Holocene hydrological changes in the Bolivian Andes from wetland deposits in a glacial valley.

Simone Servant-Vildary [1], Naima Miskane [1], Michel Servant [2]
[1]IRD-MNHN, Laboratoire de Géologie, Muséum National d'Histoire Naturelle, 43 Rue Buffon , 75005 Paris, [2] IRD, 32 Rue Henri Varagnat, 93143 Bondy, France
mone@mnhn.fr

Introduction

In the northern Bolivian Andes, the Holocene climate is known from three different types of data: 1) In the Lake Titicaca, estimated variations in water level reveal P-E changes on the regional scale (Cross *et al*., 2000; Mourguiart *et al*., 1998); 2) In the non glacial valleys, the variations of the river regime as reflected from the fluvial deposits give information on the intensity of individual precipitation events and their distribution throughout the year (Servant and Fontes, 1984); 3) In the glacial valleys, few data are provided from the study of moraines and glacier-fed lake deposits. They are too rare to clarify the combined effects on the past hydrology of P-E, the distribution of precipitation throughout the year, and the glacier melt water inputs. The traces of the Holocene glaciers were largely obliterated by the neoglacial readvance which occurred in the last centuries (Gouze *et al*., 1986; Heine, 1996). Only one record is available on the water level variations of the glacier lakes (Abbott *et al*., 1997). We propose here a reconstruction of the Holocene water levels from wetland deposits in the valley of Hichu Kkota (16°10' S, 68°22' W).

Study site

In this valley, the characteristics of the aquatic environments are described from the upper to the lower part: up to 4700 m, the wetlands (*bofedales*) are composed of Juncaceae cushions and very shallow canals with running water, directly related to the glacier melt water; from 4700 m to 4310 m, three deep glacier-fed lakes at different elevations are connected by a main stream along which wetlands have developed; at 4300 m, the valley is wide and is occupied by a shallow pond (called Hichu Kkota) with several small islands, covered by a vegetation of Poaceae ; below 4300 m, the soils are colonized by a continuous vegetation cover (humid meadow) with a pellicular running water surface (*vegas*). Two Holocene records were studied. W (Wila Llojeta) is located at 4800m in elevation. The Holocene deposits are overlain by glacial deposits, with interbedded reworked peats dated 220 ^{14}C yr BP. The core IC1 (4300 m in elevation) was collected near the center of the Hichu Kkota pond, on a small island. In addition, a 10 m core KK, located on the north-eastern border of the lake Khara Kkota at ~4310 m in elevation, at 1m above the natural outlet, provides some data about the Holocene water level of this lake (Servant-Vildary and Roux, 1990).

Methods

Modern reference

To aid the interpretation of the fossil diatom flora, we look for modern analogs in the same valley. Surface sediments samples were collected on several transects at different elevations in a large range of microhabitat types (Miskane, 1997; Servant-Vildary, 1986). The wetlands contain two main groups of diatoms: (1) the aerophilous species which are dominant in the very shallow habitats, humid meadows with pellicular superficial running water, sensitive to short episodic dryness; (2) the tychoplanktonic, benthic, and epiphytic diatoms which are dominant in the permanent open-water bodies, small deep holes, and/or deep canals. The complexity of the microhabitats on the meter scale gives way to a spatial heterogeneity of the diatom flora; overlapping microhabitats frequently give way to mixed diatom flora. In order to precisely relate the diatom flora to the water levels, both in the pond and in the peat bogs, we use a Correspondence Analysis (CA) on the modern assemblages. The first principal axis of inertia is ecologically easy to interpret: a cloud composed of modern samples collected in the permanent (high) water bodies is on the positive part of the axis. On the contrary, the cloud composed of samples collected in the ephemeral water bodies or in the humid soils is on the negative part. Intermediary samples are close to the origin of the axis. By crossing the modern and the fossil diatom data sets in a single analysis (the fossil data set as illustrative elements), the degree of proximity (coordinates) of the fossil samples to modern samples whose ecology is known characterize the fossil environments. The fossil assemblages located on the positive part of axis 1 are assumed to represent the high water level while the fossil assemblages located in the negative part are assumed to represent shallow environments (Figure 1).

Planktonic diatoms (e.g. *Cyclotella stelligera*) are lacking in the wetlands of the upper part of the valley, largely dominant in the deep glacier-fed lakes and are present (but rare) downstream in the wetlands located at the base of the valley. We assume that they are transported from the glacial lake (Laguna Khara Kkota) located upstream. These diatoms are used as an indicator of Laguna Khara Kkota overflowings.

