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Late Quaternary climate history of the Bolivian Altiplano

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Abstract

Sediment cores and outcrops from the Bolivian Altiplano are used to interpret late Pleistocene/Holocene paleoclimates and lake evolution based on a multi-proxy approach (ostracod content, palynology, sedimentology, and radiocarbon dating). Despite the different sensitivity of the lacustrine basins to environmental changes, interpreting the records in terms of paleohydrology, climate, and more especially timing of events is difficult. Notwithstanding these problems, Lake Titicaca in the north and Lake Poopó (Lake Poopó, salars of Coipasa and Uyuni) in the south reveal a similar evolution in general trends through the course of time. During the Minchín phase (until 30–26 kyr BP), the Altiplano was wetter than present. The Last Glacial Maximum (ca. 26–14 kyr BP), marked by cooler, drier conditions, was followed by a return to a wetter climate, interrupted by short arid events, between ca. 14 and 10.5 kyr BP. Another cycle of aridity, between 10.5 and 8 kyr BP, took place abruptly just after the humid Tauca phase. The mid-Holocene is interpreted as climatically unstable, with an alternation of humid and dry episodes. Since 3.9 kyr BP, wetter conditions have persisted and intensified to the present. The data are interpreted in terms of changes in inter-tropical convergence zone extension (summer precipitation) and in polar air mass intensity (winter precipitation). © 2000 Published by Elsevier Science Ltd and INQUA. All rights reserved.



1. Introduction

Beyond any doubt, the Last Glacial Maximum and the current Interglacial are among the most intensively studied and best known periods of the history of our planet (see, for example, Wright et al., 1993). By contrast, very few data are available covering this time-span in the tropical Andean zone of South America (Schubert, 1988; Markgraf, 1989, 1993; Clapperton, 1993; Argollo and Mourguiart, 1995a). As regards the south-equatorial zone, the sedimentary record before 20,000 yr BP is documented only at a limited number of sites. These include borings at Mera and San Juan Bosco in Ecuador (Liu and Colinvaux, 1985; Bush et al., 1990; Fig. 1) and at Junín in Peru (Hansen et al., 1984; Fig. 1), as well as cores taken in the Bolivian sector of Lake Titicaca (Wirmann et al., 1992; Fig. 7) and those collected on the eastern slopes of the Cordillera Oriental of the Andes, also in Bolivia, at a locality known as Siberia (Sifeddine et al., 1997; Fig. 1). A large amount of more sporadic informa-

tion at high-elevation sites has been collected in parallel with the above-mentioned studies, mainly by geomorphologists (see Clapperton, 1993). In addition, from the lowlands of the continent, material of this age has been cored at Carajás in Brazilian Amazonia (Absy et al., 1991; Sifeddine et al., 1994a, b; Fig. 1) as well as in the Salitre area (Ledru, 1993; Sondag et al., 1993; Bertaux et al., 1996; Fig. 1) and from the Tamandú River (Turcq et al., 1997; Fig. 1). Numerous other studies (mainly from sedimentologists and geomorphologists) have recently improved our knowledge of climate changes in the tropics and subtropics during the last 30,000 yr (Iriando, 1993, 1995; Iriando and García, 1993; Dumont and Fournier, 1994; Latrubesse and Ramonell, 1994; Van der Hammen and Absy, 1994; Latrubesse and Franzinelli, 1995; Behling and Lichte, 1997). All the increasing evidence deduced from these terrestrial paleorecords suggest that the tropics and subtropics were affected by important climatic fluctuations during the late Pleistocene and the Holocene.

As regards the Bolivian Altiplano, successive studies have been carried out for more than a century. In this context, we may cite the pioneering work of Agassiz (1875), as well as the more recent studies of Ahlfeld (1946), Newell (1949) and Ahlfeld and Branisa (1960). A complete bibliographical review is available in Argollo

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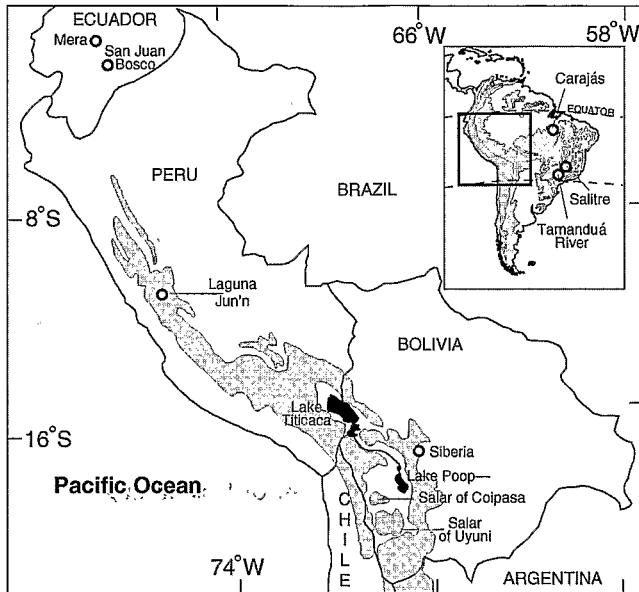


Fig. 1. Map of the central Andes showing the locations of published Full Glacial sites.

and Mourguiart (1995c). These different authors found and described sedimentary deposits that cover wide areas over the entire Altiplano. In this way, a succession of high lake levels and phases of glacier advance were recognised within the Andes. The previous existence of very large bodies of water in this region accounts for the observed lacustrine deposits. The ages of the different lacustrine phases remained unknown until the works of Servant and Fontes (1978, 1984) and Lavenu et al. (1984). In particular, these last-mentioned authors established the chronostratigraphic framework of the main lacustrine episodes as a function of their respective elevation (Fig. 2). The three oldest lacustrine phases, which also correspond to the highest lake levels (Mataro, Cabana and Ballivián), have been assigned to the middle to early Quaternary and/or the late Pliocene, even though no detailed stratigraphic argument supports such an attribution (see discussion of this point in Clapperton, 1993). The Minchín and Tauca phases have been dated by the radiocarbon method as being older than 27,000 and 13,000–10,500 yr BP, respectively (Servant and Fontes, 1978). More recent dating work has made it possible to define the age of these two lacustrine phases (Bills et al., 1994; Argollo and Mourguiart, 1995b, c; Servant et al., 1995).

By means of new data reported in the present study, we take stock of the paleohydrological and paleoclimatological information obtained on the period from about 40,000 yr BP in the region of Lake Titicaca as well as in the lacustrine interior basins ("salars") of the central Altiplano and southern Bolivia. In addition, a discussion is presented concerning the timing of the main hydrological phases.

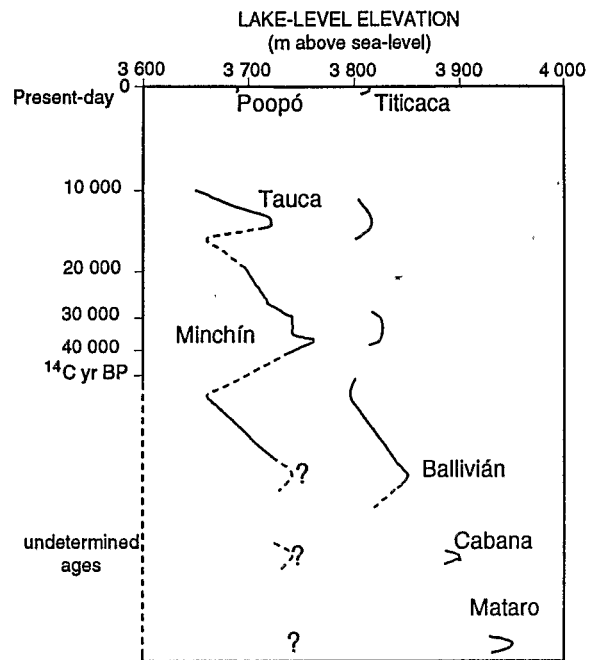


Fig. 2. Stratigraphy and relationship between the northern and central Altiplano lacustrine episodes (after Lavenu et al., 1984).

