III. PALEOHYDROLOGY
III.1. A 20,000 years paleohydrological record from Lake Titicaca

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The Bolivian Altiplano is an endorheic basin which extends from 16° to 20° S. Lat. and from 65° to 69°W. Long., with altitudes ranging from 3700 to 4600 metres, covering 200,000 km^2 between the Western and Eastern Cordilleras which are 6500 m high (Fig. 1). From north to south, three major lacustrine areas occupy this high plateau:

- Lake Titicaca at 3809 metres above sea level, covering 8562 km^2;
- Lake Poopo at 3686 m.a.s.l. covering 2530 km^2;
- Coipasa-Uyuni, a group of dry salt lakes, covering 11,000 km^2 at 3653 m.a.s.l.

Over the last 1.8 million years these basins have registered episodes of greatly enlarged lake areas. According to Lavenu *et al.* (1984) and to Servant and Fontes (1978, 1984), the Pleistocene record of Titicaca lake level fluctuations can be summarised as follows:

- during the Early Pleistocene the paleolake Mataro rose with a water level established at 140 metres above the present level. This stage is related to the end of the Calvario glaciation (Servant, 1977) and the corresponding deposits are recognisable mainly at the NW edge of the basin;
- the paleolake Cabana occurred during the middle Pleistocene with a water level established at 90 metres above the present Lake Titicaca level; the associated sediments are present on the eastern and western shores of the basin;
- then with the retreat of the Sorata glaciation (Servant, 1977) the Ballivian stage occurred with a paleolake in which the water level was 50 metres higher than the present level; its deposits are located in the southern and western coasts of the basin;
- a lacustrine terrace, located at 15 metres above the present lake level, is attributed to the paleolake Minchin (Upper Pleistocene, between 27,000 and 21,000 years BP), according to correlations with the Central Altiplano;
- the last Pleistocene lacustrine episode, at approximately 10 500 BP, corresponds to the Tauca stage, giving rise to a paleolake slightly larger in area than the Lake Titicaca. According to Hastenrath and Kutzbach (1985) and Kessler (1985) this stage is attributed to an increase of 50% to 30% in the rainfall over the Altiplano.

C. Dejoux and A. Iltis (eds.), Lake Titicaca, 40–48.
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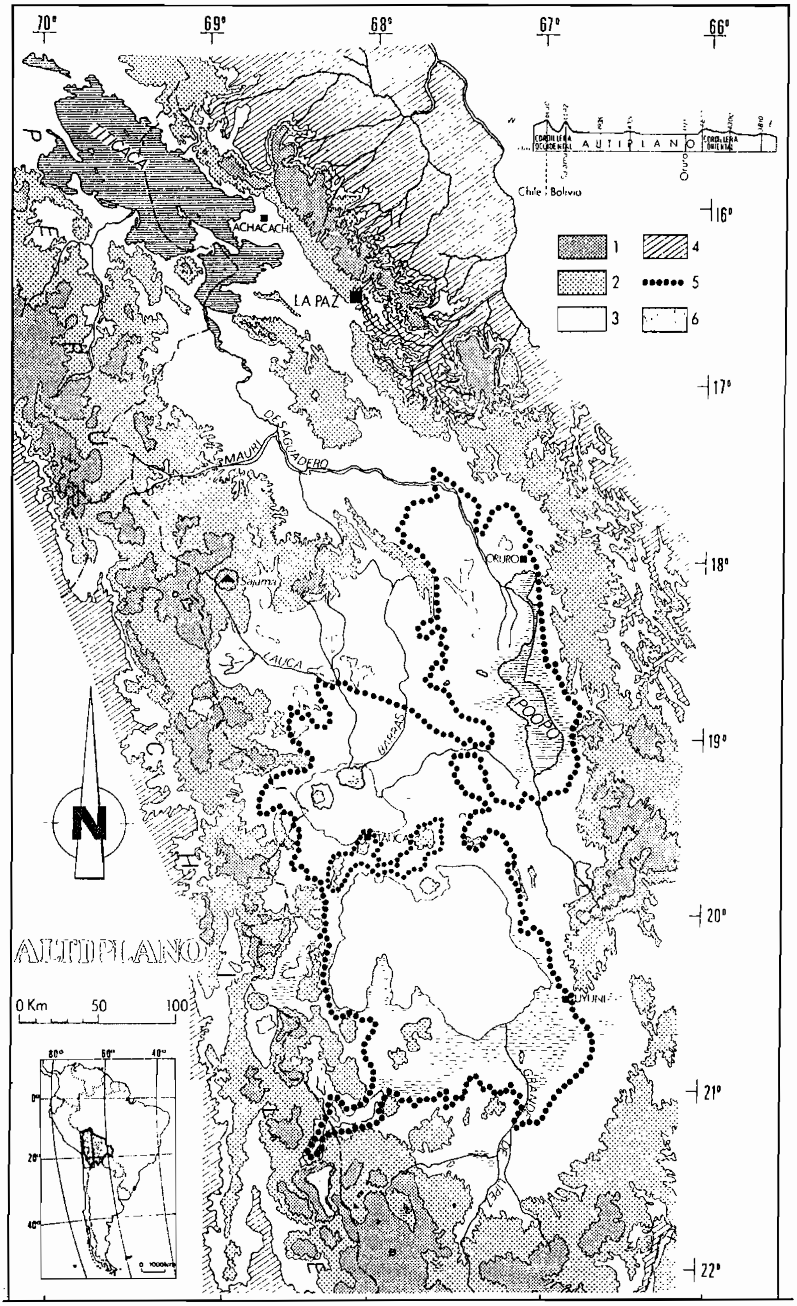

