

Palaeohydrology of the Quaternary saline Lake Ballivian (southern Bolivian Altiplano) based on diatom studies

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Abstract

Diatoms are usually used for reconstructing variations in past lacustrine depth. In a small endorheic basin located in the southern Bolivian Altiplano, we used a comparative method based on basin morphology, stratigraphy, sediment samples, altitude and diatom ecology to infer depth variations more precisely in both marginal and central parts of the basin. Before ca. 22,000 yr BP, the general tendency was a progressive increase in water-level from 4,135 to 4,155 m altitude, but Lake Ballivian rose to 4,160 m twice, and dropped below 4,135 m twice. After ca. 22,000 yr BP, a long dry period occurred, as indicated by a sedimentation hiatus. At ca. 13,000 yr BP, the water-level slightly increased again but the lake stayed very shallow, at less than 4,125 m altitude.

Introduction

The Bolivian Altiplano of the central Andes (Fig. 1) contains three main basins. These are from north to south: (1) the freshwater Lake Titicaca, (2) the Poopo and the Coipasa-Uyuni basins presently occupied by shallow saline lakes and/or a salt crust, and (3) the Lipez area, a volcanic landscape where small closed basins are presently occupied by shallow lagoons.

Studies of lacustrine cores from Lake Titicaca (Ybert, 1992) and of lacustrine terraces on the margins of the large basins of the south (Servant and Fontes, 1978) show that two main lacustrine events occurred during the last glacial period. The detailed chronology of the first one, the so-called Minchin, is still poorly documented. In the Titicaca basin, the

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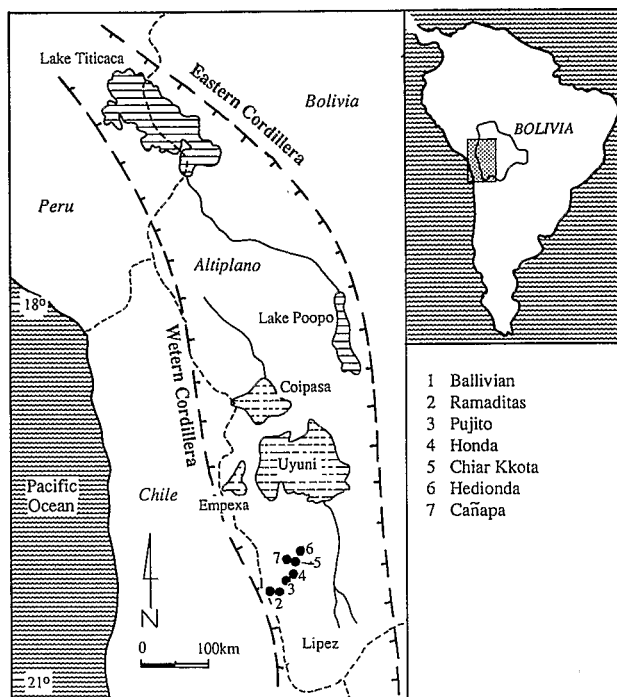


Fig. 1. Location of Lake Ballivian (areas with broken hatching, dry hypersaline lakes or salares located in the central Altiplano).

Minchin finished at *ca.* 20,000 yr BP. In the Poopo basin, littoral deposits (altitude 3,720 m) are dated *ca.* 27,000 yr BP. The second event, the so-called Tauca, is better documented. It occurred during the last glacial-interglacial transition, *ca.* 13,000–10,000 yr BP. Observations in the Coipasa-Uyuni basin suggest that at least two lacustrine phases occurred during the Tauca. One reached 3,720 m (Servant and Fontes, 1978); it has been explained by higher precipitations than at present (Hastenrath and Kutzbach, 1985). An older one reached 3,740 m (unpublished data). Diatom studies (Servant-Vildary, 1978) and geochemical models (Risacher and Fritz, 1991a) indicate that Minchin and Tauca palaeolakes were deep and saline. Palaeoclimatical interpretations are still contradictory because the water budget was related both to precipitation-evaporation on the lakes and the water input from a very large catchment area where melting of glaciers in the western and eastern cordilleras was in progress.

The hydrology of the closed basins of the Lipez, on the other hand, are more directly related to regional climatic conditions because they have a catchment area smaller than the Coipasa-Uyuni basin. Several shallow

lakes presently occur (Fig. 2). Their chemistry (Risacher and Fritz, 1991b) and diatom flora are well known (Servant-Vildary, 1983; Servant-Vildary and Roux, 1990). Geological studies show that both Minchin and Tauca events took place in this area (Fernandez, 1980).

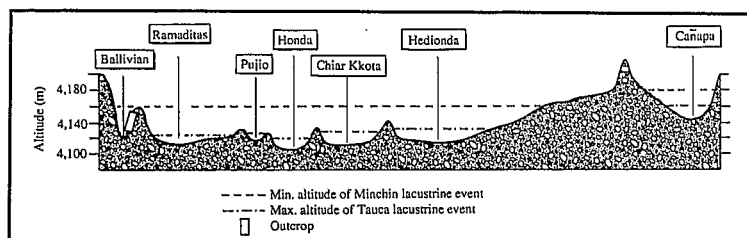


Fig. 2. Topographical cross-section of the Lipez area.

The purpose of the present paper is to reconstruct the palaeohydrological variations of the Ballivian lake. This lake is located in a small basin separated from a nearby larger basin, Ramaditas, by a threshold at 4,160 m altitude (Fig. 2). During the Upper Quaternary, the Ballivian basin remained isolated excepted during major rises in the water-level of the Minchin event. For both Minchin and Tauca events, palaeosalinities and ion concentrations were estimated from diatom studies (Roux *et al.*, 1991): during the Minchin, dominant ions were Na-Cl-CO₃, Na-Cl-SO₄ and Na-Cl, and during the Tauca, Na-Cl-SO₄.

