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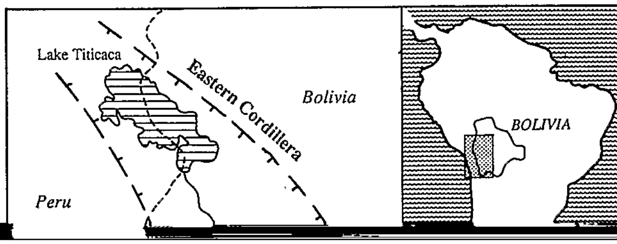
# Palaeohydrology of the Quaternary saline Lake Ballivian


Lake Titicaca
Eastern Cordillera
Bolivia
Peru
BOLIVIA

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).

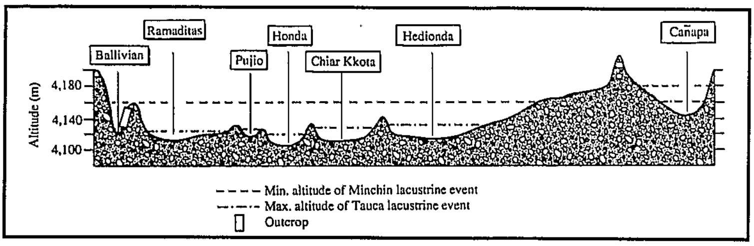
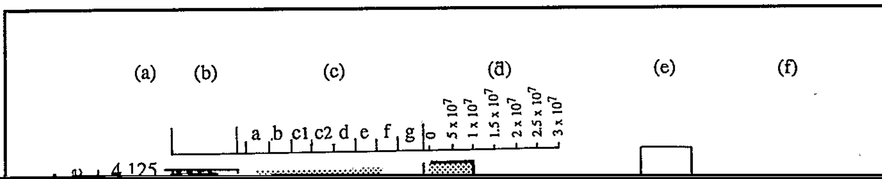



**Fig. 2.** Topographical cross-section of the Lipez area.

The purpose of the present paper is to reconstruct the palaeo-hydrological variations of the Ballivian lake. This lake is located in a small


(a)
(b)
(c)
(d)
(e)
(f)
a b c1 c2 d e f g
0
5 x 10^7
1 x 10^7
1.5 x 10^7
2 x 10^7
2.5 x 10^7
3 x 10^7

