythere* sp. A1) to a mesohaline environment (presence of *L. bradburyi*). For segments C and E, *L. titicaca* and *L.* sp. A1 are dominant in association with *Candonopsis* sp. C1 and *Darwinula* aff. *incae* or *Amphicypris* aff. *nobilis*. Both ostracod assemblages characterize high lake level and freshwater conditions. This agrees with the fossil remains containing an abundant and diverse mollusc association, consisting of several species of *Littoridina*, *Taphius montanus* d'Orbigny 1835, *Anysancylus crequii* Bavay 1904, and *Ecpomastrum mirum* Haas 1957 — all species found in the modern oligohaline Lake Titicaca (Dejoux, 1992). According to the present-day occurrences of *L. bradburyi*, section G implies a low lake level and saline waters. The range of total dissolved salts has varied on a broad scale, from 2 to more than 30 g · liter^{-1}. The mollusc remains consist of *Littoridina poopoensis* Bavay 1904.

The water depth of paleolake Minchin at the Estancia Vinto location, evaluated by applying the transfer function, varied from a few cm to 12 m, i.e., the paleolake level fluctuated between 3700 and 3712 m. At the same time, the salinity was highly variable, with several oligohaline phases especially in the basal profile section. Then a marked drought period transformed this area into an evaporitic basin (gypsum deposits). At the top of the sequence, it became a saline and shallower lake. This lacustrine stage of paleolake Minchin, dated around 37,000 yr B.P., developed over the Coipasa-Uyuni and Poopó

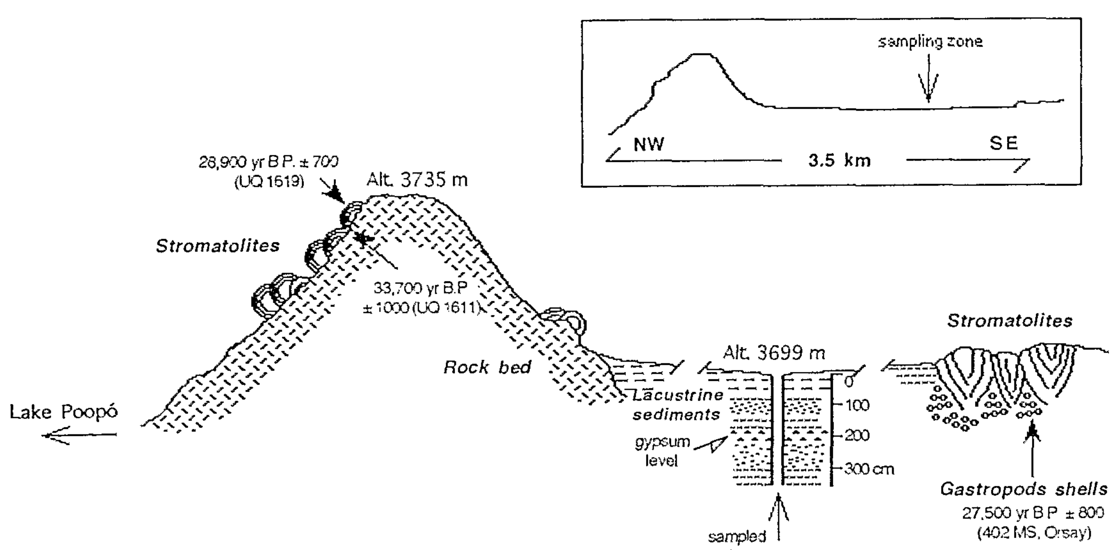

FIG. 6. Location and schematic environment of the record taken at "Estancia Vinto," stromatolites ages after Rondeau (1990).