Material and Methods

Fossil diatoms were studied in a 20 m column in an outcrop at the eastern margin of the Ballivian basin (Fig. 2). This outcrop comprises two lacustrine formations with sediments of the older one reaching 4,155 m altitude (Fig. 3(a)). A radiocarbon date from plant remains near the top of the section gave an age of 22,000 yr BP \pm 1,500, indicating that the underlying 17 m were deposited during the Minchin event. These deposits then underwent erosion during a dry climatic period. On the erosion surface, a terrace reaching 4,125 m altitude represents the second lacustrine formation. This formation is well developed throughout the area. Its base dates from 14,590 \pm 630 yr BP according to data from the Laguna Honda. In Chiar Kkota, radiocarbon dates on shorelines give ages of 1,2420 \pm 240 and 10,970 \pm 230 yr BP. These dates indicate that the last lacustrine formation can be correlated to the Tauca event of the Coipasa-Uyuni basin.

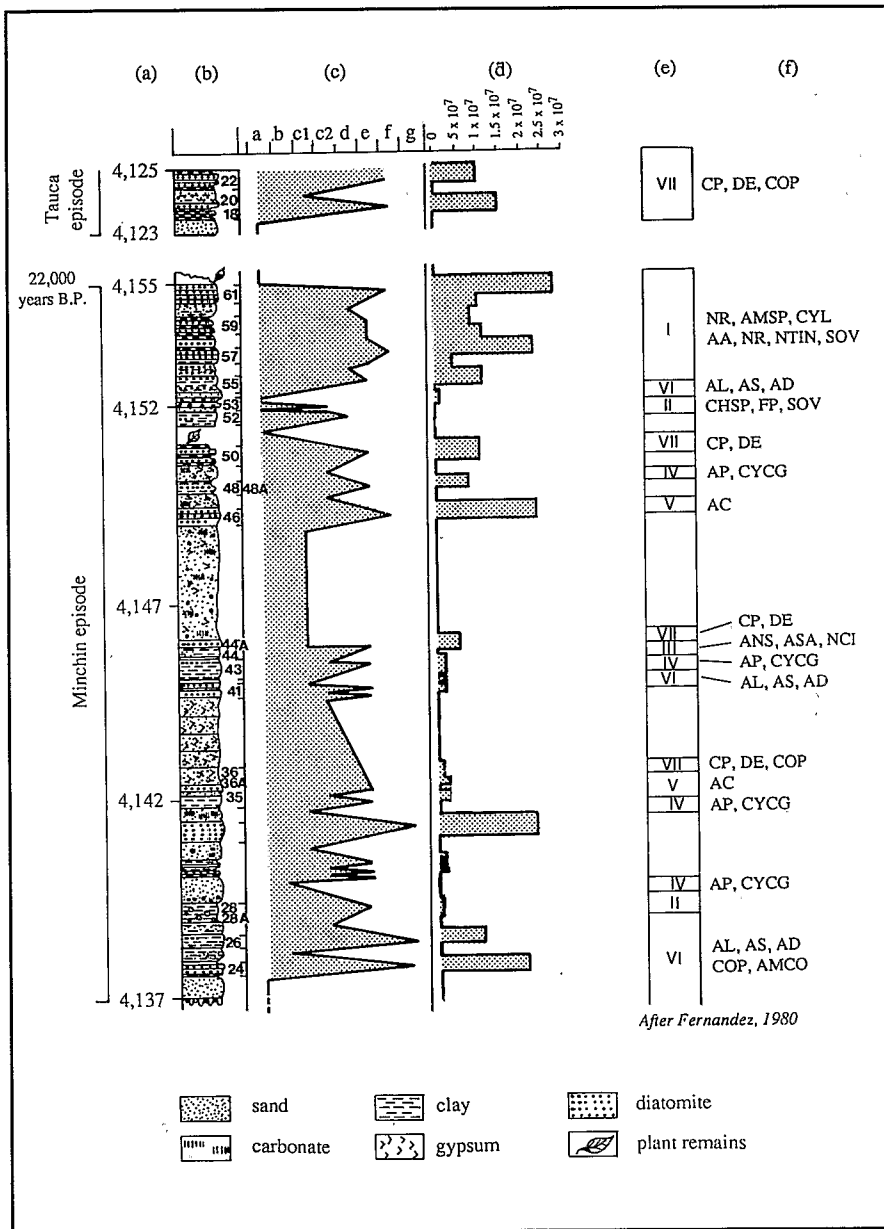


Fig. 3. Distribution of hierarchical classes in the columnar section of Lake Ballivian. (a), Minchin and Tauca events, age and altitudes; (b), lithology and numbers of the samples; (c), sedimentology (a, gravels; b, coarse sand; c1, medium sand; c2, small sand; d, silts; e, clays; f, bio-clastics; g, evaporites); (d), diatom contents (number of frustules in 1 g of sediment); (e), classes of samples; (f), main species (for index to codes see Tables 1, 2 and 3).

Twenty-eight samples were examined from the Lake Ballivian columnar section (Fig. 3(b)). In the lower third of the section, the sediments are mainly beds of sand intercalated with clays (Fig. 3(c)). In the middle, gypsum is intercalated with diatom-rich clays which, together with diatomite beds, increase in abundance upwards (Fig. 3(d)). The sediments deposited during the Tauca event are similar to those of the upper portion of the Minchin section (Fernandez, 1980).