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

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 *Achnanthes delicatula* | –1 | | | | **21** | –1 | |
| AL *Achnanthes arenaria* | –1 | –2 | | | | **26** | –1 |
| AS *Achnanthes speciosa* | –1 | –2 | | | | **24** | –1 |
| AA *Amphora atacamae* | **5** | | | | | | |
| AAM *Amphora atacamae minor* | 2 | | | | | | |
| AC *Amphora carvajaliana* | –8 | –14 | –3 | –5 | **93** | –76 | –8 |
| AMCO *Amphora coffaeformis* | | –1 | | | | 1 | |
| AP *Amphora platensis* | –18 | –34 | –7 | **83** | –3 | –10 | –6 |
| AMSP *Amphora* spp. | **12** | –1 | | | | | |
| ASA *Anomoeoneis sphaerophora angusta* | | | | 22 | | | |
| ASP *Anomoeoneis sphaerophora platensis* | –1 | –2 | **55** | | | –1 | |
| CHSP *Chrysophyceae* | | 22 | | | | | |
| CP *Cocconeis placentula* | –15 | 1 | –6 | –5 | –2 | –2 | **65** |
| COP *Cocconeis placentula euglypta* | | | | | | 1 | 1 |
| CYCG *Cyclotella gamma* | –1 | –1 | | **3** | | –1 | |
| CYMC *Cymbella cistula* | | | | | | | 1 |
| CYL *Cymbella gracilis* | **11** | –1 | | | | | –1 |
| DE *Denticula elegans* | –1 | –2 | | | | –1 | **10** |
| FP *Fragilaria pinnata* | | **7** | | | | | |
| MELO *Melosira octogona* | | | | | | 1 | |
| NCI *Navicula cincta* | | | 3 | | | | |
| NHUN *Navicula hungarica* | | **1** | | | | | |
| NLA *Navicula pseudolanceolata* | 1 | | | | | | |
| NR *Navicula rhynchocephala* | 3 | –1 | | | | –1 | –1 |
| NTIN *Nitzschia ingens* | 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 *Amphora* sp.** | **86** | | | | | | |
| **NTIN *Nitzschia ingens*** | **86** | | | | | | |
| RW *Rhopalodia wetzeli* | 86 | | | | | | |
| CW *Caloneis westi* | 86 | | | | | | |
| **AA *Amphora atacamae*** | **85** | | | | | | |
| RHM *Rhopalodia musculus* | 85 | | | | | | |
| NTS *Nitzschia sigma* | 84 | | | | | | |
| CYL *Cymbella gracilis* | 82 | | | | | | |
| **AAM *Amphora atacamae minor*** | **81** | | | | | | |
| NPU *Nitzschia pusilla* | 80 | | | | | | |
| NR *Navicula rhynchocephala* | 80 | | | | | | |
| NAC *Navicula placentula* | 80 | | | | | | |
| NLI *Navicula peudolittoricola* | 73 | | | | | | |
| NTVA *Nitzschia valdestriata* | 73 | | | | | | |
| **NLA *Navicula pseudolanceolata*** | **70** | | | | | | |
| NCC *Navicula cari* | 69 | | | | | | |
| **RHGI *Rhopalodia gibberula*** | **57** | | | | | | |
| **CHSP Chrysophyceae** | | **93** | | | | | |
| GOML *Gomphonema lanceolatum* | | 93 | | | | | |
| NC *Navicula cryptocephala* | | 89 | | | | | |
| **FP *Fragilaria pinnata*** | | **81** | | | | | |
| **NHUN *Navicula hungarica*** | | **74** | | | | | |
| OM *Opephora martyi* | | 73 | | | | | |
| **ASA *Anomoeoneis sphaerophora angusta*** | | **96** | | | | | |
| NR *Navicula rhynchocephala* | | | 96 | | | | |
| **ASP *Anomoeoneis sphaerophora platensis*** | | **89** | | | | | |
| **NCI *Navicula cincta*** | | | **80** | | | | |
| SUP *Surirella peisonis* | | | 59 | | | | |
| SYR *Synedra rumpens* | | | 40 | | | | |
| DIS *Diploneis smithii* | | | 23 | | | | |
| GP *Gomphonema parvulum* | | | 79 | | | | |
| AEX *Achnanthes exigua* | | | | 79 | | | |
| SUO *Surirella ovalis* | | | | 79 | | | |
| NTS *Nitzschia sigma* | | | | 79 | | | |
| SYNA *Synedra acus* | | | | 79 | | | |
| NTSI *Nitzschia sigmoidea* | | | | 79 | | | |
| SYNA *Synedra ulna* | | | | 79 | | | |
| **CYCG *Cyclotella gamma*** | | | | **78** | | | |
| NTGR *Nitzschia gracilis* | | | | 77 | | | |
| **AP *Amphora platensis*** | | | | **77** | | | |
| **AC *Amphora carvajaliana*** | | | | | **89** | | |
| NTCM *Nitzschia commutata* | | | | | 89 | | |
| SP *Scoliopleura peisonis* | | | | | 88 | | |
| NTPT *Nitzschia palea tenuirostris* | | | | | 81 | | |
| CA *Ceratoneis arcus* | | | | | 66 | | |
| RG *Rhopalodia gibba* | | | | | | 82 | |
| **AD *Achanthes delicatula*** | | | | | | **82** | |
| RHGV *Rhopalodia gibba ventricosa* | | | | | | 82 | |
| **AL *Achnanthes arenaria*** | | | | | | **82** | |
| **AS *Achnanthes speciosa*** | | | | | | **82** | |
| CYMI *Cymbella microcephala* | | | | | | 82 | |
| NQ *Nitzschia quadrangula* | | | | | | 82 | |
| CYMP *Cymbella pusilla* | | | | | | 82 | |
| **MELO *Melosira octogona*** | | | | | | **81** | |
| SW *Surirella wetzeli* | | | | | | 81 | |
| NTHU *Nitzschia hungarica* | | | | | | 78 | |
| NI *Nitzschia inconspicua* | | | | | | 76 | |
| AML *Amphora lineolata* | | | | | | 69 | |
| NINS *Nitzschia* nov. sp. | | | | | | 53 | |
| AMCO *Amphora coffaeformis* | | | | | | 45 | |
| COP *Cocconeis placentula euglypta* | | | | | | 19 | |
| MA *Mastoglia atacamae* | | | | | | | 75 |
| NPA *Nitzschia palea* | | | | | | | 75 |
| **DE *Denticula elegans*** | | | | | | | **75** |
| GOMA *Gomphonema angustatum* | | | | | | | 75 |
| **CYMC *Cymbella cistula*** | | | | | | | **74** |
| **CP *Cocconeis placentula*** | | | | | | | **70** |
| NAVH *Navicula halophila* | | | | | | | 69 |
| AMFR *Amphora frenguelli* | | | | | | | 61 |
| GOMI *Gomphonema intricatum* | | | | | | | 44 |
| **COP *Cocconeis placentula euglypta*** | | | | | | | **37** |
| CYCS *Cyclotella stelligera* | | | | | | | 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.