2. Regional setting

The Altiplano is situated in the midst of the Central Andes (long. 66–71° W, lat. 14–22° S) at an elevation of between 3650 and 3900 m (Fig. 3). Three very large lacustrine basins occupy this vast depression (ca. 190,000 km²) which has been filling up since the Tertiary (Lavenu, 1992). These basins comprise Lake Titicaca in the north (8563 km²), Lake Poopó in the centre (2530 km²) and the salars of Coipasa and Uyuni lying farther to the south (12,000 km²). Titicaca is a deep freshwater lake (max. 285 m), while Lake Poopó is a very shallow body of water showing meso- or polyhaline conditions (the lake dried up completely in 1995), and the salars of Coipasa and Uyuni are seasonal hypersaline lakes. This distribution according to latitude reflects the pluviometric gradient that exists between the northern and southern parts of the zone. The mean annual precipitation varies from more than 800 mm around Lake Titicaca to less than 200 mm at the southern end of the basin. The mean evaporation rate over the entire zone is estimated at more than 1500 mm yr⁻¹ (Roche et al., 1992a, b; Grosjean, 1994). This climatic gradient is the consequence of a shift in latitude of the meteorological equator (Inter-Tropical Convergence Zone or ITCZ) which reaches the central Andes during summer in the Southern Hemisphere, between the months of November and April.

The easterly winds and the abnormally high temperatures characteristic of the Altiplano during the summer

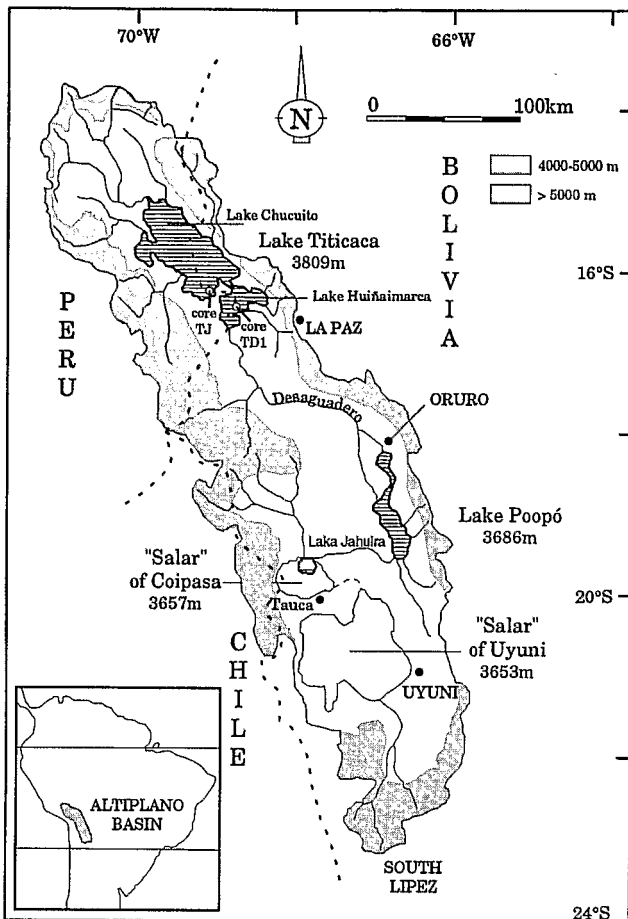


Fig. 3. Map of area showing the main lacustrine basins from the Altiplano.

3. Methods

In order to elucidate the paleohydrological history of the lacustrine basins of the Altiplano during the past 40,000 yr (Late Pleistocene and Holocene), two main types of record were studied:

- (1) sediment cores taken in different parts of the region;
- (2) lacustrine deposits visible at the present-day in sub-aerial outcrops.

The most complete records were obtained from Lake Titicaca, where 14 cores were sampled using a Mackereth corer (Barton and Burden, 1979). Materials from six of the cores were dated either by accelerator or conventional radiocarbon methods (Mourguiart et al., 1997). Core TD1 provided the fullest record, extending back to 25,000 yr BP (Wirrmann et al., 1992). It has a total length of 537.5 cm and was taken at a water depth of 19 m in the centre of the Taraco basin in the western part of Lake Titicaca (lat. 16°20'00" S, long. 68°57'45" W; Fig. 3). This core has been the object of a multidisciplinary investigation including sedimentological analysis (Wirrmann and de Oliveira Almeida, 1987) as well as studies of the palynological (Ybert, 1992) and ostracod contents (Mourguiart and Roux, 1990; Mourguiart et al., 1992; Wirrmann and Mourguiart, 1995). The above studies have made it possible to reconstruct the paleohydrology of this sub-basin of Lake Titicaca (Mourguiart et al., 1992). In broad terms, the different sedimentary facies within Lake Titicaca are distributed as a function of the coastal dynamics, biological activity and water depth (Rodrigo and Wirrmann, 1992). In addition, the pollen and spores show a distribution that depends not only on water depth (and the distance away from the banks) but also on temperature insofar as this is an expression of the elevation-related lapse rate (Ybert, 1988, 1992; Mourguiart et al., 1995b). In Lake Titicaca, the distribution of ostracods — which are essentially benthic crustaceans — is dependent on the nature of the substrate, the hydrodynamics, and the distribution of macrophyte water plant communities, as well as the dissolved oxygen concentration at the sediment/water interface, all these factors being closely correlated with water depth (Mourguiart and Carbonel, 1994). In this way, the sedimentological and palynological observations have enabled a qualitative or even semi-quantitative reconstruction of the fluctuations in water level of Lake Titicaca and the variations in atmospheric temperature over the 25,000 yr (Wirrmann et al., 1992; Ybert, 1992). The ostracod data serve as a basis for the quantitative reconstruction of variations in the water bodies, but only for the period after about 8000 yr BP, a time that corresponds to the first appearance of ostracods in most of the lake sediment cores (Mourguiart and Roux, 1990; Mourguiart et al., 1992, 1995a, b, 1997; Wirrmann and Mourguiart, 1995).

months are concurrent meteorological phenomena that can account for the frequent incursions of humid air coming from the Amazonian basin (Aravena et al., 1989; Grootes, 1993). These conditions bring about stormy precipitation that becomes more and more sporadic with increasing distance away from the northern part of the basin. In contrast, during the dry season (winter in the Southern Hemisphere) the ITCZ moves towards the north of the South American continent. The shifts in westerly winds allow only some sporadic penetration of humid Amazonian air leading to isolated rainfall of weak intensity (Taljaard, 1972; Vuille and Ammann, 1997).

More locally, the presence of peaks higher than 6000 m in the Cordillera Oriental and the orientation of certain valleys give rise to a föhn wind phenomenon that perturbs the rainfall regime of the adjoining region.

In the past, the major hydrological system of Altiplano underwent considerable variations in which climate played an essential role.