Figure 1. The Bolivian Altiplano showing the extent of the Tauca lacustrine phase (modified after Servant and Fontes, 1978):

1: over 4500 m
2: 4000–4500 m
3: 3500–4000 m
4: below 3500 m
5: extent of Lake Tauca
6: dry salt lakes

In this paper we will describe the Titicaca lake level oscillations occurring during the final stages of the Upper Pleistocene and the Holocene. This study is part of the GEOCIT programme (Géodynamique du Climat Intertropical) developed by the ORSTOM and was carried out in Bolivia with the collaboration of the Universidad Mayor de San Andrés (UMSA) at La Paz.

Materials and methods

Several sediment core samples have been collected using various coring devices depending on the water depth (Fig. 2) in the different areas recognised in Lago Grande and Lago Huiñaimarca (Chapter. II.1).

Firstly, a number of transects were made with a Züllig corer with a maximum core length 180 cm and a diameter of over 33 mm (Vargas, 1982; Wirrmann, 1982). 17 cores were later collected using a 6 metre Mackereth corer (Barton and Burden, 1979) to provide sedimentological records covering a longer time period. After that the characteristics of the present distribution of the ostracod fauna (Chapter.VI.4.f) and pollen content (Ybert 1988 and in prep.) in the superficial sediments and sediment-water interface was studied by analysing Mondsee core samples (maximum length 80 cm with a diameter of over 60 mm). A total of 56 cores samples were collected in 1981–1983 and 1986–1988.

The sedimentological results are based on a detailed lithological description of the core sections (texture, colour after the Munsell Soil Color Charts ed. 1975, faunal contents) and on quantitative and/or qualitative determination of the main components (geochemistry, X-ray, microgranulometry, binocular and microscopic observations). Exhaustive descriptions of the core samples are available in de Oliveira Almeida (1986), Wirrmann (1987) and Wirrmann *et al.* (1988).

The paleontological data relating to the ostracod fauna are presented in Mourguiart (1987) and those concerning the pollen record in the two Mackereth cores (TD, TD1) are available in Ybert (1988).

The paleoenvironmental interpretations are made in reference to qualitative changes in the sedimentological records, in the ostracod fauna and in pollen composition and their comparison with the present distribution.