Datings

In the W record, the chronological control is based on ten conventional radiocarbon ages which are internally coherent (Figure 1). In the IC1 core (Figure 1), eight AMS radiocarbon ages were performed. But the age at 55 cm is incoherent with the ages at 53 cm and 49 cm, consequently these three ages were eliminated. The chronological model was discussed in detail in Miskane, (1997). Between 0 cm and 40 cm, the model is based on an extrapolation of the sedimentation rate from 210 Pb ages at the top of the core. Between 40 cm and 80 cm, ages were extrapolated from the sedimentation rate estimated from three radiocarbon ages in the lowest part of the core.

Results

Five main paleohydrological phases are distinguished :

Phase 5: In the records W and IC1, this phase corresponds to a sedimentation gap. For W the wetland deposits, dated ~ 4400 yr BP at the base, overlay undated fluvio-glacial deposits. For IC1, the deposits, dated ~3800 yr BP at the base, overlay an unconformity with desiccation cracks. The KK core, even poorly dated shows, according to diatoms, that the lake level was below the present outlet at ~9 300 yr BP. A clear increased lake level occurred at the early Holocene and culminated at 9010 ± 75 yr BP, but we don’t know if it reached the altitude of the present outlet. Then, the lake dropped and remained low until approximately ~ 6100 yr BP. This drop should correspond to a very low level, evidenced by diatom assemblages from an undated core collected in the center of the lake, presently, under 40 m water depth (Pierre and Wirrmann, 1986). During this period, the KK site was occupied by a humid soil. Between ~6100 yr BP and ~4900 yr BP, the lake increased until ~ - 3 m below its present level and a wetland developed on the margin of the lake.

Phase 4 : A major positive hydrological event was marked in W by the settlement of a peat bog at ~ 4400 yr BP, and in IC1, the settlement of a pond slightly later, at ~ 3800 yr BP. In IC1, the presence of the planktonic *Cyclotella stelligera* (even rare) suggests that the settlement of the pond was driven by Lake Khara Kkota overflowings. Between ~3800 yr BP and ~2800 yr BP, the pond was not submitted to significant variations. During this period, the diatom assemblages of KK core show that the water level in Lake Khara Kkota was close to the altitude of the outlet. Between ~ 4400 yr BP and ~ 2700 yr BP, diatoms of W indicate a general trend of increasing water levels with superimposed secular variations. The assemblages are similar to the modern ones found in the Juncaceae peat bogs at the same altitude. This type of vegetation which does not support seasonal dryness, shows that water input was continuous throughout the year.

Phase 3 : Lower than previously water levels characterize the interval between ~ 2700 yr BP and ~ 1850 yr BP at both sites. However, in the lower part of the valley, the Hichu Kkota pond did not apparently dry up and was still fed by Lake Khara Kkota overflowings. In the upper part of the valley, strong water flow episodically occurred, sand and intercalated clay layers deposited. The few levels which contain diatoms indicate strong water flow. At the end of the phase, a short episode of higher water level is evidenced.

Phase 2 : At ~1850 yr BP, in IC1, the water level rose again and remained stable over a long period, until ~1700 AD, according to our chronological model. In the upper part of the valley, in W, the period between ~1850 yr BP and ~400 yr BP is characterized by the settlement of a humid meadow. Diatom assemblages are similar to those presently found in more or less humid soils covered by a continuous vegetation cover (*vegas*). Pellicular running water characterizes this type of environment.

Phase 1 : The last 400 years are not registered in the W record because a glacier readvance reached the site. In the lower part of the valley the water level of the pond drastically dropped between ~1700 AD and ~1800 AD. It is difficult to discriminate the cause of this drop. Is it due to a weaker water input from lakes located upstream or is it due to a stronger discharge downstream related to an altitudinal downshift of the outlet ?. A very low abundance of *Cyclotella* argues in favor of the first explanation. Between ~1800 AD and ~1920 AD, an increased water input from Lake Khara Kkota is suggested by increased abundance of *Cyclotella stelligera.* The water level increased but began to drop as early as ~1860 AD. The very recent period shows an increased water level which is probably due to the construction of a dam close to the outlet (1950 AD ?) according to oral information from the Indian people.

