Hydrobiologia **288**: 183–193, 1994.

A quantitative method of palaeolake-level reconstruction using ostracod assemblages: an example from the Bolivian Altiplano

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Received 19 May 1992; in revised form 25 September 1993; accepted 14 December 1993

Key words: transfer function, ostracods, water depth, salinity, Mg/Ca ratio, Bolivia

Abstract

This paper provides quantitative information concerning the response of ostracods to environmental variability in order to reconstruct past environments. Ostracod faunas from modern sediments of Bolivian lakes and swamps were studied. Ostracod distribution is controlled by several ecological characteristics such as lake-level and water chemistry. Statistical results indicate that three transfer functions (on water depth, Total dissolved Salts and water in Mg/Ca ratio) can be developed, from ostracod species frequencies in lacustrine sediments, with some restrictions for the two last ones.

Introduction

Lake-level fluctuations are used as an indicator of climatic change especially when considering the Evaporation/Precipitation ratio (Street-Perrott & Harrison, 1984, 1985). In most cases, past lake-levels are recognized through lacustrine shorelines or terraces. Recently, diatom remains have been used to provide quantitative records of past hydrochemical variations (Roux *et al.*, 1991, and publications mentioned in this paper).

In the present paper, we use ostracod assemblages to reconstruct past limnological conditions. This study site is situated on the Altiplano in Bolivia where a large spectrum of lakes occurs. Ostracods were chosen because of their ecological diversity and abundance in lacustrine sediments. Salinity and water depth are recognized as having an important effect on ostracod distribution (Neale, 1990; Cohen, 1984). The role of particular aspects of water chemistry has recently received attention as well (Delorme, 1969; Forester, 1983, 1985, 1986; De Deckker, 1988; De Deckker & Forester, 1990), and thus we studied the relation between these different variables (water depth, TDS and major ions) and the ostracod assemblages in Altiplano lakes.

In order to infer past lake-levels or lake water chemistry, the most important step is to develop transfer functions (Roux, 1985) using modern ostracod assemblages and pertinent environmental parameters. In the present paper, calibration models which were developed by using factorial analysis of correspondance (FAC) applied to ostracod assemblages, ostracod species and environmental classes are reported, and then, multiple linear regressions (MLR) were used. The quality of equations obtained permit us to predict (1) water depth, (2) total salinity and (3) Mg/Ca ratio.

Study area and study lakes

The Bolivian Altiplano is an endorheic basin which extends between 15 to 22°S latitude and from 65 to 69°W longitude, around 4000–4500 meters a.s.l., over an area of ≈200 000 km^2. From north to south, four main lake systems occur on the plateau (Fig. 1):

- Lake Titicaca, a deep, freshwater lake at 3809 m a.s.l., with a surface of ≈8500 km^2;
- Lake Poopó, an instable shallow meso- to hyperhaline lake at 3686 m a.s.l.;