A maximum of 2 g of sample was treated (when necessary) with 10 per cent HCl to eliminate carbonate, and then boiled in a solution of H₂O₂ to separate diatom frustules from sediments. After settlement, the supernatant liquid was siphoned off and the sample washed with distilled water. A homogenized drop of clean sediment on a glass slide was dried on a hot plate at <40°C. When dry, it was protected by a cover slip fixed with Naphrax. Samples were examined microscopically using a 100x immersion objective for species identification (Germain, 1981; Patrick, 1961). Two hundred specimens or more were counted in each sample.

Data on the frequency of the diatom species were treated statistically, first by factorial analysis, and then by hierarchical classification in accordance with the BIOMEKO program (Roux, 1985) and as used by Roux *et al.* (1987, 1991) and Servant-Vildary and Roux (1990). Using these methods, it was possible to delineate classes of samples, each characterized by a diatom assemblage. The palaeoecology of each class is determined using the ecological affinities of the 'characteristic' fossil species with extant species in lakes of the Lipez area.

Factorial correspondence analysis (Greenacre, 1984), or reciprocal averaging (Hill, 1973), is of great utility in dealing with either categorical variables or count variables. Its main feature is that it takes into account the margins of the data table, that is, the sum of the scores for species and for samples. Factorial analysis provides graphic representation both of samples as a function of their species, and of species as a function of distribution in different samples.

The final definition of the different groupings of samples, a hierarchical classification, was achieved using the so-called Ward's method of cluster analysis (Ward, 1963). Instead of directly processing the species percentage table, we computed the usual euclidean distances on samples from factor analysis coordinates. Taking into account the four most significant axes summarizing 41 per cent of the variance, we both eliminated the random fluctuations in abundances and obtained overall a more stable process. This kind of statistical analysis allowed us to regroup samples not well defined in the factorial analysis diagrams.

Having condensed samples into groups of homogeneous flora, it was possible to determine the most characteristic species of each sample class. The computations involved decomposing the generalized sum of squares interclasses deviations (CRTP-NUM program; Roux, 1985). We computed two types of ratios, providing two sorts of table. In the first (Table 1), we put the ratios for each particular class; these values allow determination of the most discriminant species. In the second (Table 2), the values indicate the most typical classes with regard to a particular variable; these also help define the ecology of accessory species and give the dispersion of each variable relative to the classes.

Table 1. Species/classes interactions. 'Characteristic' species, high positive values (bold); low positive values, 'accessory' species; negative values, species important by absence for each class of samples.

| Taxon | Classes of samples | | | | | | |
|---|--------------------|----------|-----------|-----------|-----------|-----------|-----------|
| | I | II | III | IV | V | VI | VII |
| AD <i>Achnanthes delicatula</i> | -1 | | | | 21 | -1 | |
| AL <i>Achnanthes arenaria</i> | -1 | -2 | | | | 26 | -1 |
| AS <i>Achnanthes speciosa</i> | -1 | -2 | | | | 24 | -1 |
| AA <i>Amphora atacamae</i> | 5 | | | | | | |
| AAM <i>Amphora atacamae minor</i> | 2 | | | | | | |
| AC <i>Amphora carvajaliana</i> | -8 | -14 | -3 | -5 | 93 | -76 | -8 |
| AMCO <i>Amphora coffaeiformis</i> | | -1 | | | | 1 | |
| AP <i>Amphora platensis</i> | -18 | -34 | -7 | 83 | -3 | -10 | -6 |
| AMSP <i>Amphora</i> spp. | 12 | -1 | | | | | |
| ASA <i>Anomoeoneis sphaerophora angusta</i> | | | | 22 | | | |
| ASP <i>Anomoeoneis sphaerophora platensis</i> | -1 | -2 | 55 | | | -1 | |
| CHSP <i>Chrysophyceae</i> | | 22 | | | | | |
| CP <i>Cocconeis placentula</i> | -15 | 1 | -6 | -5 | -2 | -2 | 65 |
| COP <i>Cocconeis placentula euglypta</i> | | | | | | 1 | 1 |
| CYCG <i>Cyclotella gamma</i> | -1 | -1 | | 3 | | -1 | |
| CYMC <i>Cymbella cistula</i> | | | | | | | 1 |
| CYL <i>Cymbella gracilis</i> | 11 | -1 | | | | | -1 |
| DE <i>Denticula elegans</i> | -1 | -2 | | | | -1 | 10 |
| FP <i>Fragilaria pinnata</i> | | 7 | | | | | |
| MELO <i>Melosira octogona</i> | | | | | | 1 | |
| NCI <i>Navicula cincta</i> | | | 3 | | | | |
| NHUN <i>Navicula hungarica</i> | | 1 | | | | | |
| NLA <i>Navicula pseudolanceolata</i> | 1 | | | | | | |
| NR <i>Navicula rhynchocephala</i> | 3 | -1 | | | | -1 | -1 |
| NTIN <i>Nitzschia ingens</i> | 3 | | | | | | |
| NPU <i>Nitzschia pusilla</i> | 1 | | | | | | |
| RHGI <i>Rhopalodia gibberula</i> | 1 | | | | | | |
| SOU <i>Surirella ovata utahensis</i> | 3 | | | | | | |

Table 2. Classes/species interactions. Bold font, ecology of the species very well explained by the class; standard font, ecology of the species quite well explained by the class.