Although other core samples have been analysed in parallel with core TDI, the scope of these studies is not as comprehensive. Moreover, small lacustrine terraces occur around the rim of Lake Titicaca, providing evidence of ancient high stands in lake-level. Material from some of these terraces has been dated by the radiocarbon method.

In general, another type of approach has been adopted in the study of the southern basins. Traces of ancient lake shorelines are found for tens of km around the present-day basins, associated with calcareous crusts, sometimes remarkably well developed, that form a sort of barrier reef (Rondeau, 1990; Rouchy et al., 1996). These different relict structures have been dated (Servant and Fontes, 1978; Bills et al., 1994; Argollo and Mourguiart, 1995b, c; Servant et al., 1995) and mapped (Servant and Fontes, 1978; Wirrmann, unpublished data). Several stages have thus been revealed with different amplitudes and ages (Fig. 2). During the last two lacustrine phases (Minchín and Tauca), the central Altiplano was occupied by a vast lake (Servant and Fontes, 1978; Hastenrath and Kutzbach, 1985; Risacher, 1992; Bills et al., 1994; Wirrmann and Mourguiart, 1995). In drying up, this paleolake produced three distinct sub-basins: Poopó, Coipasa and Uyuni (Fig. 3). In order to avoid any possible ambiguity, we propose to call this lake POCOYU (Poopó-Coipasa-Uyuni) and to consider its relative variations in level through the course of time (Figs. 4 and 5).

Along with the geomorphological and geochronological work cited above, a number of core sections and outcrops have been studied (Wirrmann and Mourguiart, 1995; Sylvestre et al., 1996, 1997), although no precise dating is available. The longest of these sections (121 m) was obtained by coring in the salar of Uyuni, but unfortunately none of the material has been dated (Risacher, 1992).

4. Results

4.1. Stratigraphy

The age of cored and outcropping sedimentary material was determined by radiocarbon dating using a series of conventional or accelerator mass spectrometric (AMS) analyses (see Table 1). The dated material does not always have the same composition from one site to another or even within the same site, being chiefly made up of calcareous organic remains and bioclastic debris (molluscs, ostracods, characeans, stromatolites), as well as chemical precipitates (calcite and aragonite) and vegetal organic matter (algae and macrophyte fibres). This great diversity in the nature of the dated material hinders the correlation of core profiles, especially since the reservoir effect of a lacustrine system can be greatly different from

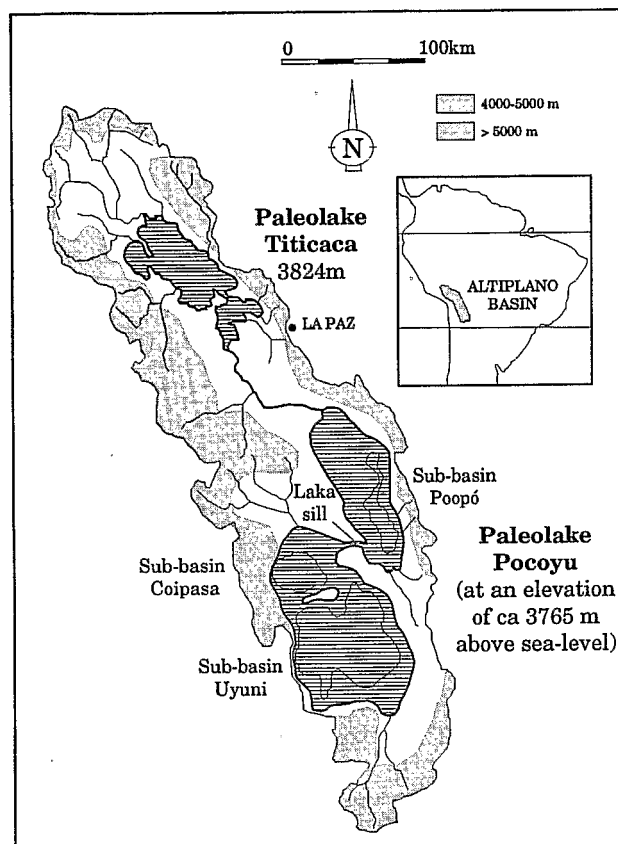


Fig. 4. Map showing the extension of Lake Pocoyu (after Wirrmann and Mourguiart, 1995).

one basin to another and can vary through the course of time within the same basin.

In the case of Lake Titicaca, different authors interested in this problem have dated lacustrine carbonates (molluscs, ostracods, characeans) and vegetal fibres (subaerial macrophytes) which occur within the same depth interval in the core. According to different studies, it would appear necessary to consider a reservoir effect of 250 yr (Abbott et al., 1997a) or 400 yr (Curtis et al., 1993). Other data on Lake Titicaca (Wirrmann, unpublished data) indicate an augmentation of the order of 300 yr for the carbonate ages with respect to the ages determined from organic matter, which is in good agreement with certain other sources. As these age estimates were obtained on relatively recent samples, it is possible that such corrections are not applicable under different hydrological conditions (with low lake levels or, on the other hand, very high lake levels). Therefore, we do not take account of these age corrections in the present study.

In the southern basins (Lake Pocoyu; Fig. 4), the absence of organic-rich deposits makes it impossible to apply the same approach as used for Lake Titicaca. Thus, it is necessary to interpret the obtained results with great prudence and a more detailed discussion would appear

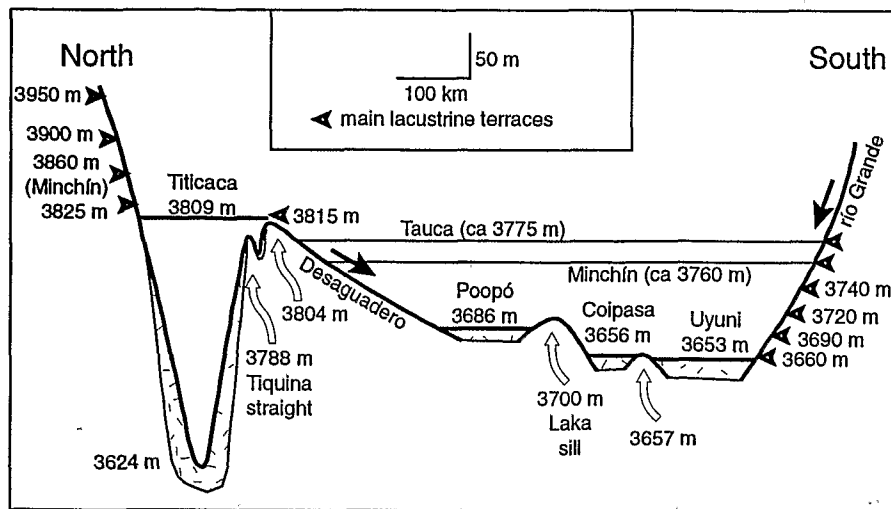


Fig. 5. Topographic cross-sections showing physiographic relationships between altiplanean lakes and salars (after Risacher, 1992).

indispensable. Two main processes lead to the probable errors in the ^{14}C ages obtained on carbonates from the Altiplano paleolakes. The low initial $^{14}\text{C}/\text{C}$ ratios in the lake waters is due to the input of old carbonate material into the system ("reservoir effect") coupled with the introduction of modern carbon into previously precipitated carbonates.