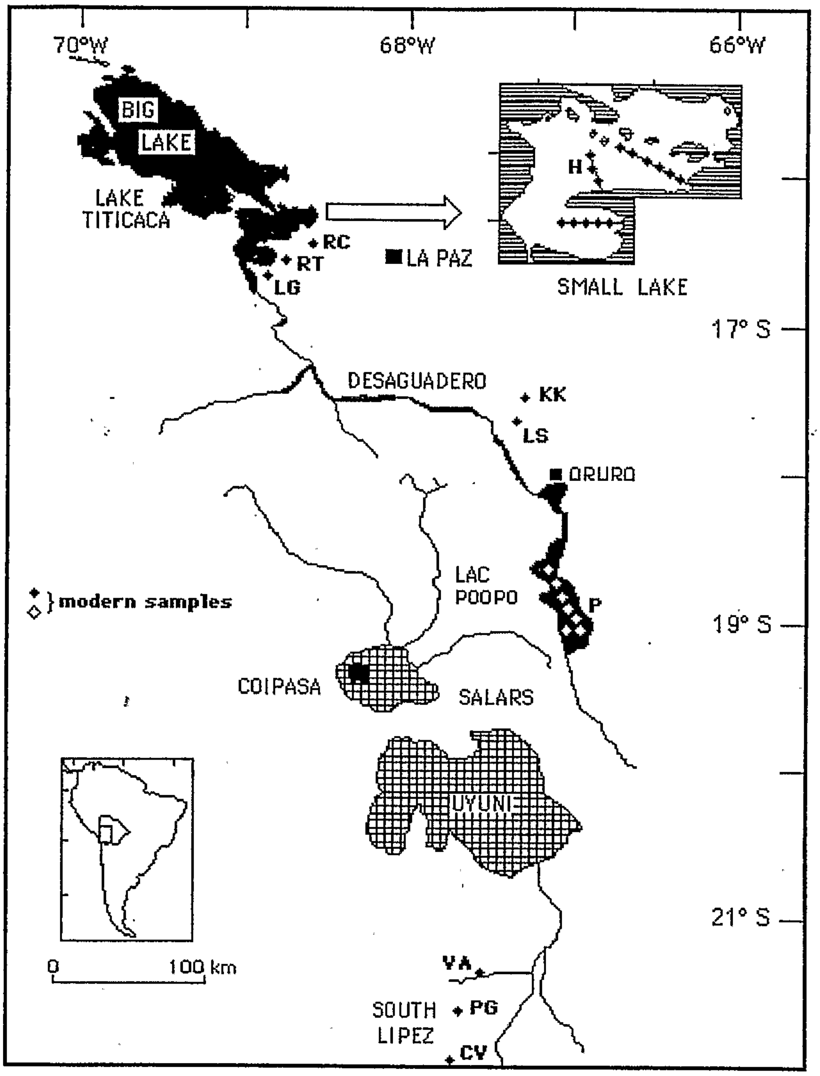

Fig. 1. Location of the samples studied. Codes used for samples are: H for Huiñaimarca, RC for Rio Catari, RT for Rio Tiwanaku, LG for Laguna 'Guaqui', KK for Kollpa Kkota, LS for Laguna Soledad, P for Poopó, VA for Villa Alota, PG for Pastos Grandes and CV for Challviri.

- Salars of Coipasa and Uyuni, two dry lakes covered by salt crust ($\approx$10 000 km^2) in winter, at an altitude of 3653 m;
- South Lipez, a volcanic region with numerous shallow saline lakes at 4100–4500 m a.s.l..

This extraordinary diversity of lacustrine environments provided a good field for ecological studies.

Materials and methods

Figure 1 shows the study locations on the Bolivian Altiplano. They were chosen to provide a maximum coverage of aquatic biotopes. In each of the 115 samples with known water depth and chemistry, ostracods were examined. A large majority of ostracod species has not been identified at specific level but only recognized as different. Our ostracod segregation is based on carapace characteristics (size, shape, ornamentation and muscle scars) but more information (anatomy of the appendages) is necessary for taxonomic identification, especially the genus *Limnocythere* (Mourguiart & Carbonel, in prep.). About fifty species were collected, with only 28 species used in the present study because of the partial (in the littoral environments) or total (in the profundal hypolimnetic zones) dissolution of thin-

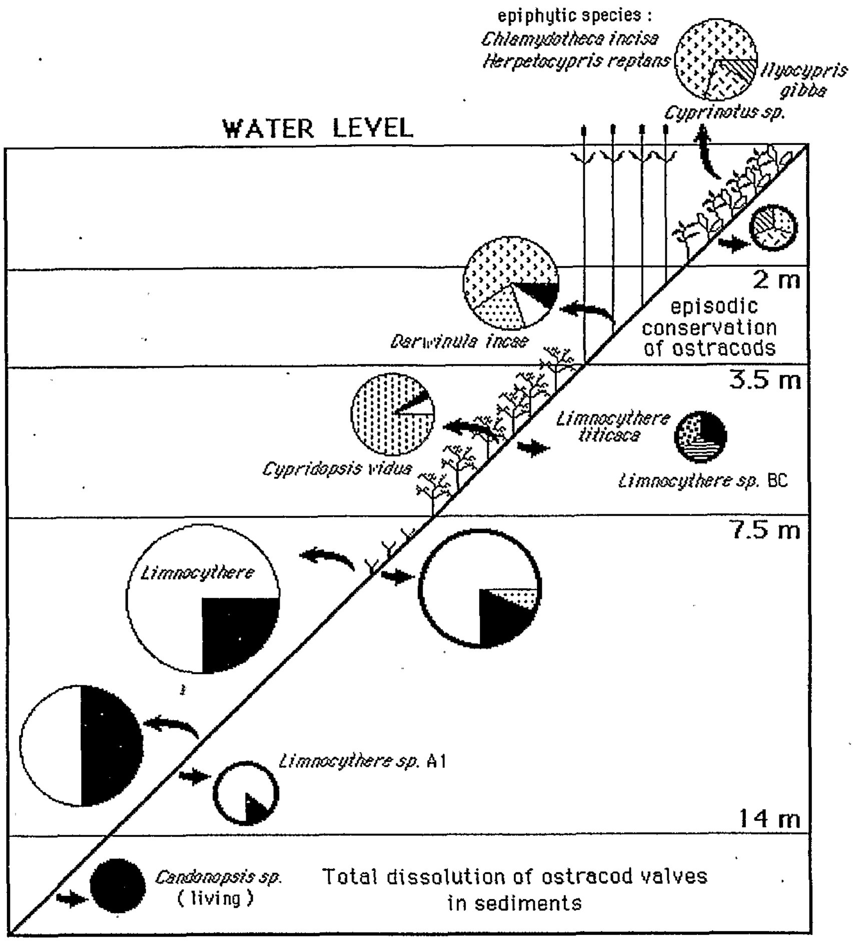

Fig. 2. Ostracod assemblages of Lake Titicaca versus water depth: biocœnoses (thin circles) and thanatocœnoses (thick circles).