| Taxon | I | II | III | IV | V | VI | VII |
|--|----|----|-----|----|----|----|-----|
| AMSP <i>Amphora</i> sp. | 86 | | | | | | |
| NTIN <i>Nitzschia ingens</i> | 86 | | | | | | |
| RW <i>Rhopalodia wetzeli</i> | 86 | | | | | | |
| CW <i>Caloneis westi</i> | 86 | | | | | | |
| AA <i>Amphora atacamae</i> | 85 | | | | | | |
| RHM <i>Rhopalodia musculus</i> | 85 | | | | | | |
| NTS <i>Nitzschia sigma</i> | 84 | | | | | | |
| CYL <i>Cymbella gracilis</i> | 82 | | | | | | |
| AAM <i>Amphora atacamae minor</i> | 81 | | | | | | |
| NPU <i>Nitzschia pusilla</i> | 80 | | | | | | |
| NR <i>Navicula rhynchocephala</i> | 80 | | | | | | |
| NAC <i>Navicula placentula</i> | 80 | | | | | | |
| NLI <i>Navicula pseudolittoricola</i> | 73 | | | | | | |
| NTVA <i>Nitzschia valdestrata</i> | 73 | | | | | | |
| NLA <i>Navicula pseudotanceolata</i> | 70 | | | | | | |
| NCC <i>Navicula cari</i> | 69 | | | | | | |
| RHGI <i>Rhopalodia gibberula</i> | 57 | | | | | | |
| CHSP Chrysophyceae | | 98 | | | | | |
| GOML <i>Gomphonema lanceolatum</i> | | 98 | | | | | |
| NC <i>Navicula cryptocephala</i> | | 89 | | | | | |
| FP <i>Fragilaria pinnata</i> | | 81 | | | | | |
| NHUN <i>Navicula hungarica</i> | | 74 | | | | | |
| OM <i>Opephora martyi</i> | | 73 | | | | | |
| ASA <i>Anomooneis sphaerophora angusta</i> | | 96 | | | | | |
| NR <i>Navicula rhynchocephala</i> | | | 96 | | | | |
| ASP <i>Anomooneis sphaerophora platensis</i> | | 89 | | | | | |
| NCI <i>Navicula cineta</i> | | | 80 | | | | |
| SUP <i>Surirella peisonis</i> | | | 59 | | | | |
| SYR <i>Synedra rumpens</i> | | | 40 | | | | |
| DIS <i>Diploneis smithii</i> | | | 23 | | | | |
| GP <i>Gomphonema parvulum</i> | | | 79 | | | | |
| AEX <i>Achnanthes exigua</i> | | | | 79 | | | |
| SUO <i>Surirella ovalis</i> | | | | 79 | | | |
| NTS <i>Nitzschia sigma</i> | | | | 79 | | | |
| SYNA <i>Synedra acus</i> | | | | 79 | | | |
| NTSI <i>Nitzschia sigmoidea</i> | | | | 79 | | | |
| SYNA <i>Synedra ulna</i> | | | | 79 | | | |
| CYCG <i>Cyclotella gamma</i> | | | | 78 | | | |
| NTGR <i>Nitzschia gracilis</i> | | | | 77 | | | |
| AP <i>Amphora platensis</i> | | | | 77 | | | |
| AC <i>Amphora carvajaliana</i> | | | | | 89 | | |
| NTCM <i>Nitzschia commutata</i> | | | | | 89 | | |
| SP <i>Scolioleura peisonis</i> | | | | | 88 | | |
| NTPT <i>Nitzschia palea tenuirostris</i> | | | | | 81 | | |
| CA <i>Ceratoneis arcus</i> | | | | | 66 | | |
| RG <i>Rhopalodia gibba</i> | | | | | | 82 | |
| AD <i>Achnanthes delicatula</i> | | | | | | 82 | |
| RHGV <i>Rhopalodia gibba ventricosa</i> | | | | | | 82 | |
| AL <i>Achnanthes arenaria</i> | | | | | | 82 | |
| AS <i>Achnanthes speciosa</i> | | | | | | 82 | |
| CYMI <i>Cymbella microcephala</i> | | | | | | 82 | |
| NQ <i>Nitzschia quadrangula</i> | | | | | | 82 | |
| CYMP <i>Cymbella pusilla</i> | | | | | | 82 | |
| MELO <i>Melostrva octogona</i> | | | | | | 81 | |
| SW <i>Surirella wetzeli</i> | | | | | | 81 | |
| NTHU <i>Nitzschia hungarica</i> | | | | | | 78 | |
| NI <i>Nitzschia inconspicua</i> | | | | | | 76 | |
| AML <i>Amphora lineolata</i> | | | | | | 69 | |
| NINS <i>Nitzschia nov. sp.</i> | | | | | | 53 | |
| AMCO <i>Amphora coffaeiformis</i> | | | | | | 45 | |
| COP <i>Cocconeis placentula euglypta</i> | | | | | | 19 | |
| MA <i>Mastoglia atacamae</i> | | | | | | | 75 |
| NPA <i>Nitzschia palea</i> | | | | | | | 75 |
| DE <i>Denticula elegans</i> | | | | | | | 75 |
| GOMA <i>Gomphonema angustatum</i> | | | | | | | 75 |
| CYMC <i>Cymbella cistula</i> | | | | | | | 74 |
| CP <i>Cocconeis placentula</i> | | | | | | | 70 |
| NAVH <i>Navicula halophila</i> | | | | | | | 69 |
| AMFR <i>Amphora frenguelli</i> | | | | | | | 61 |
| GOMI <i>Gomphonema intricatum</i> | | | | | | | 44 |
| COP <i>Cocconeis placentula euglypta</i> | | | | | | | 37 |
| CYCS <i>Cyclotella stelligera</i> | | | | | | | 32 |

Results

By factorial correspondence analysis, we obtained the distribution of groups of samples with respect to axes 1–2 and axes 3–4 (Figs 4 and 5). In Fig. 4, two groups of samples are clearly differentiated along axis 1 with respect to the others. Indistinctly defined groups are situated in the positive portion of this axis; they are better differentiated in Fig. 5.