In a recent study, Servant et al. (1995) allude to this problem in stating that "*L'extension négligeable des formations géologiques calcaires dans le bassin versant (des salars de Coipasa et Uyuni) permet d'admettre qu'il n'y a pas eu vieillissement apparent des sédiments lacustres par incorporation de carbone inorganique ancien*" (the negligible areal extent of calcareous geological formations in the drainage basins (of the salars of Coipasa and Uyuni) allows us to assume that there has been no apparent ageing of lake sediments by incorporation of ancient inorganic carbon). On the contrary, Grosjean (1994) provides evidence for considerable reservoir effects of the order of 8000 yr for carbonates and 2000 yr for organic matter derived from subaquatic macrophytes from a small lacustrine basin, Laguna Lejía, northern Chile. Although the context of the material studied by Grosjean (1994) is clearly different from the Bolivian Altiplano, the area concerned is nevertheless very close geographically. Between these two extreme cases (Lake Pocoyu from Servant et al. (1995) and Laguna Lejía from Grosjean (1994)), it is difficult to define accurately which situation really applies to the salars of the central Bolivian Altiplano.

Fig. 6 shows a series of "snapshots" illustrating three distinct hydrological states, thus enabling a better understanding of the sources of error on the carbonate ages. Let us consider an arbitrary initial state, corresponding to an arid phase, in which Lake Pocoyu is dried up (state 1). The basin floor is covered with a saline crust, while the

bioherms and stromatolites are subject to subaerial erosion. Following a climatic change (return of more humid conditions), runoff waters wash out the ancient carbon by leaching of the calcrete produced during previous lacustrine phases (state 2). The waters of Lake Pocoyu continue to rise, eventually submerging the algal formations (state 3). A new generation of algal structures starts to grow on top of the previous deposits, and Lake Pocoyu finally develops into a very large lake of considerable volume (Figs. 4 and 5).

In this region, which has been characterised by sparse vegetation for several tens of thousands of years (Graf, 1992, 1994; Schuler et al., 1995), the winds are often very strong. Since the lake waters in the nearshore zone were certainly well mixed, the CO_2 dissolved in the water was probably in equilibrium with atmospheric CO_2 . When the level of Lake Pocoyu fell once more, vast areas of spectacularly developed bioherms were left exposed. The sparse precipitation from infrequent summer storms that still characterises this region would have brought about the entrainment of ancient organic carbon into the nearshore waters of the lake. In view of the total volume of the water body, a non-negligible proportion of ancient carbon was introduced into the system. On the other hand, the crusts which had become exposed to the air would be contaminated with modern atmospheric CO_2 since the extremely porous texture of many of the algal crusts favours this type of exchange process. In summary, there would be an apparent rejuvenation of the deposits upstream and ageing towards the basin floor. In order to minimise the rejuvenation problem, only the freshest and most compact parts of the bioherms were dated. By contrast, it is more difficult to assess the effects of apparent ageing. Some lines of evidence suggest that the ages are at least correct for the high lake-level phases. In the first place, dating carried out on samples sometimes

Table 1

Radiometric dates from Lake Titicaca cores and altiplanean outcrops. The radiocarbon dates were calibrated using the Calib 3.0 program (Stuiver and Reimer, 1993)

¹⁴ C ages	Calendar ages	U/Th ages	Lab. number	Main basin	Approx. altitude (m)	Reference
4165 ± 75	4832–4561		Beta 32216	Titicaca	3809	Wirrmann and Mourguiart (1995)
8100 ± 280	8550–9424		Orsay	Titicaca	3808	Wirrmann and Mourguiart (1995)
10,450 ± 160	12,552–12,115		Orsay	Pocoyu	3660	Servant et al. (1995)
10,580 ± 50	12,589–12,420		OB DY 1055	Pocoyu	3657	Servant et al. (1995)
10,760 ± 50	12,762–12,615		OB DY 927	Pocoyu	3657	Servant et al. (1995)
10,810 ± 50	12,809–12,664		OB DY 1046	Pocoyu	3660	Servant et al. (1995)
10,830 ± 180	12,934–12,572		Orsay	Pocoyu	3660	Servant and Fontes (1978)
10,960 ± 50	12,984–12,809		OB DY 1057	Pocoyu	3660	Servant et al. (1995)
11,020 ± 60	13,012–12,860		OB DY 1045	Pocoyu	3660	Servant et al. (1995)
11,390 ± 50	13,390–13,222		OB DY 925	Pocoyu	3660	Servant et al. (1995)
11,730 ± 350	14,107–13,284		Orsay	Pocoyu	3695	Servant and Fontes (1978)
11,860 ± 60	13,958–13,702		OB DY 1035	Pocoyu	360	Servant et al. (1995)
11,920 ± 40	14,020–13,779		OB DY 911	Pocoyu	3700	Servant et al. (1995)
11,980 ± 50	14,101–13,843		OB DY 1290	Pocoyu	3657	Servant et al. (1995)
12,090 ± 40	14,237–13,976		OB DY 914	Pocoyu	3700	Servant et al. (1995)
12,100 ± 370	14,628–13,664		OB DY 364	Pocoyu	3745	Servant et al. (1995)
12,210 ± 270	14,650–13,902		OB DY 257	Pocoyu	3720	Servant et al. (1995)
12,270 ± 50	14,489–14,189		OB DY 1214	Pocoyu	3745	Servant et al. (1995)
12,290 ± 50	14,517–14,214		OB DY 1049	Pocoyu	3740	Servant et al. (1995)
12,380 ± 50	14,648–14,327		OB DY 919	Pocoyu	3690	Servant et al. (1995)
12,390 ± 50	14,663–14,339		OB DY 918	Pocoyu	3690	Servant et al. (1995)
12,490 ± 80	14,830–14,449		OB DY 700	Pocoyu	3690	Servant et al. (1995)
12,560 ± 160	15,027–14,463		OB DY 929	Pocoyu	3635	Servant et al. (1995)
12,790 ± 120	15,334–14,847		Orsay	Pocoyu	3720	Servant and Fontes, 1978
12,830 ± 80	15,348–14,959		OB DY 681	Pocoyu	3690	Servant et al. (1995)
12,870 ± 50	15,380–15,056		OB DY 997	Pocoyu	3657	Servant et al. (1995)
12,880 ± 70	15,413–15,055		OB DY 1025	Pocoyu	3690	Servant et al. (1995)
12,930 ± 50	15,470–15,160		OB DY 923	Pocoyu	3735	Servant et al. (1995)
12,960 ± 60	15,524–15,202		Beta 73080	Pocoyu	3660	Servant et al. (1995)
12,990 ± 40	15,551–15,270		OB DY 916	Pocoyu	3690	Rouchy et al. (1996)
		15,070–16,200		Pocoyu	3750–3760	Servant et al. (1995)
13,030 ± 80	15,649–15,301		OB DY 926	Pocoyu	3735	Servant et al. (1995)
13,130 ± 60	15,777–15,493		Beta 73081	Pocoyu	3660	Wirrmann and Mourguiart (1995)
13,180 ± 130	15,928–15,486		Beta 38775	Titicaca	3808	Servant et al. (1995)
13,350 ± 50	16,318–16,087		OB DY 879	Pocoyu	3690	Servant et al. (1995)
13,620 ± 60	16,441–16,198		OB DY 1007	Pocoyu	3690	Causse et al. (1995)
		16,650 ± 300		Pocoyu	?	Bills et al. (1994)
13,790 ± 70	16,661–16,410		—	Pocoyu	3772–3784	Servant et al. (1995)
15,430 ± 80	18,458–18,231		Beta 73088	Pocoyu	3657	Wirrmann and Mourguiart (1995)
18,185 ± 180	21,994–21,436		Beta 32217	Titicaca	3807	Wirrmann and Mourguiart, 1995
19,090 ± 200			Beta 32218	Titicaca	3807	Wirrmann and Mourguiart (1995)
19,625 ± 220			Beta 32219	Titicaca	3807	Wirrmann and Mourguiart (1995)
21,000 ± 260			Beta 32220	Titicaca	3806	Mourguiart et al. (1997)
24,040 ± 100			OB DY 1475	Titicaca	3860	Wirrmann and Mourguiart (1995)
27,500 ± 800			Orsay 402 MS	Pocoyu	3697	Mourguiart et al. (1997)
28,230 ± 100			OB DY 1459	Titicaca	3860	Wirrmann and Mourguiart (1995)
28,900 ± 700			UQ 1619	Pocoyu	3735	Mourguiart et al. (1997)
30,510 ± 80			OB DY 943	Titicaca	3860	Wirrmann and Mourguiart (1995)
33,700 ± 1000			UQ 1611	Pocoyu	3735	Wirrmann and Mourguiart (1995)
36,820 ± 1200			Beta 38781	Pocoyu	3696	Wirrmann and Mourguiart (1995)
37,060 ± 1120			Beta 38780	Pocoyu	3697	Wirrmann and Mourguiart (1995)