ner carapaces of some species in the sediment water interface (Mourguiart, 1987). For example, common epiphytic species like *Chlamydotheca incisa* Claus or *Herpetocypris reptans* Baird are never found in lake Titicaca sediments although they are found living in the lake (Fig. 2), and therefore are not incorporated in the species/sample matrix of the statistical analysis. This case is a good illustration of the problems occurring when faunas transit from biocœnoses to thanatocœnoses.

The different ecological tolerances of ostracod species explain in part their spatial distribution. Only three species are living in environments characterized by salinities of more than about 3.5 g l^{-1} (Fig. 3). These are:

- *Cyprideis aff. hartmanni* Ramirez, 1967,
- *Limnocythere bradburyi* Forester, 1983,
- *Cypridopsis sp.* (this species present high similarities with *C. pseudoparva* Löffler, 1963).

The two last ones live in Lake Poopó (at salinity less than 15–17 g l^{-1}): *L. bradburyi* at the water–sediment interface and *Cypridopsis sp.* on plant stems (*Characeae*). *Limnocythere bradburyi* has a wide distribution, from marshes near Lake Titicaca to small lakes of South Lipez, and a wide salinity tolerance (see Fig. 3). *Cyprideis aff. hartmanni* lives in numerous South Lipez lakes ('lagoon' Pastos Grandes, for example). The presence/absence of one taxon or another in a special environment seems to explain differences of water Mg/Ca ratio (Fig. 4), but it is possible that minor ions like Mn or Li could have an important effect on ostracod distribution. The third variable that affects ostracod distribution is water depth (or more exactly macrophyte zonation, food supply, and oxygen concentration, all being directly correlated with

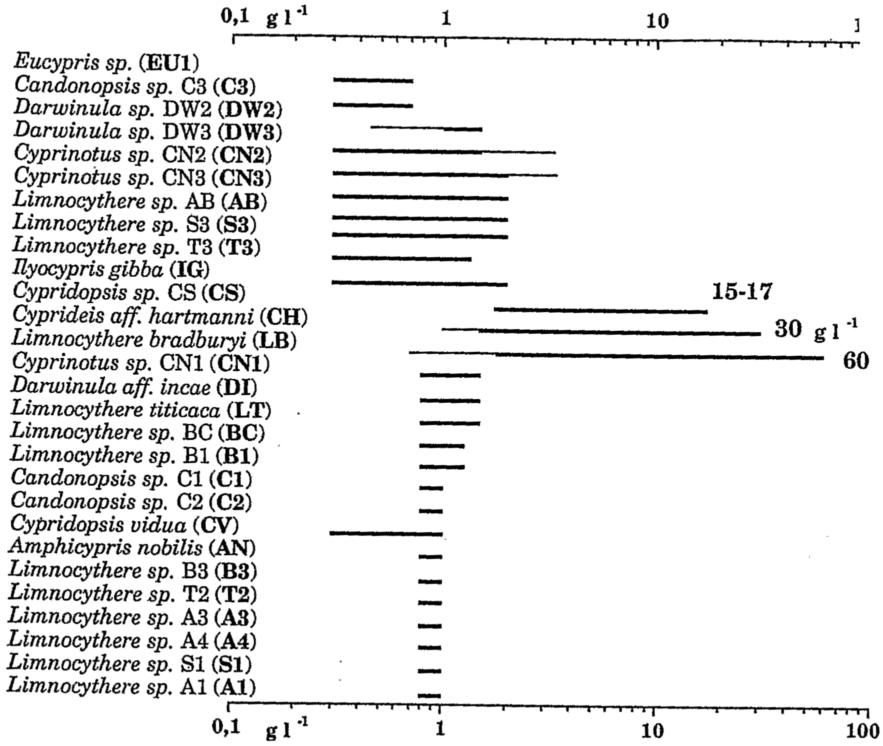

Fig. 3. Salinity ranges of the 28 living ostracod species integrated in the FAC.