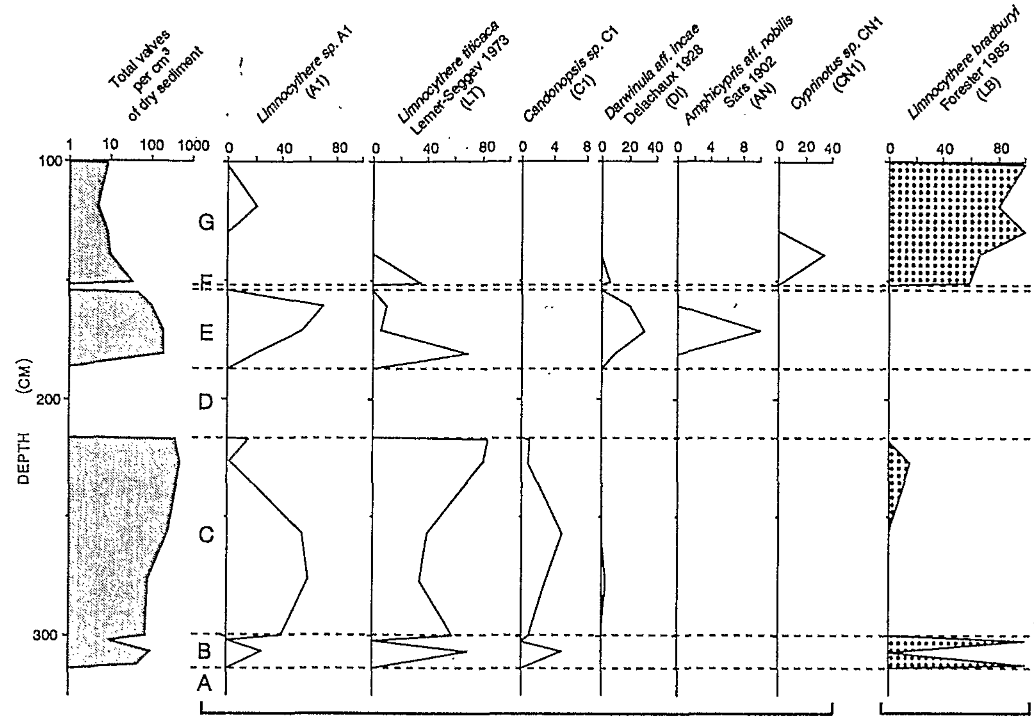

FIG. 7. Detailed ostracod stratigraphy for Estancia Vinto profile. The specific abundances are expressed in % of adult valves.

basins, and its level lay 60 m above the saline crust of the present-day salar (3653 m). During that time, the waters were mesohaline (Servant-Vildary, 1978), but our results indicate important oligohaline episodes.

Our radiocarbon ages of carbonates may be too old due to contamination by "old" carbon, but the ages we present agree with those of Servant and Fontes (1984) based on peat-bog analysis, which also indicates a wet phase before 35,000 yr B.P. in high-altitude Andean valleys. Moreover, the highly variable salinity and lake levels agree with the results of a previous study based on the analysis of fossil diatoms from lacustrine sediments sampled in "laguna Ballivian" (South Lipez, Fig. 1) and correlated with the Minchin lacustrine phase (22,000 yr B.P. at the top of the sequence (Servant-Vildary and Mello E Sousa, 1993). Nevertheless, the lack of a precise chronology hinders a finer correlation between our observations and those of others.

The Holocene

The general trend during the Holocene is a negative hydrological balance marked by a sharply decreasing lake level (Risacher and Fritz, 1992; Servant and Fontes, 1978; Wirrmann and De Oliveira Almeida, 1987) and by glacier retreat (Gouze *et al.*, 1986; Seltzer, 1991).

For Lake Titicaca, core TD1 taken in 19 m of water in Lago Pequeño (Fig. 1) provides the most complete record (Fig. 9). Ostracods are present only in the uppermost 152 cm of the core, and five assemblages (A, B, C, D, and E) are differentiated (Figs. 10 and 11).

Sections A and E do not contain ostracods. Part A, which represents a very low paleolake level with probable brief emersion events, marks the end of the Tauca lacustrine phase while section E marks a high paleowater level similar to the present one and unfavorable for the preservation of ostracod valves (dissolution in the sediment–water interface; Mourguiart *et al.*, 1992). The abundance of *L. bradburyi* associated with *Cypridopsis* sp. in level B indicates the presence of shallow polyhaline waters similar to the modern brines of Lake Poopó. In section C, the ostracod assemblage is dominated by *L. bradburyi,* but other species like *Limnocythere* sp. A1, *L.* sp. S1, *L. titicaca, Candonopsis* sp. C1, or *D.* aff. *incae* are also present. This mixing suggests brief but strong salinity variations, ranging from 1 to >30 g · liter^{-1}. In interval D, the Poopó species disappear and the ostracod assemblage corresponds to a deep lake with fresh to oligohaline waters. The presence of *Cyprideis* aff. *hartmanni* in a few levels denotes a slight enrichment in Na and Cl (Carbonel *et al.*, 1988).