We will present here paleohydrological data back to 20,000 BP, based on a radiochronology obtained by dating organic matter or ostracod carapaces (^{14}C Accelerator Mass Spectrometry methodology) or the bulk sediment (classical ^{14}C method).

Results

Comparative analysis of the sedimentological and paleological data based on this chronology and assuming the absence of turbid or biological perturbation

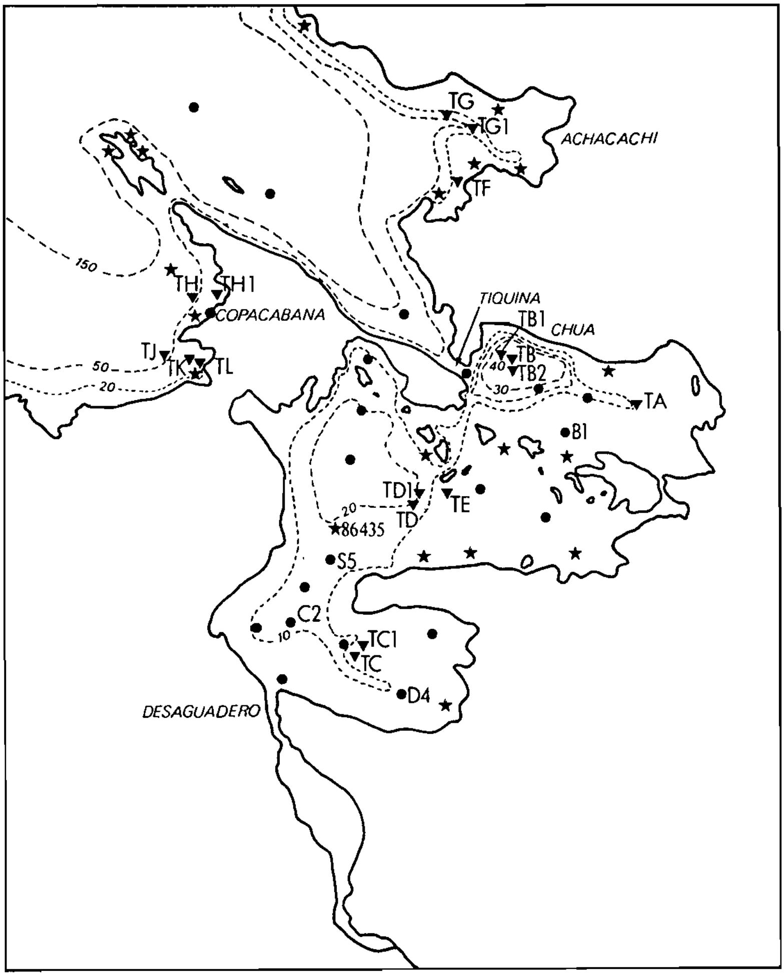

Figure 2. Core localities in Lake Titicaca:

Mackereth core:	▼
Züllig core:	●
Mondsee core:	★

in the core samples, allows us to propose the following interpretative curves for lake level fluctuations (Fig. 3).

The Upper Pleistocene

There is only one core, TD1, which provides a partial radiochronology for this period. The ages obtained span a time interval of between 18,000 and 21,000 BP (Wirrmann, 1991), but the base of the core may roughly corre-