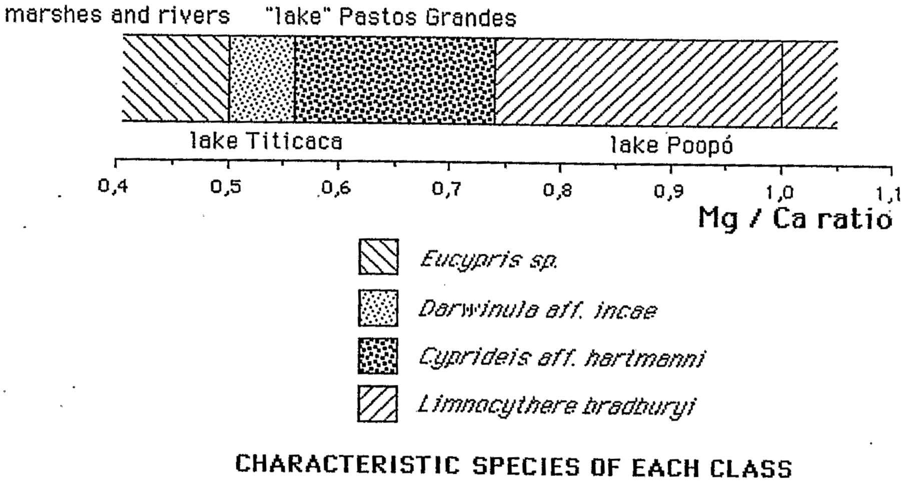

Fig. 4. Mg/Ca ratio ranges of the 4 ostracod groups integrated in the FAC.

water depth; Fig. 2), especially for the typical assemblages of Lake Titicaca (including numerous species or subspecies of *Limnocythere*). In summary, the ostracod distribution depends on 3 major ecological variables: (a) water depth, (b) total salinity and (c) ratio Mg/Ca (Mourguiart & Roux, 1991).

So, a matrix of 28 rows (species) and 1
(samples) was subjected to a BIOMECO f
sis of correspondences (FAC), as discussed
Vildary & Roux (1990) and Roux *et al.* (19

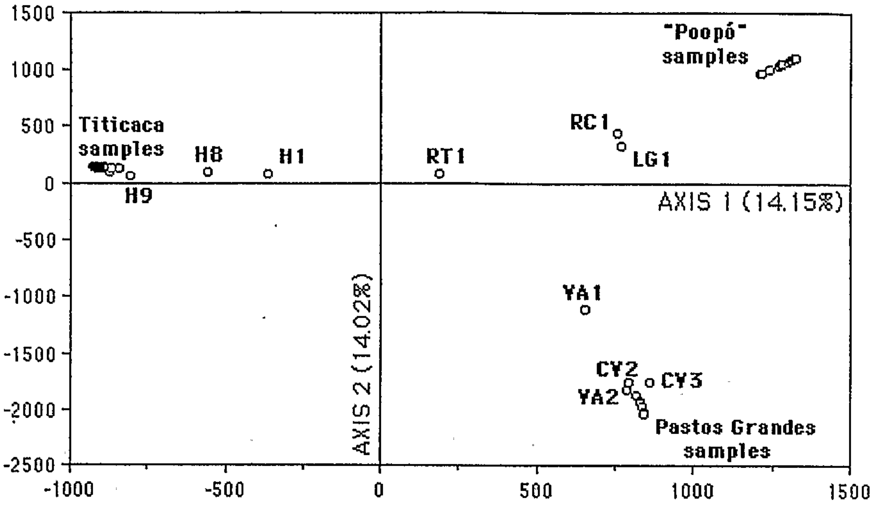

Fig. 5. Correspondence analysis of data. Modern samples are active elements.

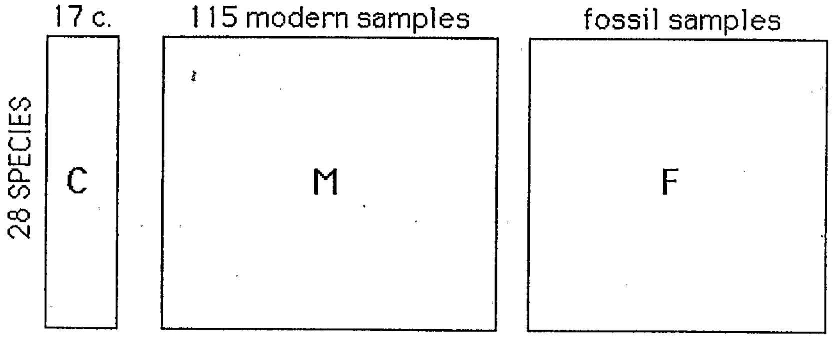

Fig. 6. The union of tables C (17 classes), M and F (variable column number) subjected to Reciprocal Averaging. Only the class table was considered as active.