These results and the sedimentological evidence (Figs. 9 and 11) when compared with data obtained in previous studies (Mourguiart *et al.*, 1992; Wirrmann *et al.*, 1992) allows us to synthesize the evolution of Lake Titicaca as follows:

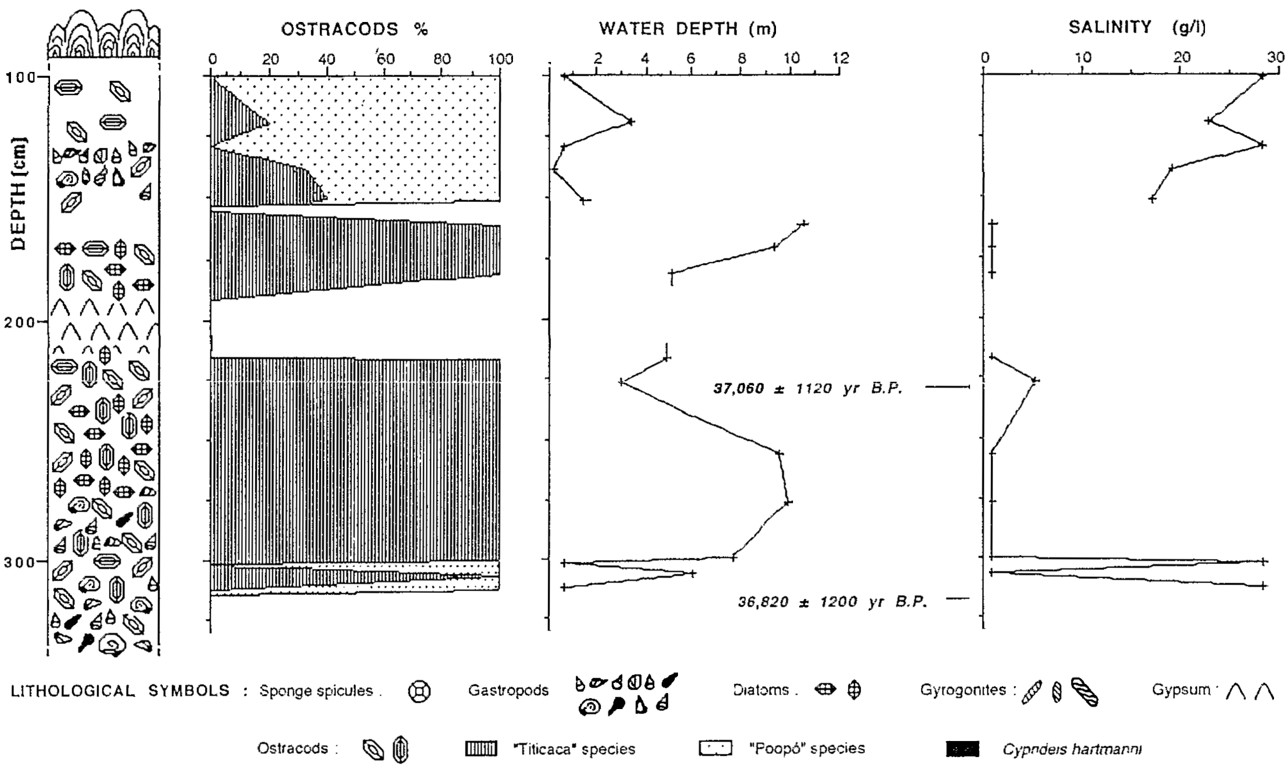

FIG. 8. Estancia Vinto: Lithology versus plots of water depth and total salinity inferred from the transfer function.