Hierarchical classification (Fig. 6) shows class I clearly isolated, with class V more closely related by this treatment to other classes (II, III, IV, VI, VII). In spite of their close interrelationship, it is possible to differentiate between classes II, III, IV, V, VI and VII. Classes VI and VII are more closely associated with class V than with classes II and III.

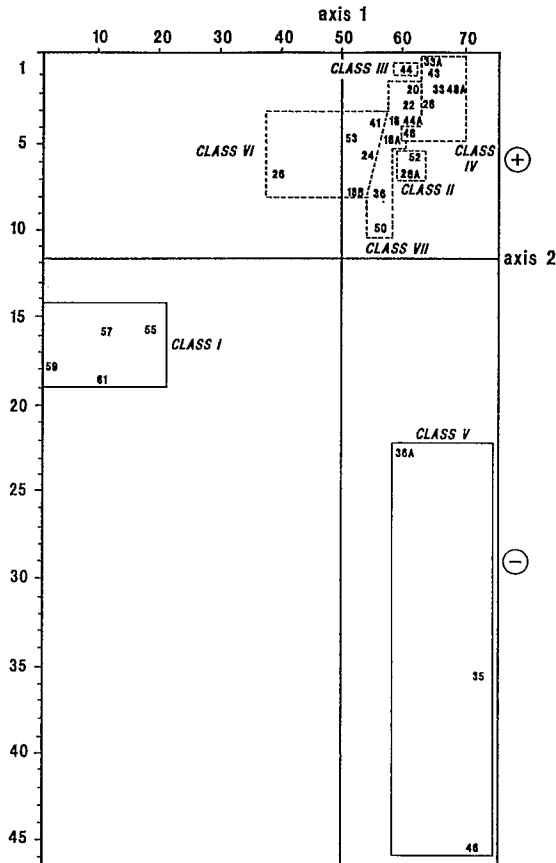


Fig. 4. Plot of sediment samples on axes 1 and 2.

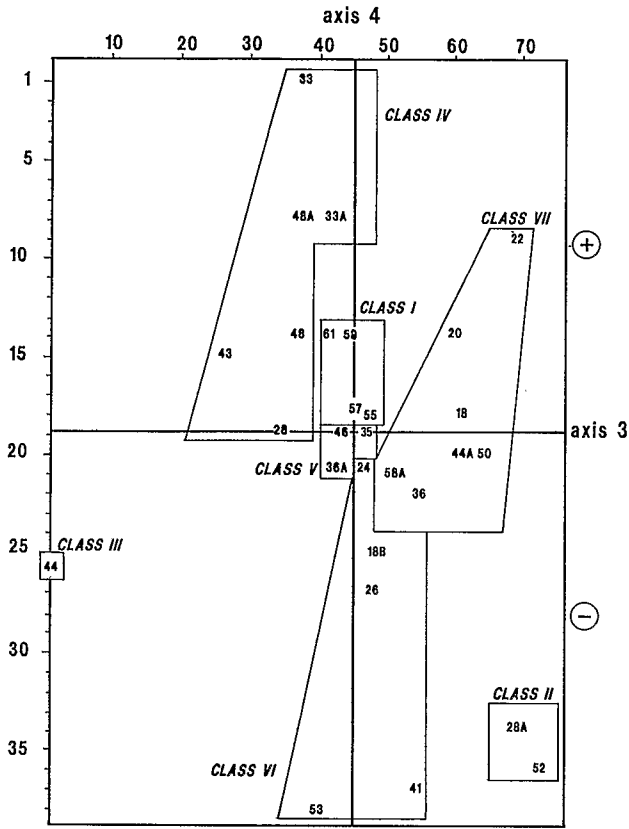


Fig. 5. Plot of sediment samples on axes 3 and 4.

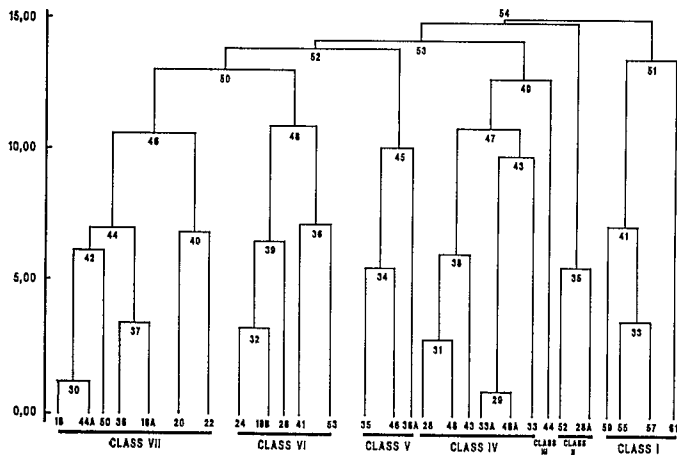


Fig. 6. Hierarchical classification of sediment samples. Dendrogram expresses sample similarity based upon diatom species composition.

In quantifying the rôle of floristic variables, the highest positive value identifies the 'characteristic' species of that class, e.g. *Cymbella gracilis* and *Amphora* spp. in class I (Table 1, bold characters), while lower positive values determine the 'accessory' species, e.g. *Amphora atacamae*. Negative values in this table identify species which influence the class by absence, e.g. *Cocconeis placentula* or *Amphora carvajaliana* in class VI and *Amphora platensis* in class II. In Table 2, values indicate the most typical classes with regard to a particular species; these also help to define the ecology of the accessory species, e.g. *Gomphonema lanceolatum* is well related to the ecological conditions of class II, *Amphora carvajaliana* with the ecological conditions of class V, and *Amphora platensis* to those of class IV.