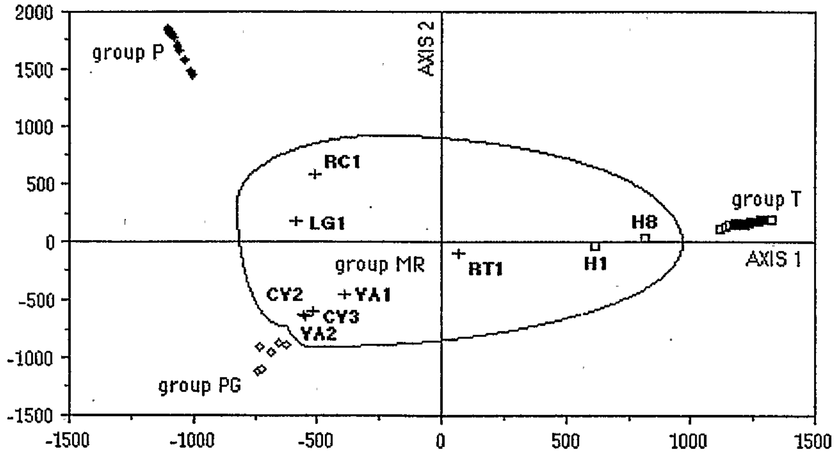

Fig. 7. Correspondence analysis of data. Modern samples are passive elements (only classes are active elements in this case, see Fig. 6).

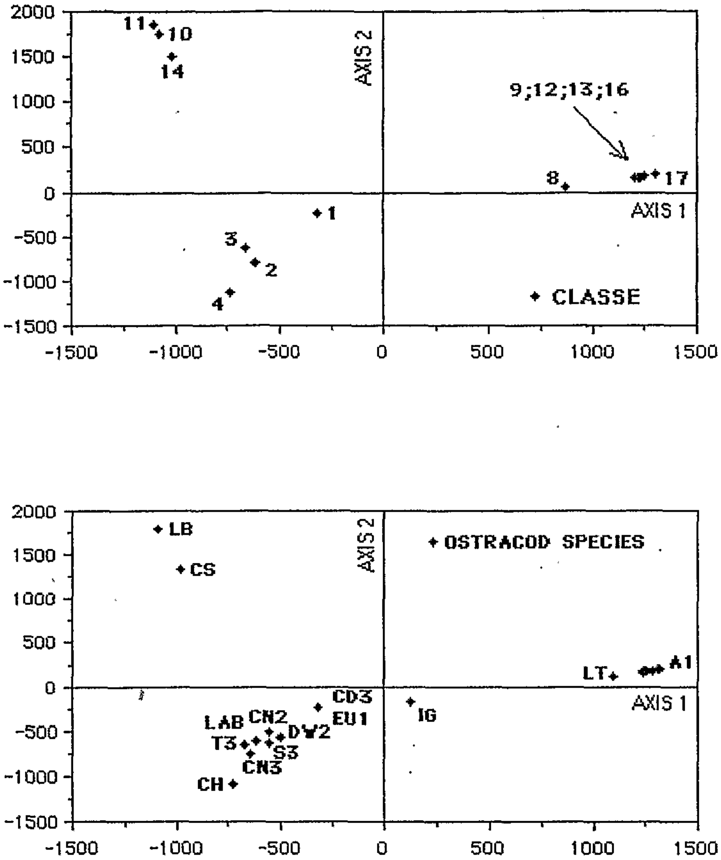

Fig. 8. Correspondence analysis of data. The first (horizontal) factorial axis accounts for 21.69% of variance, the second one (vertical) for 20.72%.
1. Class (active elements) representation.
2. Species representation.

Results

The FAC works with the relative abundances of the 28 species in the 115 samples. The first six factors extracted account for 64.87% of the total variance (Table 1). The factor matrix gives the composition of each sample and species in terms of the 6 factors. Factors 1 and 2 represent 28.17% of the variance (14.15% and 14.02%, respectively). According to these 2 factors, three groups are well individualized and a fourth occupies the central part of the plot (Fig. 5). The first three groups correspond to samples from lakes Titicaca (group T), Poopó (group P) and Pastos Grandes (group PG). The 4th group can be considered as an 'intermediate' case and corresponds to samples of particular environments like temporary marshes and rivers (group MR). Samples H1 and H8 from Lake Titicaca have an original position compared to other ones because they contain characteristic species of this lake (*Darwinula aff. incae* Delachaux, for example) but also others typical of temporary environments (*Ilyocypris gibba* Ramdohr). This sample distribution on plot can be associated with water Mg/Ca ratio differences (see Fig. 4). In the three well defined groups, the sample distribution can be correlated with water salinity and/or depth ranges (see above).