separated by more than 100 km yielded ages that are consistent among themselves. Moreover, a series of U/Th radiometric analyses were performed on certain samples. The first results obtained from untreated samples (Rondeau, 1990) clearly show the existence of problems

due to rejuvenation and ageing (Fig. 7). Subsequently, U/Th dating has been carried out with a method requiring very small amounts of material (Ghaleb et al., 1991; Causse et al., 1995). For the Tauca phase of Lake Pocoyu, as well as for the highest lake levels, there is a large degree

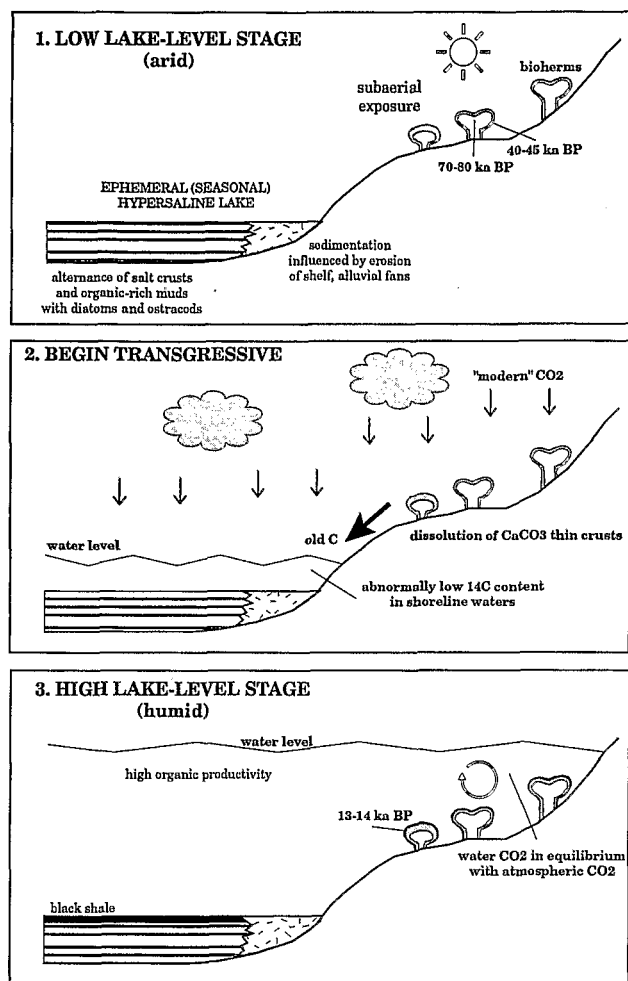


Fig. 6. Schematic model showing the main processes in the ¹⁴C system for Lake Pocoyu according to prevailing climate and lake level.

of consistency between the ¹⁴C calendar ages and the U/Th ages (Table 1). The dates obtained for the low lake-level stands, on the other hand, should be interpreted with great caution, especially in the case of isolated ages.

4.2. Lake Titicaca

Of all the studied material in this basin, the greatest number of analyses were provided by core TDI. The age profile of the sediment core was determined from seven radiometric dates obtained by ¹⁴C (Wirrmann and Mourguiart, 1995; Table 1). Between two dated horizons, the ages were calculated by linear interpolation, with the exception of the lowermost and uppermost layers where extrapolation was used from adjacent intervals (Mourguiart et al., 1992). Three sedimentary breaks can be recognised (Mourguiart et al., 1995c). The most important of these, between ca. 18,000 and ca. 15,000 yr BP, probably corresponds to a phase of emergence associated

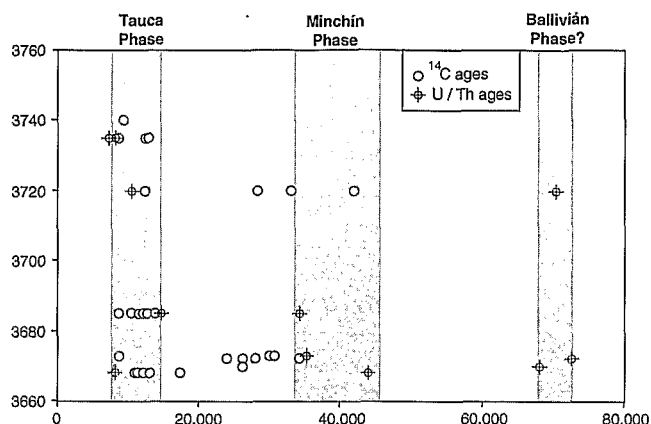


Fig. 7. Radiocarbon and U/Th ages versus site elevations from Lake Pocoyu basin (data from Rondeau, 1990).

(or not) with erosive processes. A later break occurs at around 8000 yr BP, while the most recent is observed at the top of the core (last few hundred years). Two types of essential information are obtained from sedimentological and palynological studies (Fig. 8) as well as from analysis of the benthic microfauna (ostracod assemblages), i.e., the fluctuations in water depth and an estimate of ambient temperature at the time of deposition (Fig. 9).

The lower part of the core (200–540 cm; ca. 18,000–25,000 yr BP) is characterised by low lake levels (height of Lake Huiñaimarca comprised between 3790 and 3795 m) with temperatures generally 3.5–4°C lower than present-day mean values, apart from the 300–360 cm interval (ca. 19,000–20,000 yr BP) which is marked by intense cooling of the order of 6°C. Following a major hiatus, the late glacial (ca. 15,000/14,000 to ca. 10,500 yr BP) is characterised by a distinct warming and a well-marked rise in water levels.