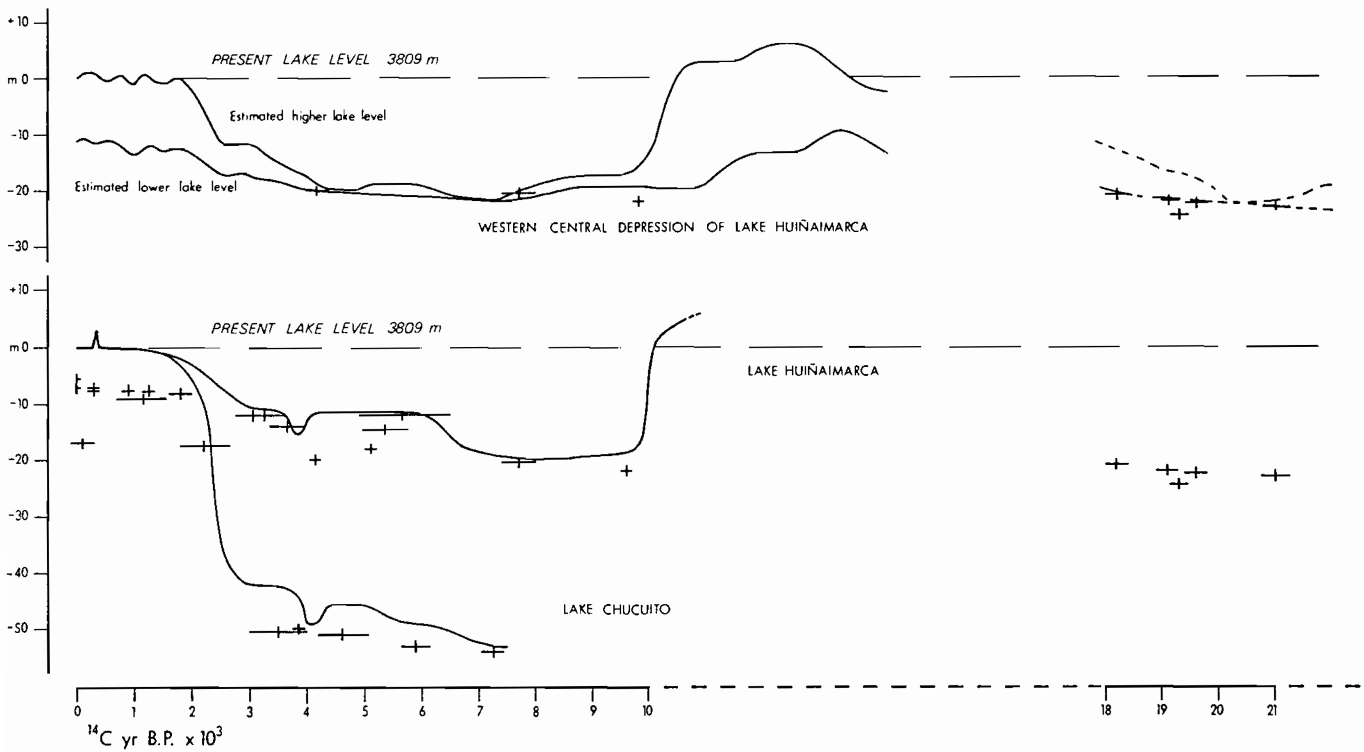

Figure 3. Composite curves of lake level fluctuations. From top to bottom:
- the empirical extreme values of the water level are indicated for the western central depression of Lago Huiñaimarca, based on palynological evidence;
- based on sedimentology and ostracod associations for Lago Huiñaimarca and Lago Grande;
- ^{14}C dates with error intervals: ⊥

spond to an estimated age of 24,000 BP, assuming a constant sedimentation rate.

The palynological records argue in favour of a very low lake level in comparison with the present level:

- before 21,000 BP, pollen contents are equivalent to those from the *Isoetes* zone of present-day high altitude glacial lakes of the Hichu Kkota valley (Ybert in prep.). They imply a water depth of between 0.4 to 4 metres;
- from about 21,000 to 20,000 BP, a stage of very shallow water depth (less than 0.2 metres) is inferred by the very low amounts of algae;
- from 20,000 to 19,100 BP the water depth increases to 4 metres;
- from about 19,100 to 18,000 BP, the water depth is estimated at between 1 and 8 metres.

The overall trend in sediment composition up until 18,000 BP (i.e. very fine mineral deposits of 71 to 47 % of clay, containing scattered grains of vivianite, greigite and framboidal pyrite from the base of the core to the top of this section and with a mean amount of 10 % carbonates), does not allow lake level fluctuations to be determined during this time interval. Moreover these deposits have no present equivalent in Lake Titicaca or in the glacial lakes. The absence of evaporites during this period of very low lake level, when the Desaguadero outlet could not have been functioning, is still not explained. Hence it is difficult to be precise about the paleobathymetrical environment from sedimentological evidence.