Therefore we have regrouped the samples in classes of water Mg/Ca ratio, water salinity and water depth (Table 2). These modalities are obtained by combination between 5 ranges for the water depth, 4 for the salinity (TDS) and 4 for the Mg/Ca ratio. A new FAC is thus collated, and data comprising a species/classes matrix as active elements (28 rows and 17 columns) and two matrices consisting of the percentages of the 28 species distributed in modern (115 subliving) and fossil samples (as supplementary or passive elements

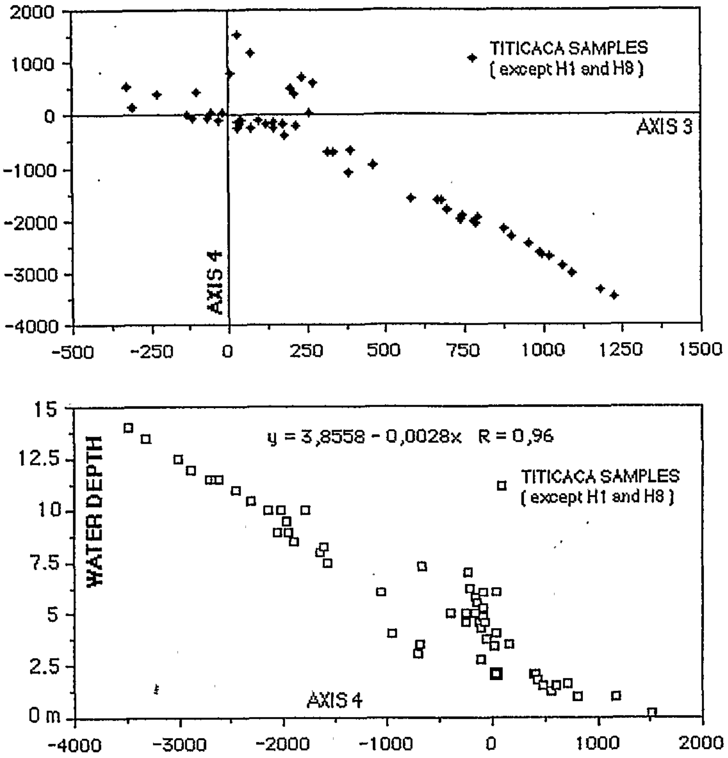

Fig. 9. 1. Axis 4 (12.41% of variance) versus axis 3 (13.82% of variance) 2. Water depth versus axis 4 of the FAC (only classes are active elements) and corresponding correlation coefficient.

Table 1. Factor analysis of correspondances of data, inertia values. 1. Modern samples are active elements. 2. Ecological classes are active elements (*).

Axis	Eigenvalues	Inertia	Cumulate inertia
1	0.9894702	14.15%	14.15
2	0.9802653	14.02	28.17
3	0.8112326	11.60	39.77
4	0.6850839	9.80	49.57
5	0.5550738	7.94	57.51
6	0.5147444	7.36	64.87%
1*	0.9727050	21.69%	21.69
2*	0.9293810	20.72	42.41
3*	0.6198077	13.82	56.23
4*	0.5565896	12.41	68.64
5*	0.4376901	9.76	78.40
6*	0.3676360	8.20	86.60%

-*sensu* Benzecri, 1973) are obtained (Fig. 6). Factors 1 and 2 represent 42.41% of the total information (Table 1). According to these 2 factors, the same groups as in the precedent FAC are individualized (Figs 7 and 8). Group T is characterized by living lake Titicaca species with water depth (1–14 m) and salinity (0.8–1.4 g l^{-1}) ranges (see Table 2). Group P and PG are characterized by *Limnocythere bradburyi* and *Cyprideis aff. hartmanni* respectively. Physico-chemical ranges are:

– 0.15–2.75 m and 2.5–60 g l^{-1} for group P;
– 0–0.1 m and 1.2–30 g l^{-1} for group PG.

Others samples correspond to group MR (see above for details on group signification). The results on fossil samples will be discussed in a future publication.

The patterns support the qualitative observations based on ostracod ecology that the Mg/Ca ratio is the principal control over their presence-absence, and the water levels and salinity the major controls over their distribution in each lacustrine system (Fig. 9).