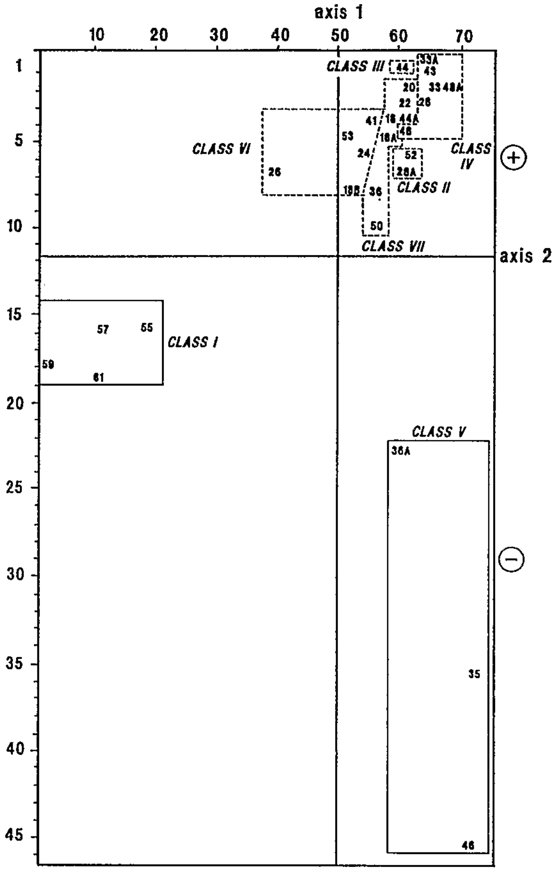



**Fig. 4.** Plot of sediment samples on axes 1 and 2.

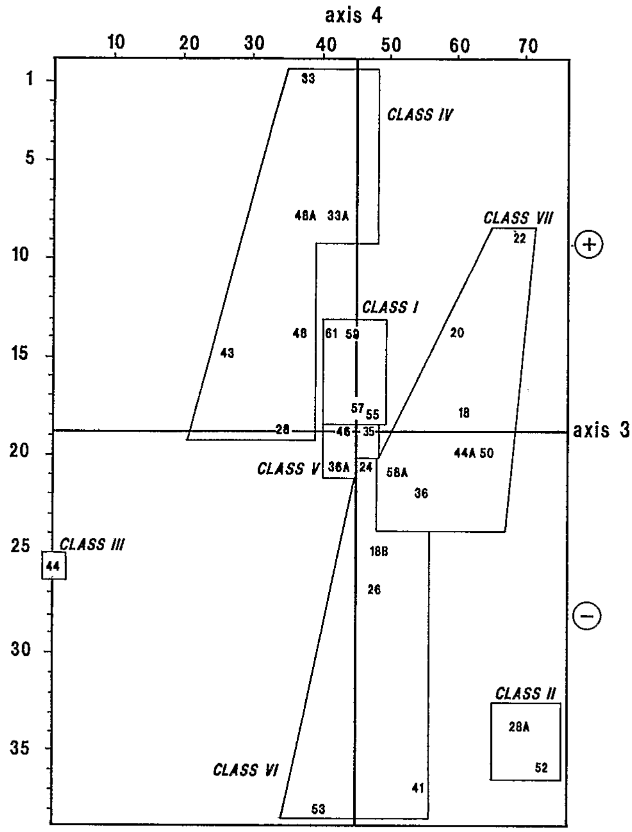



**Fig. 5.** Plot of sediment samples on axes 3 and 4.

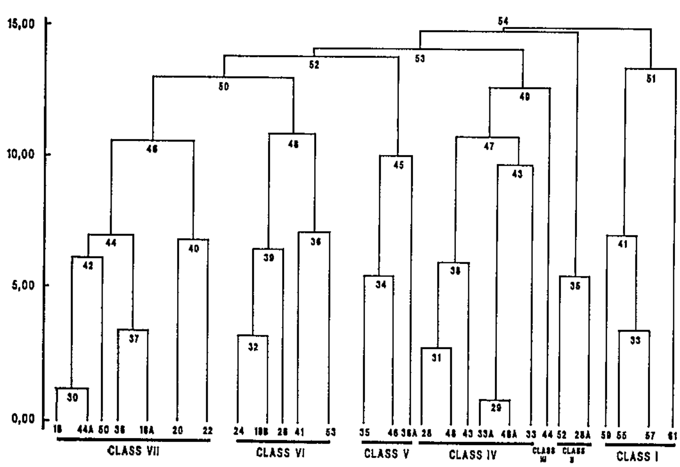



**Fig. 6.** Hierarchical classification of sediment samples. Dendrogram expresses sample similarity based upon diatom species composition.

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.

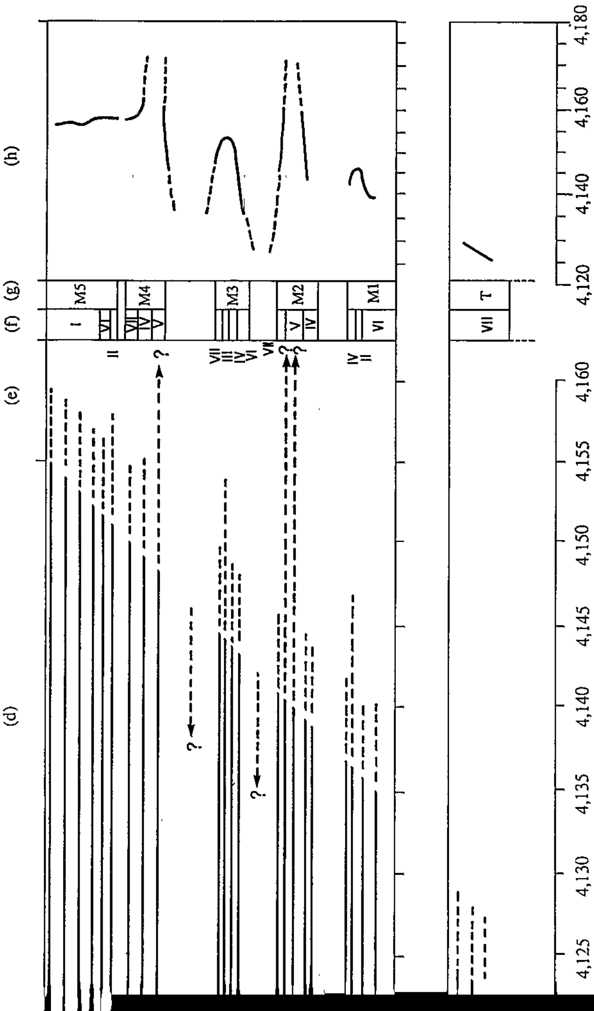
## Hydrochemical variations through time

The various lacustrine phases identified (Fig. 7(g)) enables determinaation 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 Chrysophyseae cysts and a euryhaline tychoplanktonic 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 | |


(h)
(g)
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M5
M4
M3
M2
M1
T
4,180
4,160
4,140
4,120
4,160
4,155
4,150
4,145
4,140
4,135
4,130
4,125

[redacted]

**Phase M3** (samples 33A to 36). The thin sand layer between samples

## 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 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 palaeoecological 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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