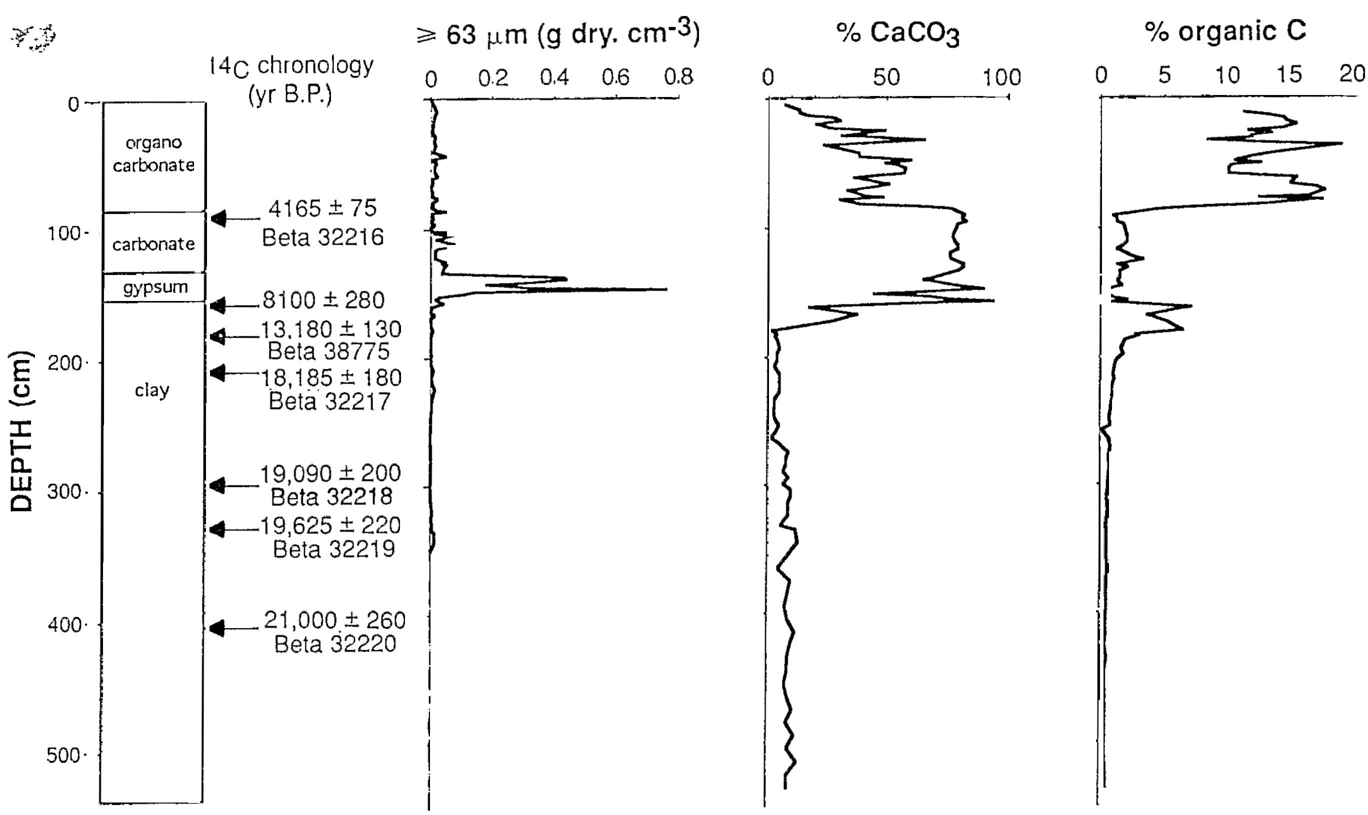

FIG. 9. Sedimentological stratigraphy and chronology of core TD1 (Lake Titicaca). Beta results are AMS datings made on disseminated organic carbon and the other age is a conventional date obtained on total $CaCO_3$ (completed after Wirrmann, 1992b).