Therefore a multiple linear regression (MLR) including the 3 environmental controls (a, b and c) is obtained. The MLR results are given in plots between observed and estimated variates (Figs 10, 11 and 12). Plots of residuals show that the estimates are

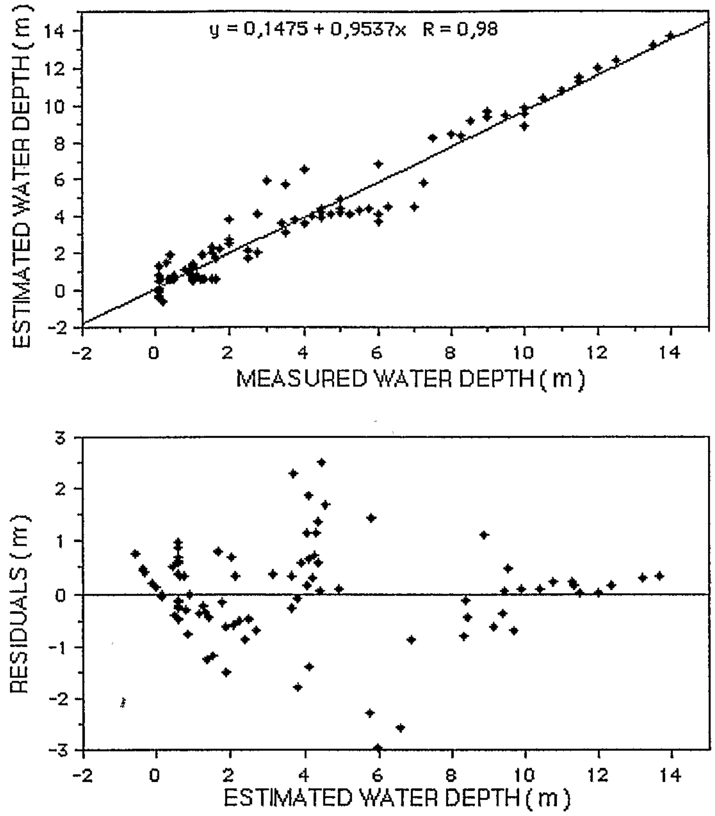

Fig. 10. Estimated versus measured water depth for the 115 samples and plot of the MLR residuals.

within±0.82 m of the observed water depths with a corresponding correlation coefficient of 0.9766, ±6.83 g l^{-1} of the observed salinities with a correlation coefficient of 0.8627 and ±0.062 of the observed Mg/Ca ratios with a correlation coefficient of 0.9645. Salinity plots (Fig. 11) show (1) a lack of values witin the range 1,5–15 g l^{-1} and (2) incorrect estimations above 17 g l^{-1} salinity. These samples are caused by monospecific occurrence of ostracods (*e.g. Limnocythere bradburyi or Cyprideis aff. hartmanni*) in lakes.

Conclusion

The data indicate that ostracod assemblages can be used to quantitatively reconstruct several ecological variables by using transfer functions. There are strong correlations between ostracod faunas and water depth. Nevertheless, it seems that transfer functions may be developed between ostracods and (a) Mg/Ca ratio and (b) water salinities in the 0–15 g l^{-1} range using more samples and better chemical analyses. It is possible that other chemical variables may have an important rôle on ostracod distribution, and consequently other transfer functions ought to be developed. With this statistical analysis in hand, model applications to Holocene ostracode palaeoassemblages will become possible.

Acknowledgements

We thank Dr M. Servant and Dr P. De Deckker for reviewing the manuscript, and Prof. H. Löffler for constructive criticism and suggestions on the manuscript. This work was supported by ORSTOM (GEOCIT program) within UMSA La Paz (Bolivia) / ORSTOM Paris agreement.