Discussion

Few studies on the hydrological changes were previously performed in the glacial valleys of the Lake Titicaca watershed. The only available record is located in Lake Taypi Chaca Kkota, 4 km east of Hichu Kkota (Abbott *et al*., 1997). Lower than present water levels, between 9300 yr BP and 2290 yr BP are interpreted as a consequence of the absence (or the weak extension) of the glaciers in the watershed, the seasonal variations were not buffered by melt water input. In the Lake Titicaca, the water level was lower than presently between 10 000 yr BP and 4000 yr BP and reached its present level only after ~1000 yr BP (Mourguiart *et al*., 1998) suggesting lower value of the regional P-E during the main part of the Holocene. However, fluctuations occurred during this period : a slight increase occurred at ~9000 yr BP (Ybert, 1992) and a strong increase between 4000 yr BP and 3500 yr BP (Mourguiart *et al*., 1998). This shows significant enhanced P-E. These events are not evidenced in the Taypi Chaca Kkota record. On the contrary, they are well-registered in our records respectively in the core KK and IC1 showing a clear response of the water balance in the glacial valley. However, the P-E changes cannot explain alone the variations evidenced in this valley. The rise of Lake Titicaca occurred ~2000 years after the elevation of Lake Khara Kkota and at least ~ 400 years after the settlement of the Juncacae peat-bog in W. The drastic drop in P-E evidenced in Lake Titicaca at ~ 2300 yr BP, is also observed in the Hichu Kkota valley but with attenuated effects. Two explanations can be proposed, or the glacier was present in the watershed (melt water input partially obliterated the effects of the dryness) or precipitation was well-distributed throughout the year. In fact, these two processes are not contradictory and can be combined. Well distributed precipitation (and nebulosity) were favorable to a positive water balance of the glacier, even if the mean annual precipitation was lower than present. We thus assume that the glaciers have contributed to the hydrological changes in the Hichu

Kkota valley before the neoglacial readvance of the last centuries since 4400 yr BP and perhaps since ~ 6000 yr BP.

References

Abbott, M. B., Seltzer, G. O., Kelts, K. R., and Southon, J. (1997). Holocene Paleohydrology of the Tropical Andes from Lake Records. *Quaternary Research* **47,** 70-80.

Cross, S. L., Baker, P. A., Seltzer, G. O., Fritz, S. C., and Dunbar, R. B. (2000). A new estimate of the Holocene lowstand level of Lake Titicaca, central Andes, and implications for tropical palaeohydrology. *The Holocene* **10,** 21-30.

Gouze, P., Argollo, J., Saliege, J. F., and Servant, M. (1986). Interprétation paléoclimatique des oscillations des glaciers au cours des 20 derniers millénaires dans les régions tropicales ; exemple des Andes boliviennes. *C.R. Acad. Sc. Paris* **303,** 219-224.

Heine, K. (1996). The extent of the last glaciation in the Bolivian Andes (Cordillera Real) and paleoclimatic implications. *Z. Geomorph. N.F* **104,** 187-202.

Miskane, N. (1997). “Les paléoenvironnements de haute montagne pendant l'Holocène récent d'après l'étude des diatomées actuelles et fossiles de deux vallées glaciaires de Bolivie. Implications paléoclimatiques.” Unpublished PhD thesis, Muséum National Histoire Naturelle, 385 pp.

Mourguiart, P., Corrège, T., Wirrmann, D., Argollo, J., Pourchet, M., and Carbonnel, P. (1998). Holocene paleohydrology of lake Titicaca estimated from an ostracod-based transfer function. *Palaeogeography, Palaeoclimatology, Palaeoecology* **143,** 51-72.