The beginning of the Holocene is marked by an arid phase which led to complete drying up of the lake at the core sampling site at around 8000 yr BP (core depth: 155 cm). For most of the time, temperatures during the Holocene were comparable to present-day values. It has been possible to reconstruct the water levels by applying an ostracod versus bathymetry transfer function, thus providing the results which are published extensively elsewhere (Mourguiart and Roux, 1990; Mourguiart et al., 1992, 1995a, b, 1997; Wirrmann and Mourguiart, 1995). From a synthesis of these data, the middle Holocene (from ca. 8000 to ca. 3900 yr BP) appears to be characterised by low lake levels. An abrupt rise in the level of the water bodies followed this dry period. Subsequently, and probably up until the Little Ice Age, the lake levels remain generally stable at a few metres below the present-day elevation, with the exception of some brief dry episodes, the most important of which occurred around 2300 yr BP. Even though a record of the last few hundred years is missing in core TDI, the rare but

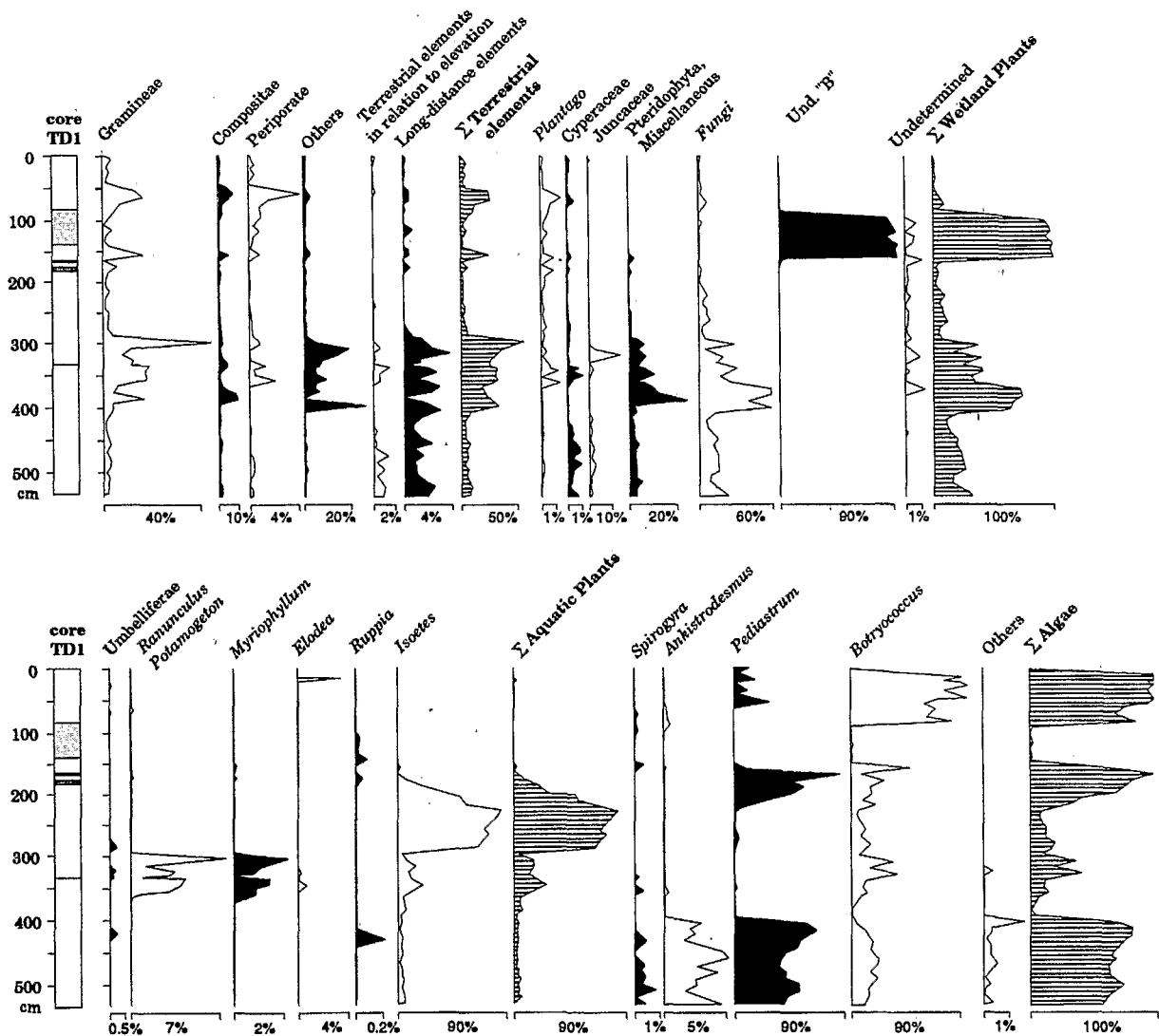


Fig. 8. Summary pollen percentage diagram for core TD1, Lake Titicaca (from Mourguiart et al., 1995c).

existing historical data allow a partial filling of the gap suggesting that Lake Titicaca reached exceptionally high levels during the 16th and 17th centuries (Wirrmann and de Oliveira Almeida, 1987).

Other cores have also provided interesting information on the paleohydrology of Lake Titicaca during the Holocene. Detailed results and discussion are presented elsewhere in a series of articles by Mourguiart et al. (1992, 1995a, b, 1997). The main curve showing variations in the level of Lake Chucuito is reported in Fig. 11.

Furthermore, three ^{14}C ages obtained from ancient lake terraces to the south of Lake Huinaimarca (area around Tiwanaku and Catari) have made it possible to establish the minimum elevation of Lake Titicaca during the Minchín phase (Table 1; Mourguiart et al., 1997).

4.3. Lake Pocoyu

About 50 radiometric dating results obtained by ^{14}C and U/Th have led to a partial reconstruction of the hydrological history of this vast paleolake (Table 1). Fig. 10 shows a plot of the ages obtained solely for the Taucu phase as a function of the approximate height of the sampling site in the field. Since the datings were carried out mostly on the remains of aquatic organisms, any point on this constructed curve corresponds to the minimum level reached by the water body at a given moment in time. The Taucu lacustrine phase appears to have had a far more complex development than that assumed by Servant and Fontes (1978). Moreover, the maximum levels attained by Lake Pocoyu at the culmination of the Taucu phase (Fig. 10) are far in excess of the estimates given by the last-mentioned authors

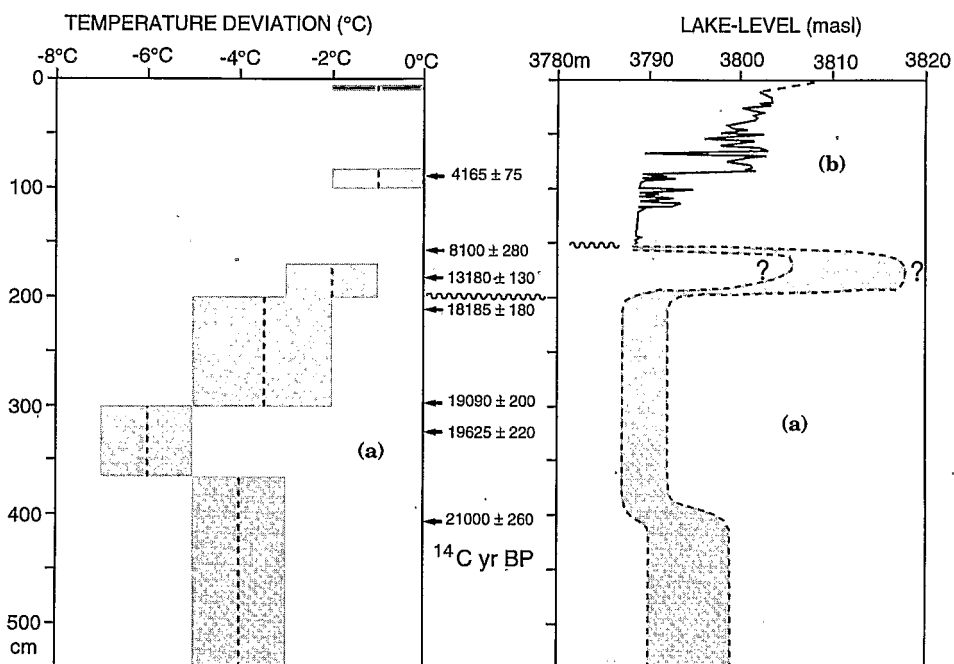


Fig. 9. Temperature and water depth variations reconstructed from (a) pollen and (b) ostracod studies (core TDI, Lake Titicaca; after Argollo and Mourguiart, 1995b, c).