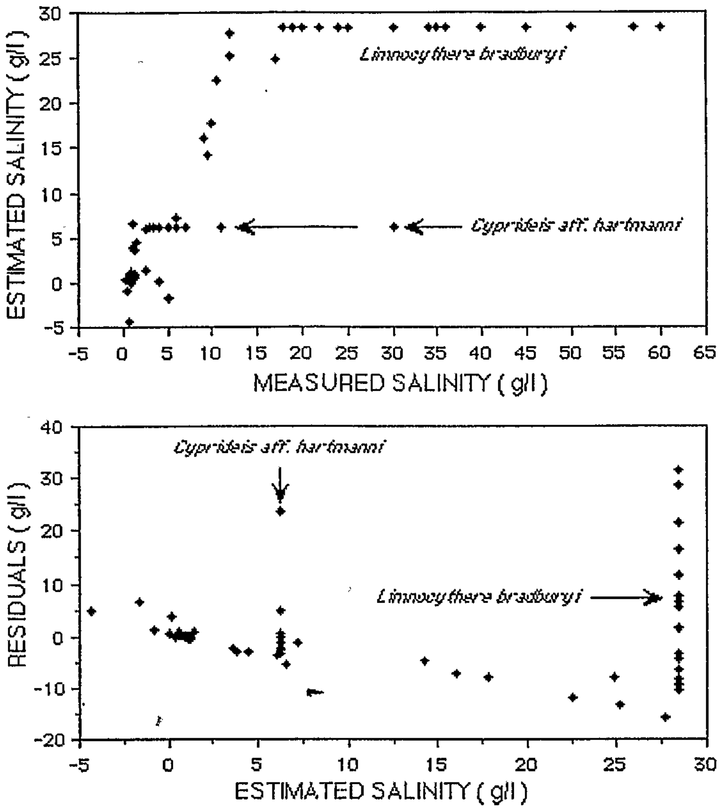

Fig. 11. Estimated versus measured water salinity for the 115 samples and plot of the MLR residuals.

Table 2. Ecological class combinations and codes used in the FAC.

Depth ranges (m)	Salinity ranges (g/l)	Mg/Ca ratio ranges	Code
nb = 5	*nb* = 4	*nb* = 4	*nb* = 17
0–0.14 (1)	0–0.95 (1)	0–0.5 (1)	111 = 1
0–0.14	0.96–3.5 (2)	0–0.5	121 = 2
0–0.14	0.96–3.5	0.57–0.73 (3)	123 = 3
0–0.14	3.6–17.5 (3)	0.51–0.56 (2)	132 = 4
0–0.14	3.6–17.5	0.57–0.73	133 = 5
0–0.14	3.6–17.5	0.74–1.05 (4)	134 = 6
0–0.14	17.5–60 (4)	0.57–0.73	143 = 7
0.15–1.25 (2)	0–0.95	0.51–0.56	212 = 8
0.15–1.25	0.96–3.5	0.51–0.56	222 = 9
0.15–1.25	3.6–17.5	0.74–1.05	234 = 10
0.15–1.25	17.5–60	0.74–1.05	244 = 11
1.26–2.75 (3)	0–0.95	0.51–0.56	312 = 12
1.26–2.75	0.96–3.5	0.51–0.56	322 = 13
1.26–2.75	3.6–17.5	0.74–1.05	334 = 14
1.26–2.75	17.5–60	0.74–1.05	344 = 15
2.76–7.50 (4)	0–0.95	0.51–0.56	412 = 16
7.51–14.05 (5)	0–0.95	0.51–0.56	512 = 17

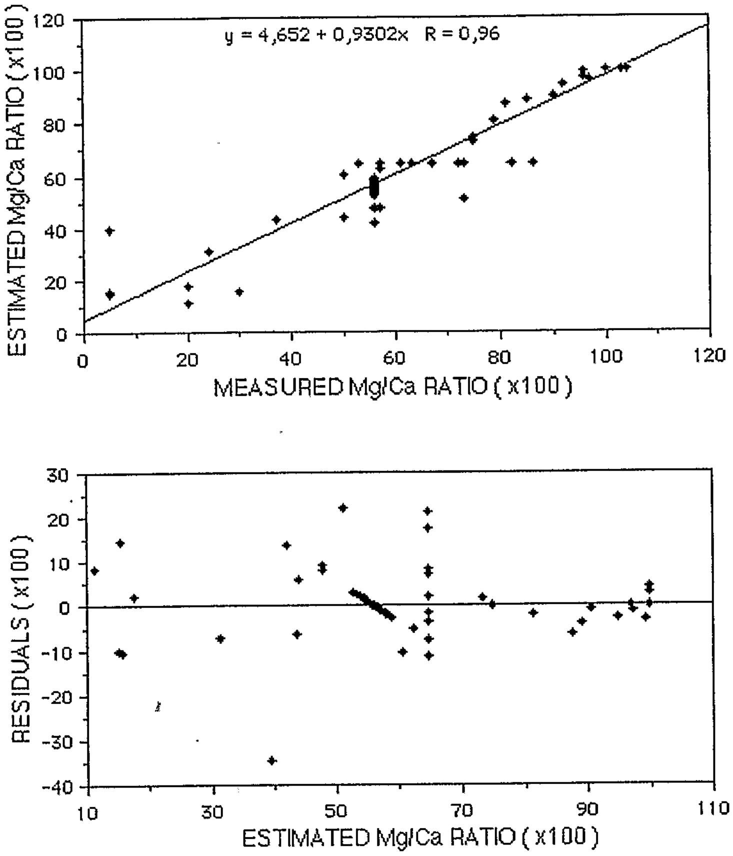

Fig. 12. Estimated versus measured water Mg/Ca ratio for the 115 samples and plot of the MLR residuals.

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