For each fossil class (Table 3, A), and according to the ecology of 'characteristic species' (B) presently found in lakes of the Lipez area (C), we reconstruct the ecological significance of each class of diatom samples and infer important chemical features, mainly salinity (D) and major ions (E).

Palaeolimnological variations were identified according to the ecology (Fig. 3(f)) of the classes and their distribution (e) through the columnar section representative of the Minchin (M1 to M5) and Tauca (T) lacustrine events (see Fig. 7(g)). The interlacustrine phases are represented by sandy layers (Fig. 3(c)) without diatoms (d) or by depositional hiatuses. Some classes (class II, IV, V, VI) appear several times through the section, a pattern suggesting that the same hydrochemical conditions may have occurred several times during the Minchin and Tauca events (e). Two classes are more restricted through time; class I is only present at the top of the section, and class III in the middle portion of the section of the Minchin event.

Hydrochemical variations through time

The various lacustrine phases identified (Fig. 7(g)) enables determination of the main hydrological and climatological sequences of the Minchin and Tauca events (phases M1 to M5, and phase T). The main features of these phases are as follows.

Phase M1 (samples 24 to 28). The Minchin event begins with phase M1, characterized by the presence of class VI (samples 24 and 26). The characteristic species are three species of *Achnanthes* (AL, AS, AD) all of which presently live in Ballivian (BA67) and Pujio lakes (PJ30) where salinities are 36 and 45 g L⁻¹. They indicate low water levels. Class VI is superposed by class II (sample 28A), characterized by a mix of planktonic Chrysophyceae cysts and a euryhaline tycho planktonic species, *Fragilaria*

pinnata, presently abundant in the oligohaline station at Pastos Grandes Lake (PG82). This suggests a rise in the water-level and a decrease of salinity. M1 finishes with class IV (sample 28) where *Amphora platensis*, presently living in Ballivian Lake, indicates a decrease in depth and an increase in salinity (Fig. 7(h)).

Table 3. Ecological significance of sample classes. A, fossil classes of samples (I to VII). B, characteristic species of fossil classes. Class I: NR *Navicula rhynchocephala*, AMSP *Amphora* sp., CYL *Cymbella gracilis*, AA *Amphora atacamae*, AAM *Amphora atacamae* minor. Class II: CHSP *Chrysophyceae*, SOU *Surirella ovata utahensis*, FP *Fragilaria pinnata*. Class III: ANS *Anomoeoneis sphaerophora platensis*, ASA *Anomoeoneis sphaerophora angusta*, NCI *Navicula cincta*. Class IV: AP *Amphora platensis*, CYCG *Cyclotella gamma*. Class V: AC *Amphora carvajaliana*. Class VI: AL, *Achnanthes arenaria*, AS, *Achnanthes speciosa*, AD, *Achnanthes delicatula*. Class VII: CP, *Cocconeis placentula*, DE, *Denticula elegans*. C, lakes where characteristic fossil species are presently most abundant: BA67 Ballivian, PJ30 Pujio, VER5 Laguna Verde, CHI5 Chiar Kkota, CHU4 Chulluncani, PG Pastos Grandes. D, measured salinity of these lakes in g L⁻¹. E, chemical ions highly related to fossil dominant species. F, fossil samples.

| A | B | C | D | E | F |
|-----|------|--------------------|------|---------------------------------------|-----------------|
| I | NR | PG78 | 144 | Cl, Na, Li | 55,57 |
| | CYL | PJ30 | 36 | Cl, Na, SO ₄ | 59,61 |
| | AA | PG78 | 144 | Cl, Na, Li | |
| | AAM | PG78 | 144 | Cl, Na, Li | |
| | AMSP | no modern analogue | | | |
| II | CHSP | no modern analogue | | | |
| | SOU | CHU4 | 144 | Cl, Na, SO ₄ , K | 28A,52 |
| | FP | PG82 | 0.19 | Na, Cl | |
| III | ANS | CHU4 | 144 | Cl, Na, SO ₄ , K | 44 |
| | | PG70 | 13.1 | Cl, Na, K, Li | |
| | ASA | PG74 | 12.1 | Cl, Na, K | |
| | NCI | PG72 | 0.6 | Na, Cl | |
| IV | AP | BA67 | 47 | Cl, Na, SO ₄ , K, Ca | 28,33,33A |
| | | CHU4 | 11.2 | Cl, Na, SO ₄ , K | 43,48,48A |
| | CYCG | no modern analogue | | | |
| V | AC | CHI5 | 69 | Cl, Na ₄ , SO ₄ | 35,36A,46 |
| VI | AL | PJ30 | 36 | Cl, Na, SO ₄ | 18B,24,26,41,53 |
| | AS | BA67 | 45 | Cl, Na, SO ₄ , K, Ca | |
| | AD | PJ30 | 36 | Cl, Na, SO ₄ | |
| VII | CP | VER5 | 13 | Na, Cl, SO ₄ | 18,18A,20,22,36 |
| | DE | BA67 | 45 | Cl, Na, SO ₄ , K, Ca | 44A,50 |