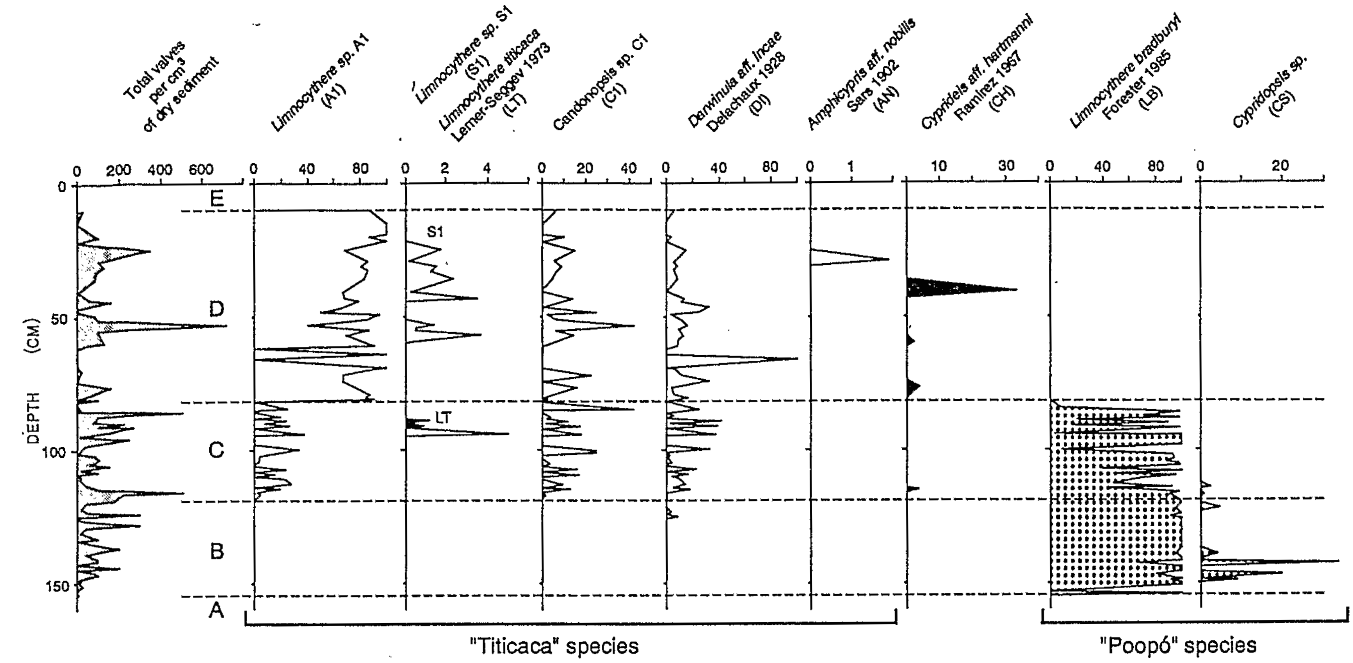

FIG. 10. Detailed ostracod stratigraphy for core TD1. The specific abundances are expressed in % of adult valves.

After 13,000 yr B.P., the sedimentological record is represented by a progressive evolution from deep, freshwater lacustrine sediments without ostracods (argillaceous facies) to shallower water (sponge spicules compose 99% of the ≥63-μm fraction of the sediment between 160 and 170 cm), and eventually turning into an evaporite deposit (lenticular gypsum, level 132–155 cm) dated between 8100 ± 280 yr B.P. (base of gypsum level