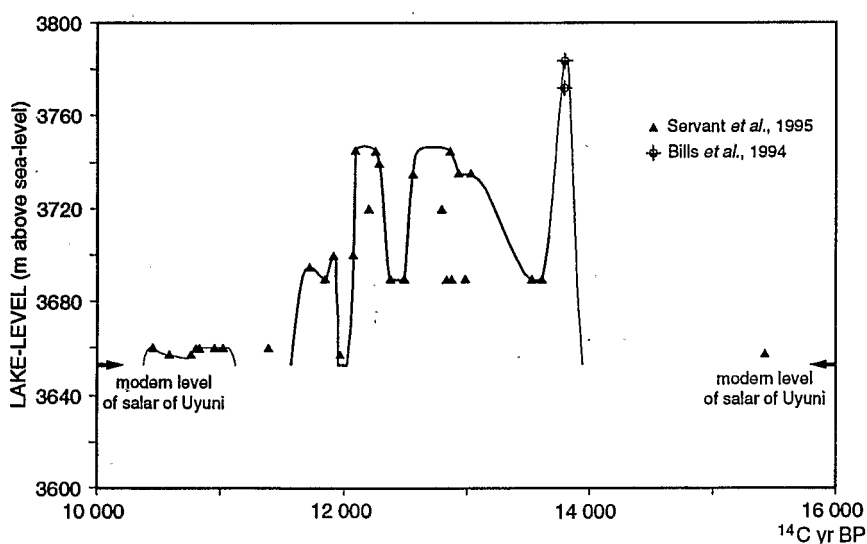


Fig. 10. Radiocarbon ages versus site elevations from Lake Pocoyu basin (data from Bills et al., 1994; Servant et al., 1995). The curve represents the minimum elevation reached by Lake Pocoyu.

(~ 3775 m given by Bills et al. (1994) versus ~ 3720 m from Servant and Fontes (1978), or ~ 3740 m from Servant et al. (1995)).

To summarise, these data (see Table 1 and Figs. 7 and 10) support the existence of several phases of high lake level during the last 100,000 yr. As regards the two most recent and best known phases (Minchín and Tauca), the geochronological framework can now be established

with satisfactory precision, provided that the problems inherent in dating carbonate material are not a source of excessive errors (cf. discussion above). The ideal solution would be to obtain a series of radiometric ages on terrestrial organic material. Otherwise, very little is known about the interlacustrine phases and the few core profiles carried out on the basin floors have not been well dated (e.g. see Risacher, 1992).

5. Discussion

Several remarks need to be made before discussing the reconstructions established for the two studied lacustrine basins (Lake Titicaca in the north and Lake Pocoyu in the south). As a matter of fact, the direct comparison of data is problematic due to several factors. First of all, in the case of Lake Huiñaimarca the favoured approach involved the coring of deep zones, thus enabling particularly the precise reconstruction of low lake level stands. By contrast, in the case of Pocoyu the emphasis was placed on the reconstruction of high lake levels by the dating of subaerial deposits. Furthermore, dating was carried out on a range of different materials since results obtained in this way are expected to facilitate correlations between lacustrine basins. However, it cannot be totally ruled out that the lakes were subject to variable reservoir effects through the course of time.

Taking the above restrictions into account, it is nevertheless possible to draw some general conclusions which are presented here as a direct comparison between the two lacustrine systems (Fig. 11). We show for the first time, on the basis of dating carried out in both major lacustrine basins of the Altiplano, that lake levels were clearly much higher during the Minchín phase than at the present-day. This conclusion applies equally well in the north as in the south, and covers the period before ca. 30,000 ^{14}C yr BP (ca. 40,000 U/Th yr BP; Rondeau, 1990; Causse et al., 1995). This humid phase is well recorded in other regions of South American lowlands (Absy et al., 1991; Latrubesse and Franzinelli, 1995; Ledru et al., 1996; Behling and Lichte, 1997).

After this, both altiplanean bodies of water underwent a regressive phase. Although data are lacking in the south, the gradual drying up of Lake Huinaimarca is well recorded in the TD1 core section. Thus, conditions during the Last Glacial Maximum would appear on the whole as dry and cold. This fact is already well recognised in other regions of South America (Markgraf, 1989, 1993; Latrubesse and Ramonell, 1994; Van der Hammen and Absy, 1994), even though at the great majority of sites this period corresponds to sedimentary breaks (Ledru, 1993; Sifeddine et al., 1994a, b; Latrubesse and Franzinelli, 1995; Ledru et al., 1998) and important eolian activity (Iriondo and Latrubesse, 1994). In the tropical lowlands of South America, it appears that only one site has registered the period corresponding to the LGM, Laguna Pata near the geographical equator (Colinvaux et al., 1996). The main conclusions of these authors, based on palynological studies, suggest that this area does not experience important hydrological changes during the LGM but only much cooler conditions than today. Recently, the Colinvaux point of view has been challenged (Ledru et al., 1998). In any way, it is possible that the humid conditions registered at Laguna Pata are synchronous with episodes of relative warming, occurring

during the cold LGM interval, deduced from high-latitude climatic records of northern hemisphere (Bond et al., 1993; Dansgaard et al., 1993) and from high-altitude tropical data (Helmens et al., 1996).

In South America, the late glacial is characterised by an overall rapid warming (Markgraf, 1989, 1993), and Lake Titicaca is not excluded from this general pattern. Even though it is not possible to determine the maximum level attained by the lake, the high abundance of algal material (Mourguiart et al., 1995c; Fig. 8) as well as the low sedimentation rates, and their lithology, characteristic of deep zones (Pourchet et al., 1994), are factors suggesting that Lake Titicaca could have attained or even risen above its present-day level during the Tauca phase (ca. 14,000–10,500 ^{14}C yr BP). Moreover, studies carried out in adjoining regions lead to the same conclusions (Messerli et al., 1993; Seltzer, 1994; Clayton and Clapperton, 1995; Grosjean et al., 1995a, b; Juvigné et al., 1997). Otherwise, Lake Pocoyu reached its greatest development at this time.

The beginning of the Holocene corresponds to a major lowering in the level of Lake Titicaca, which was subsequently divided into sub-basins (cf. Fig. 11; Mourguiart et al., 1995a, b). In contrast to climatic conditions on the Altiplano during the preceding period, the northern part of Chile does not appear to have undergone the same evolution. The regional climate here remained relatively humid (Messerli et al., 1993; Grosjean, 1994; Grosjean et al., 1995a, b). However, the Andean glaciers showed a very rapid retreat at this time (Seltzer, 1992; Clapperton, 1993; Francou et al., 1995; Seltzer et al., 1995). This paradox has been discussed in detail in a recent study (Martin et al., 1997). According to these authors, during the period between 10,500 and 8000 ^{14}C yr BP (12,400–8800 cal yr BP) the ITCZ was located on average farther north than its present-day position, thus producing a deficit in summer rainfall on the Altiplano, but, on the contrary, winter precipitation increased.