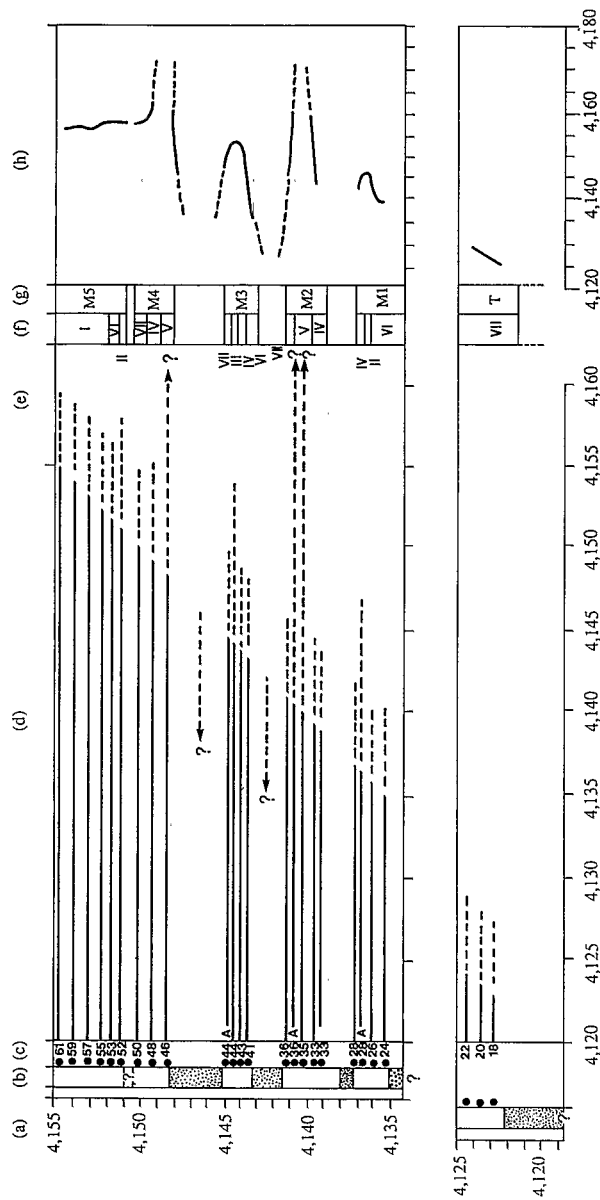


Fig. 7. Reconstructed palaeolevels of water in Lake Ballivian during Minchin event (upper part) and Tauca event (lower part). (a), altitudes (m) of the sediments; (b), simplified lithology; (c), sample numbers; (d) horizontal solid line = measured water depth under sediment samples (m); (e), horizontal dashed line = presumed water depth above sediment samples or under sediment samples during dry phases; (f), classes of samples; (g), lacustrine phases; (h), variations of depth (horizontal scale indicates depth in m above the bottom of the basin).

Phase M2 (samples 33A to 36). The thin sand layer between samples 28 and 33A does not modify the diatom flora; class IV of phase M1 continues (samples 33A and 33) and reveals that the chemical composition of the water has not changed. Class V (sample 35, 36A) superposes class IV and it is mainly characterized by *Amphora carvajaliana*. This species represents a strong modification in the environment. *Amphora carvajaliana* is presently absent from Lake Ballivian but is the most abundant species in the shallow meso-polyhaline sodium-sulphate lakes (Chiar Kkota, Pujio, Honda and Hedionda; Fig. 2). This species of *Amphora* was transported to Ramaditas by an initial rise in water-level above 4,130 m altitude (the threshold altitude that separates Lake Ramaditas and the 'Amphora' lakes); a subsequent rise in water-level joined Ballivian and Ramaditas through the threshold at 4,160 m altitude. This threshold is clearly conserved in the landscape (Fig. 2) and is confirmed by a high lacustrine level that has also been identified on the margin of Ramaditas (Fernandez, 1980). The altitude of the uppermost lacustrine layer (4,140 m) implies the occurrence of water to a depth of 20 m water in Ramaditas (i.e. that depth needed to overflow the threshold). A planktonic species, *Cyclotella stelligera*, confirms the presence of a large, deep lake at the site of Ramaditas at that time. At the end of phase M2 (sample 36), *Denticula elegans* and *Cocconeis placentula* occur, presently the most characteristic species of Ballivian (BA67) and Laguna Verde lakes (VER5), both classified as calcium-sulphate lakes. *Cocconeis placentula* indicates a maximum depth of 10 m and *Denticula elegans*, a salinity very close to that of the modern Lake Ballivian. Phase M2 finishes with a sand layer with gypsum, indicating a drop of level under dry and evaporative conditions favorable to gypsum deposition.

Phase M3 (samples 41, 43, 44 and 44A). Classes VI (sample 41) and IV (sample 43) indicate a slight rise, as at the beginning of M1 and M2. The superposed class III (sample 44) suggests a change in environmental conditions from mesohaline to oligo-mesohaline. The slight dilution of the water can be explained by a rise in the water-level, similar to M1 and probably due to an increase in precipitation. M3 finishes with class VII as in M2. Sand and gypsum deposits suggest a second drying of the lake, for the depth was very shallow with a water-level below 4,146 m altitude.

Phase M4 (samples 46, 48, 50). An abrupt change in depth is represented by class V (sample 46). As in phase M2, an increase is suggested by the presence of class V, characterized by *Amphora carvajaliana*. This indicates that a link between Ballivian and Ramaditas occurred for a second time during the Minchin event. At that time, the lacustrine sediments of Ramaditas contained a rich diatom flora of mainly planktonic species. These deposits are situated at 4,145 m altitude, thus, an increase in water depth of 15 m would be needed to join together Ballivian and Ramaditas lakes. Class V is succeeded by classes IV (sample

48, 48A) and VII (sample 50). In the same way as in phases M2 and M3, class VII characterizes the end of lacustrine phase M4, indicating a decrease in water-level and an increase in salinity.