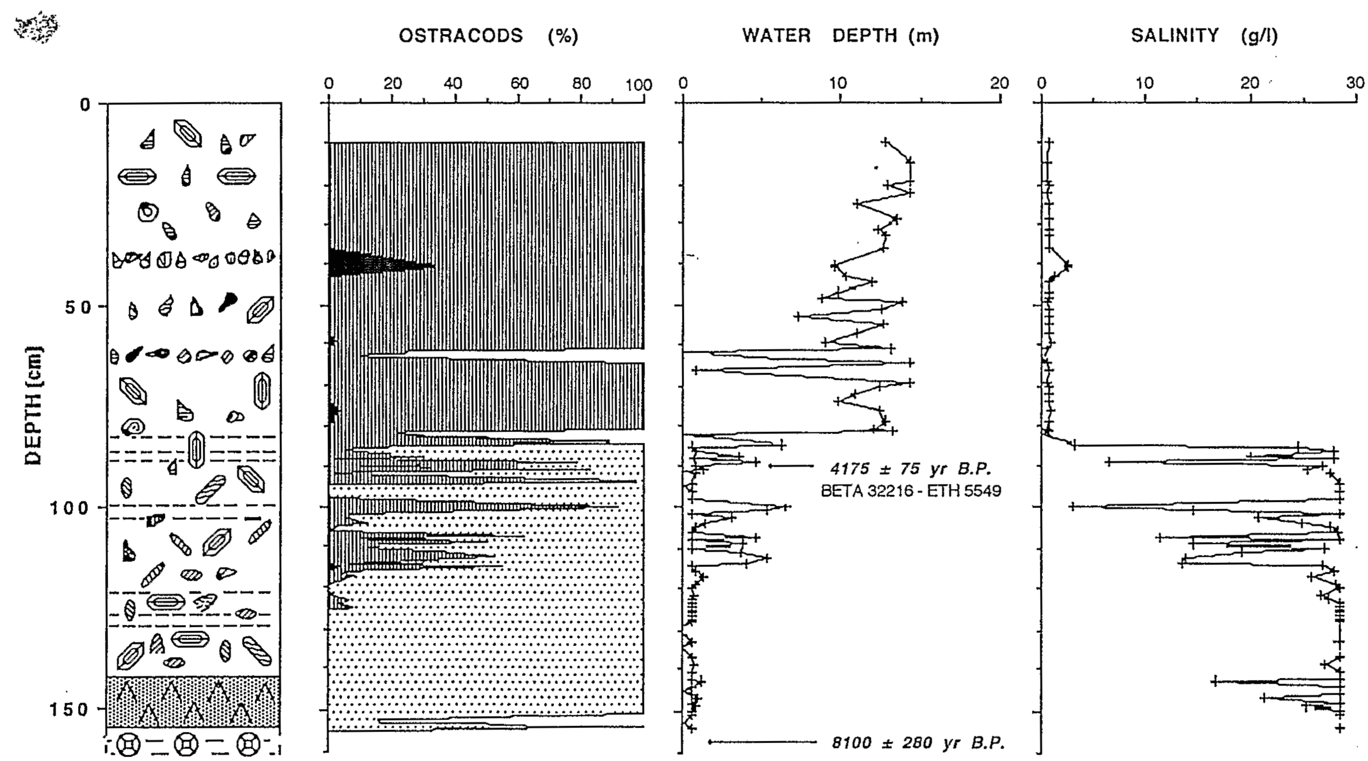

FIG. 11. Upper core section TD1: Lithology versus plots of water depth and total salinity inferred from the transfer function, with the same symbols as in Figure 8.

in core TD1, Orsay) and 7710 ± 180 yr B.P. (top of gypsum level in core TJ, taken 50 m below water in Lago Grande; Fig. 1, OBDY 104).

The lake level then rose slightly and *L.* sp. aff. *L. bradburyi*, associated in several levels with *Cypridopsis* sp., composed the ostracod fauna. The sediments of this period belong to the carbonate-detrital facies. Lake Huiñaimarca was similar to modern lake Poopó with brief salar episodes.

Between 5500–5000 and 4000 yr B.P., the ostracods characterize oligohaline to polyhaline environments and indicate strong water-level fluctuations with amplitudes of ca. 6 to 8 m. The sediments are comprised largely of biocarbonate remains.

Lake Titicaca then rose gradually in two major steps, reaching its present level ca. 1600 yr B.P. The lake level remained at ca. 3797 m from 3800 to 2200 yr B.P. and stabilized at 3800 m about 2000 yr B.P. (Mourguiart *et al.*, 1992; Wirrmann *et al.*, 1992). The sediments of this phase grade from a carbonate facies to a carbonate-organic-detrital facies. The strong water-level oscillations may correlate with strong El Niño-like conditions (Martin *et al.*, 1993).

In the central Altiplano, after 10,400 yr B.P. (Servant *et al.*, 1994), Lake Tauca fell abruptly and dried up. This water level drop was synchronous with Lake Titicaca's oscillations (Fig. 11). Our field observations agree with this general evolution and show that the water body was transformed into *salares* characterized by surficial evaporitic crusts. A 35-cm-thick gypsum bed formed of lenticular crystals and "*rose des sables*" observed at 1.6 m below the sediment–water interface in Lake Poopó is attributed to this lacustrine regression. The present surficial halite deposits on Coipasa and Uyuni also date to this event. The lower lacustrine terrace near Tauca village (Fig. 1, eastern shoreline of Coipasa at an altitude of 3658.5 m) yields a mean age of 10,100 yr B.P. [stromatolite samples TA(a): 10,310 + 400/−330 yr B.P. (OBDY 92) and Tauca 116 (a): 9900 + 480/−430 yr B.P. (OBDY 90)].

CONCLUSION

Sedimentary facies and ostracod environmental tolerances have been used to characterize recent lake status on the Bolivian Altiplano. The application of a transfer function (Mourguiart and Carbonel, 1994) based on ostracod data provides quantitative information on paleolake levels and paleosalinities for Lakes Titicaca and Poopó. This analysis suggests a moist Late Pleistocene and a dry Middle Holocene, denoting a change in the regional climate during the past 40,000 yr B.P. and an important fluctuation of the precipitation–evaporation ratio. This ratio was much greater than at present during the Late Pleistocene and much lower during the Middle Holocene. The changes in lake status were frequent and rapid, but a better chronology is needed for the interval 10,000–40,000 yr B.P. In addition, more data from other lacustrine deposits, including ostracod paleofaunas, should be gathered to permit a more precise limnological reconstruction, as well as regional and interregional correlations.

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