An important change then took place associated with a considerable rise in the level of Lake Titicaca. This event is possibly of global significance (Alley et al., 1997; Stager and Mayewski, 1997; de Vernal et al., 1997).

The middle Holocene (ca. 8000–3900 ^{14}C yr BP) is generally characterised by low lake levels that are nevertheless associated with large fluctuations of short duration. Even though there are no dated core profiles from the southern basins of the Altiplano, Risacher and Fritz (1991, 1992) and Risacher (1992) have used geochemical data to speculate on the existence of such arid phases. This long dry phase is well recognised elsewhere (Markgraf, 1989, 1993; Valero-Garcés et al., 1996; Abbott et al., 1997b; Grosjean et al., 1997a, b). Martin et al. (1993) would interpret this period rather as climatically unstable, with generally humid episodes alternating with

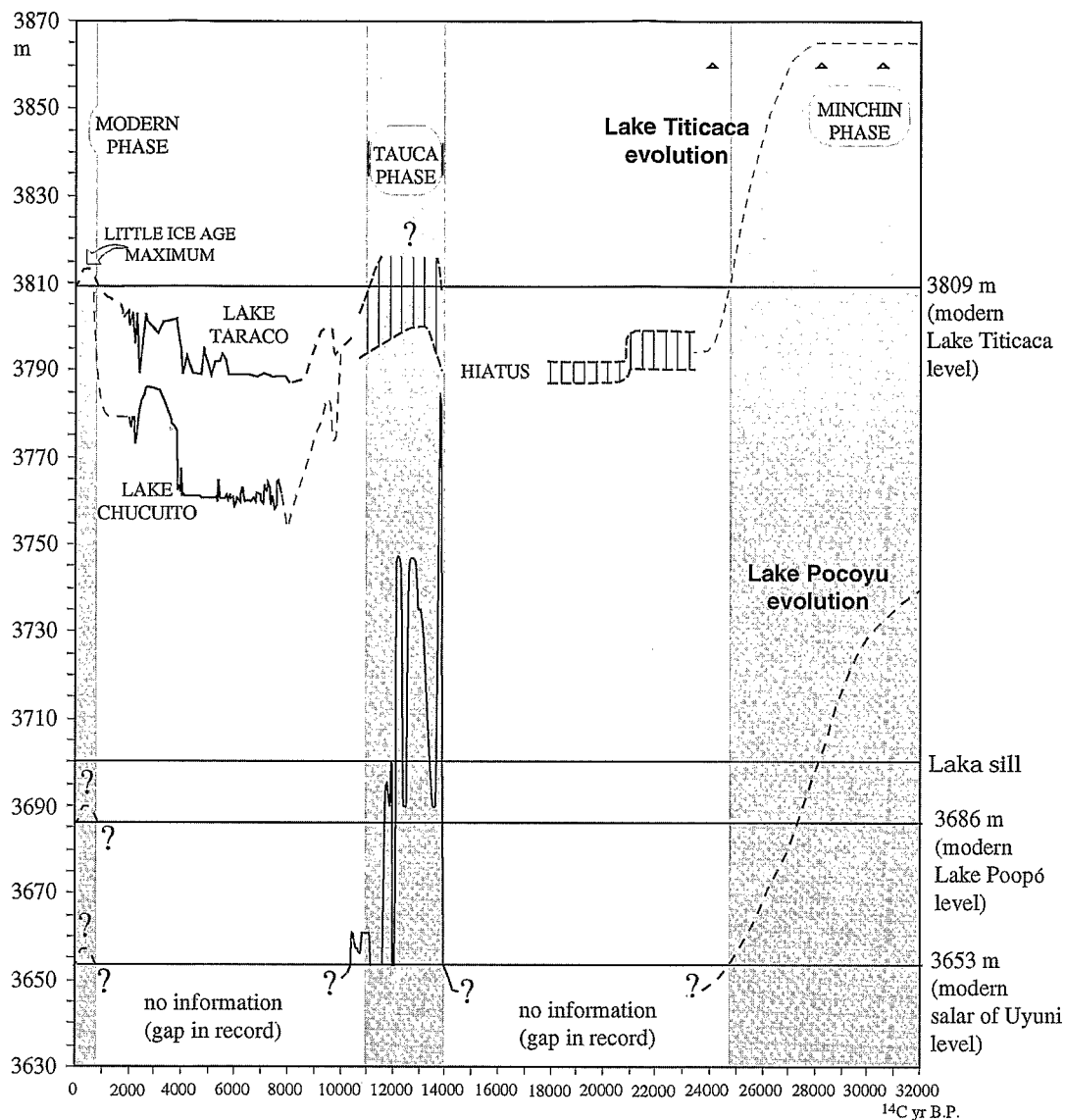


Fig. 11. Lake Titicaca and Lake Pocoyu level fluctuations during the last 32,000 yr compiled from references discussed in the text. Triangles represent dated samples from lacustrine terraces; vertical lines represent results from the pollen analysis; the full line represents results from the transfer function on ostracods (cores TD1 and TJ from lakes Taraco-Guaqui and Chucuito, respectively; standard error of 0.81 and 2 m approximately); the intermittent line represents historical data. High lake levels are highlighted with shaded bands.

shorter dry episodes. In the case of the Bolivian Altiplano, at least some of these arid phases would correspond to climatic disturbances of the same order as those observed nowadays during strong El Niño events.

A further change of likely global significance (Kelts, 1997) took place at around 3900 ¹⁴C yr BP (Fig. 11), possibly corresponding to the onset of present-day conditions. The last recorded major event occurred during historical times and would appear synchronous with the Little Ice Age. There is a full record of this event in a glacier located to the north of Lake Titicaca (Thompson et al., 1985, 1986).

6. Summary and conclusion

The multidisciplinary approach used in this study makes it possible to reveal some important changes affecting the landscape of lacustrine basins on the Altiplano during the course of the last 40,000 yr. Three phases of high lake level (Minchín, Tauca and current situation) and two arid phases of long duration (during the Last Glacial Maximum as well as a major part of the Holocene between ca. 10,500 and 3900 ¹⁴C yr BP) represent the essential features characterising the paleoenvironments in this part of the Andes. In fact, it now

remains to explain the climatic mechanisms at the origin of these major upheavals, particularly during the Pleistocene as the Holocene is more clearly understood (Markgraf, 1989; Martin et al., 1993, 1997; Grosjean et al., 1995a, b, 1997a, b; Abbott et al., 1997b). The periods of high lake levels are interpreted in terms of strengthening of summer precipitation in southern hemisphere, with the ITCZ occupying a southernmost position. The high-amplitude oscillations detected during the Tauca phase could suggest a possible interaction with the North Atlantic where a similar pattern has been evidenced (Bond et al., 1993; Dansgaard et al., 1993). A same conclusion has been pointed out by Hughen et al. (1996) from the Cariaco basin located at lat. 9° N off the Venezuelan coast. During the LGM, aridity and cooling seem to characterise tropical environments. It has been suggested that polar air advections from Arctic regions and Antarctica could have played a major rôle at that time (Leroux, 1993; Servant et al., 1993; Latrubesse and Ramonell, 1994; Sayago, 1995; Bradbury, 1997) restricting the ITCZ latitudinal displacement. Our data on Bolivian lakes confirm this hypothesis. Low lake levels are possibly associated with increased winter precipitation and reduced summer ones, especially during LGM and early Holocene times (see also Martin et al., 1997). Therefore, it appears that some of disturbances revealed by the present study correspond to global changes in the climatic system.

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