Phase M5 (samples 52, 53, 55, 57, 59 and 61). This phase contains classes II (sample 52), VI (sample 53) and I (samples 55, 57, 59 and 61). Class I is mainly represented by *Amphora* species, *Amphora atacamae*, *A. atacamae* variety *minor*, and *Navicula rhynchocephala*, all presently found in Lake Pastos Grandes (Station PG78) where salinity reaches 144 g L⁻¹. The main ions are Na⁺ and Cl⁻. After the last major rise in water-level during phase M4, the separation of lakes Ballivian and Ramaditas would have begun after deposition of the layer containing sample 48. From then on, Lake Ballivian has progressively developed its own flora, as shown by the presence of class I. This class is restricted to the upper portion of the Minchin event and shows no relationship with other classes, indicating the occurrence of hydrochemical differentiation in Lake Ballivian where evolution was probably from mainly sodium sulphate (Phases M1, M2, M3, M4) to sodium chloride-sulphate conditions (Phase M5). This hydrochemical differentiation is clearly indicated by diatoms on the margin of the basin, which can only relate to evaporative conditions, even if the altitude of the sediments (4,155 m) suggests the occurrence of a water depth of 35 m in the centre of the basin (Fig. 7(h)).

After ca. 22,000 yr BP, the section presents a sedimentation hiatus, also well known in the Uyuni-Coipasa basins, indicating a dry period.

Phase T (samples 18, 20, 22). After the dry period, lacustrine deposits dated from 13,000 yr BP indicate a slight increase in water-level under slightly wetter but still evaporative local conditions. According to the altitude of Tauca sediments (4,125 m), the water depth in the centre of the basin was 5–10 m, suggesting a decrease of depth in the water-level from ~4,155 m (late lacustrine Minchin phase M5) to ~4,130 m (Tauca phase T). During the Tauca event, the presence of only class VII indicates that modern ecological conditions had already started.

A difference similar to that between Minchin and Tauca is also observed in nearby Lake Ramaditas. The sediments representative of the Tauca event are at 4,123 m altitude, while last Minchin phase sediments are located at 4,145 m altitude, indicating a difference of 22 m. Minchin planktonic species are replaced by epiphytic *Cocconeis*, *Cymbella* and *Epithemia* species, indicating low water-levels. Thus, at that time, communication between Ramaditas and Ballivian lakes was not possible. Until now, Lake Ballivian has remained shallow and isolated. In this outcrop, the Tauca event is poorly represented compared with other outcrops recently discovered in the northern margin of the Uyuni salar. A more precise work for this period of time is now possible.

Discussion

By comparing results obtained from diatom study and geomorphology, it is possible to infer changes in water-levels during the Minchin and Tauca events from outcrops located on the margins of lakes Ballivian (Fig. 7) and Ramaditas. There are three important points in this connection. First, the altitudes of the sediment layers above the height of the bottom of the centre of the basin (4,120 m; Fig. 7(a)) give the minimum depth reached by the water at the margin of the lakes (Fig. 7(d)). Second, diatoms give the depth of water above the sediment layer. According to the presence of autochthonous epiphytic or tychoplanktonic species, we can suppose that this depth was 5–10 m. They also give the maximum depth of the water above the bottom of the centre of the basin (Fig. 7(e), dashed lines). Allochthonous species, transported from the nearby Lake Ramaditas, indicate a link between both lakes (Fig. 7(e), dashed lines). And, third, sand deposits or hiatuses suggest water-level decreases under the sediment layers.

The results of our diatom study show for the first time that the Minchin event has imposed important modifications on water-levels. During the M2 and M4 phases, the highest water-levels are reflected by a discharge of water from Lake Ramaditas; these are due to regional palaeohydrological conditions in the Lipez area (water input from local precipitation and the large catchment area of Lake Ramaditas). During all other phases, Lake Ballivian remained isolated and water-level variations can only be explained by local climatic changes (changes in precipitation/evaporation ratios on the lake).

The water-level reconstructions indicate that the maximum precipitation/evaporation ratio occurred at the end of the Minchin event, *ca.* 22,000 yr BP, and before the last glacial maximum (15,000 yr BP), (Gouze *et al.*, 1986). However, high salinity (M5) suggests that high rainfall was discontinuous during the year and was separated by long evaporative periods. We assume that the climate was strongly seasonal.

A very different situation is observed during the high lacustrine phases of M3 and M1. These phases can be explained, as for M5, by a high local precipitation/evaporation ratio. However, low salinity suggests that low evaporation was the main factor in palaeohydrological evolution.

After *ca.* 22,000 yr BP, the sedimentation hiatus confirms the onset of arid conditions also observed throughout the central Andes during the last glacial maximum (Servant and Fontes, 1978; Ybert, 1992).

During the last glacial-interglacial transition, the presence of a shallow lake in the isolated Ballivian basin cannot be explained by the

input of water from the melting of local glaciers. Thus, this confirms an increase in the precipitation/evaporation ratio during the Tauca event. However, a slight increase in water-level and the occurrence of mesohaline conditions suggest that the local climate was not very humid, though slightly more humid than at present. During the same period in the Coipasa-Uyuni basin, lacustrine extensions were much wider because of the input of water from a much larger catchment area.

As a general conclusion, our results show that salinity and depth variations were not often linearly related: during phases when the lake reached its maximum depth, it also reached its maximum salinity; and, conversely, when it reached its minimum depth, it did not reach maximum salinity. Such results emphasize the need for considerable care in palaeo-ecological interpretations and the necessity to use not only one parameter but the relationships between several ecological parameters. Different approaches to separate parameters are then required which take into account the peculiar geomorphological features of each study site. Only in this way can satisfactory conclusions be drawn concerning past climates.

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