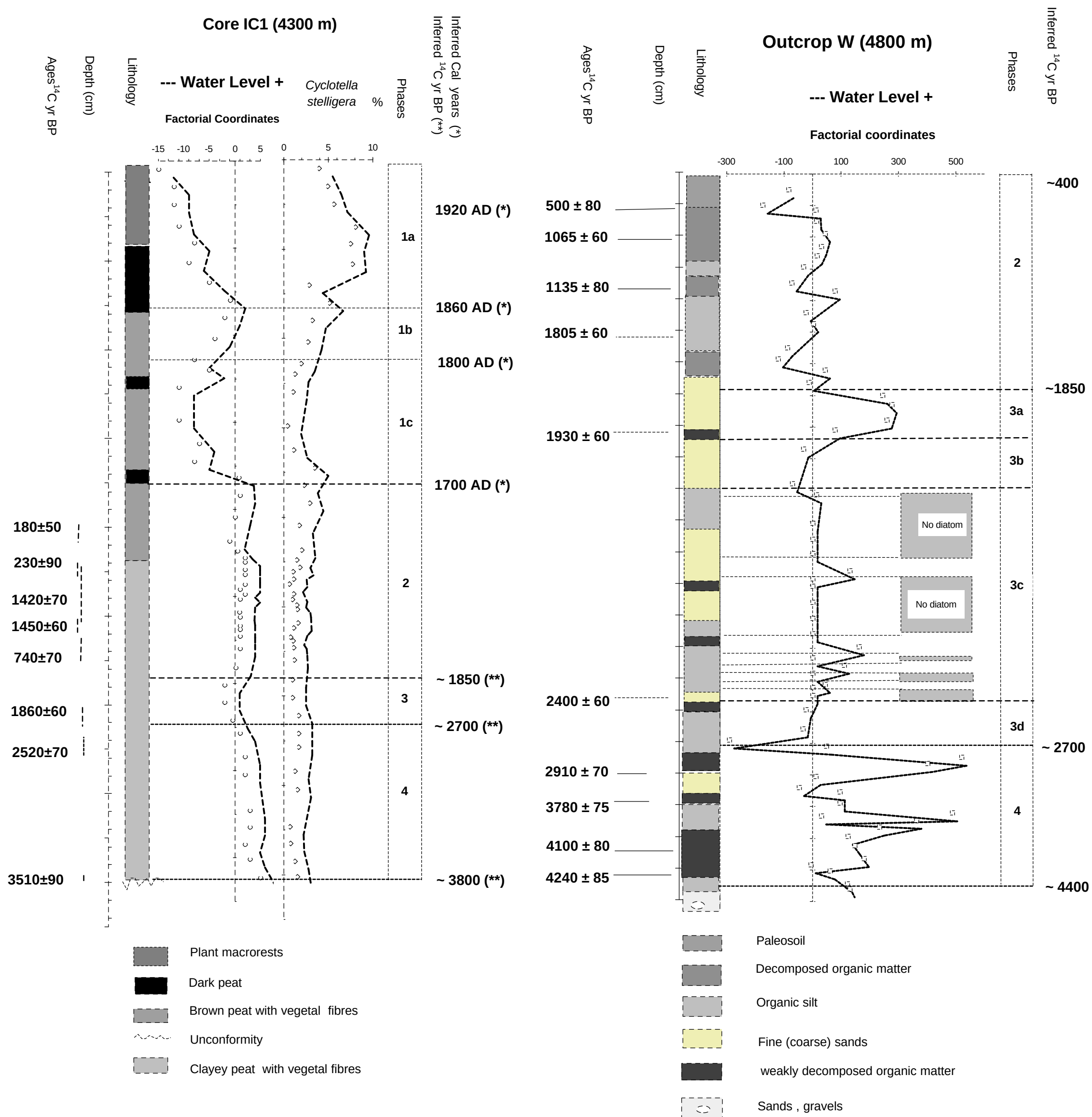
Pierre, J. F., and Wirrmann, D. (1986). Diatomées et sédiments holocènes du lac Khara Kkota (Bolivie). *Geodynamique* **1,** 135-145.

Servant, M., and Fontes, J. C. (1984). Les basses terrasses fluviatiles du Quaternaire récent des Andes boliviennes. *Cahiers ORSTOM, série Géologie,* **14,** 15-28.

Servant-Vildary, S. (1986). Les diatomées actuelles des Andes de Bolivie (Taxonomie, Ecologie). *Cah. Micropaleontol. CNRS.n.s.* **1,** 14-17.

Servant-Vildary, S., and Roux, M. (1990). Variations de température estimées à partir du déplacement en altitude des associations de diatomées dans une séquence holocène de la Cordillère Orientale de Bolivie. *C.R. Acad. Sci. Paris,* **311 II,** 429-436.

Ybert, J.P. (1992). Ancient lake environments as deduced from pollen analysis. In “*Lake Titicaca, a synthesis of Limnological Knowledge*”. C. Dejoux & A. Iltis (eds), pp 49-62. Kluwer Academic.



Core IC1 (4300 m)
Ages 14C yr BP
Depth (cm)
Lithology
--- Water Level +
Factorial Coordinates
Cyclotella stelligera %
Phases
Inferred Cal years (*)
Inferred 14C yr BP (**)
-15 -10 -5 0 5
0 5 10
1a
1b
1c
2
3
4
1920 AD (*)
1860 AD (*)
1800 AD (*)
1700 AD (*)
~ 1850 (**)
~ 2700 (**)
~ 3800 (**)
180±50
230±90
1420±70
1450±60
740±70
1860±60
2520±70
3510±90
Plant macrorests
Dark peat
Brown peat with vegetal fibres
Unconformity
Clayey peat with vegetal fibres
Outcrop W (4800 m)
Ages 14C yr BP
Depth (cm)
Lithology
--- Water Level +
Factorial coordinates
Phases
Inferred 14C yr BP
-300 -100 100 300 500
500 ± 80
1065 ± 60
1135 ± 80
1805 ± 60
1930 ± 60
2400 ± 60
2910 ± 70
3780 ± 75
4100 ± 80
4240 ± 85
No diatom
No diatom
2
3a
3b
3c
3d
4
~400
~1850
~ 2700
~ 4400
Paleosoil
Decomposed organic matter
Organic silt
Fine (coarse) sands
weakly decomposed organic matter
Sands , gravels