No dating has been obtained for the TD1 core between 18 185 BP and 7700 BP. The palynological characteristics of the corresponding core section (only 54 cm in length) argue in favour of a higher lake level than during the preceding stage, but lower than the present level at first, and then exceeding it. The presence of diatoms of deep, freshwater environments (S. Servant-Vildary, pers. comm.) at the top of this section confirms this final high lake level. From correlations with the Central Altiplano lacustrine basins, this stage can be attributed to the Tauca phase. Despite the lack of lithological unconformities, a hiatus in sedimentation is likely to have occurred. It is only with a more detailed chronology that it will be possible to be precise about the timing of this event.

From the age of 9600 BP obtained at a level of 291.5–295.5 cm, the base of the TD core (core section 320–483 cm) dates from the ultimate Upper Pleistocene. From palynological evidence, these azoic, clayey non-carbonate sediments, containing framboidal pyrite, are attributed to a lake level established between 5–10 metres below the present for the 483–420 cm, section, then quite similar to the present level and finally from 360 cm, slightly higher than at present. The top of this core section may represent the Tauca lacustrine phase, which is defined with more precision in the Central Altiplano, although still not totally reliably (Servant and Fontes, 1978, 1984).

From their lithology, cores TB and TB2 taken in the Chua hollow in Lago Huiñaimarca belong to this time period, but have not been dated radiochronologically up until now. Unfortunately the specific environmental conditions in Lago Huiñaimarca make it difficult to propose sedimentological correlations with cores TD and TD1. Here again, more ^{14}C datings are needed to clarify the chronology of lake level changes.

The Holocene

For this period the chronology is documented with more precision: 8 datings for Lago Grande and 16 datings for Lago Huiñaimarca. Five major stages are defined:

- from approximately 10,500 BP to 7700 BP, a decrease in lake area took place after the Tauca episode. Lake Titicaca registered a severe drop in level, progressive at the beginning and becoming more and more drastic afterwards. This decrease is well recorded in core TD: at 9600 BP the water level was established at around 15 metres below the present level (high amounts of terrestrial and wetland pollen and of miscellaneous algae, but with very few *Pediastrum* and *Botryococcus*). The sediments became coarser and richer in carbonates and in organic matter;
- from 7700 BP to 7250 BP, the lake level dropped by at least 50 metres in the Lago Grande, as inferred from the basal evaporites in core TJ. Gypsum precipitation also occurred in Lago Huiñaimarca: it is observed in the lower core sections of cores TB2, TC, TC1 and TE and in cores TD and TD1. Titicaca was characterised by very shallow, small and scattered individual basins in Lake Huiñaimarca (Chua hollow and western central depression) and around the central depression of Lago Grande. The consequence of this drought episode was the reduction of 42% in the water area of the lake and a loss of 30% of its water volume (Fig. 4). The communications between Lago Grande and Lago Huiñaimarca, and between the Chua hollow and the western central depression in the latter, were cut off;
- from about 7250 BP to 4000 BP, from the evidence on continuing individual basins, there was at first a stage of a very low lake level established around 10–45 metres below the present level. From the evidence of the ostracod fauna and diatom flora associations, the dissolved salts concentration rose to more than 40 g l^{-1} in the western central depression of Lago Huiñaimarca. Then, the occurrence of oligohaline to freshwater ostracod species and pollen types indicate a progressive and slight rising of the water level. The sediments belong to the carbonate facies, including variable quantities of shells and Characeae remains. The waters were oligohaline in both the Lago Grande and in the Chua hollow;
- from about 4000 BP to 2000 BP, after a short but notable phase of decrease, a progressive rise in lake level took place, giving a water depth established about 10 metres below the present level. Major inflows of water enriched in Na^{+} and Cl^{-} are noted, but the waters were fresh from 3600 BP. The communication between the Lago Grande and Lago Huiñaimarca was re-established at the end of this period;

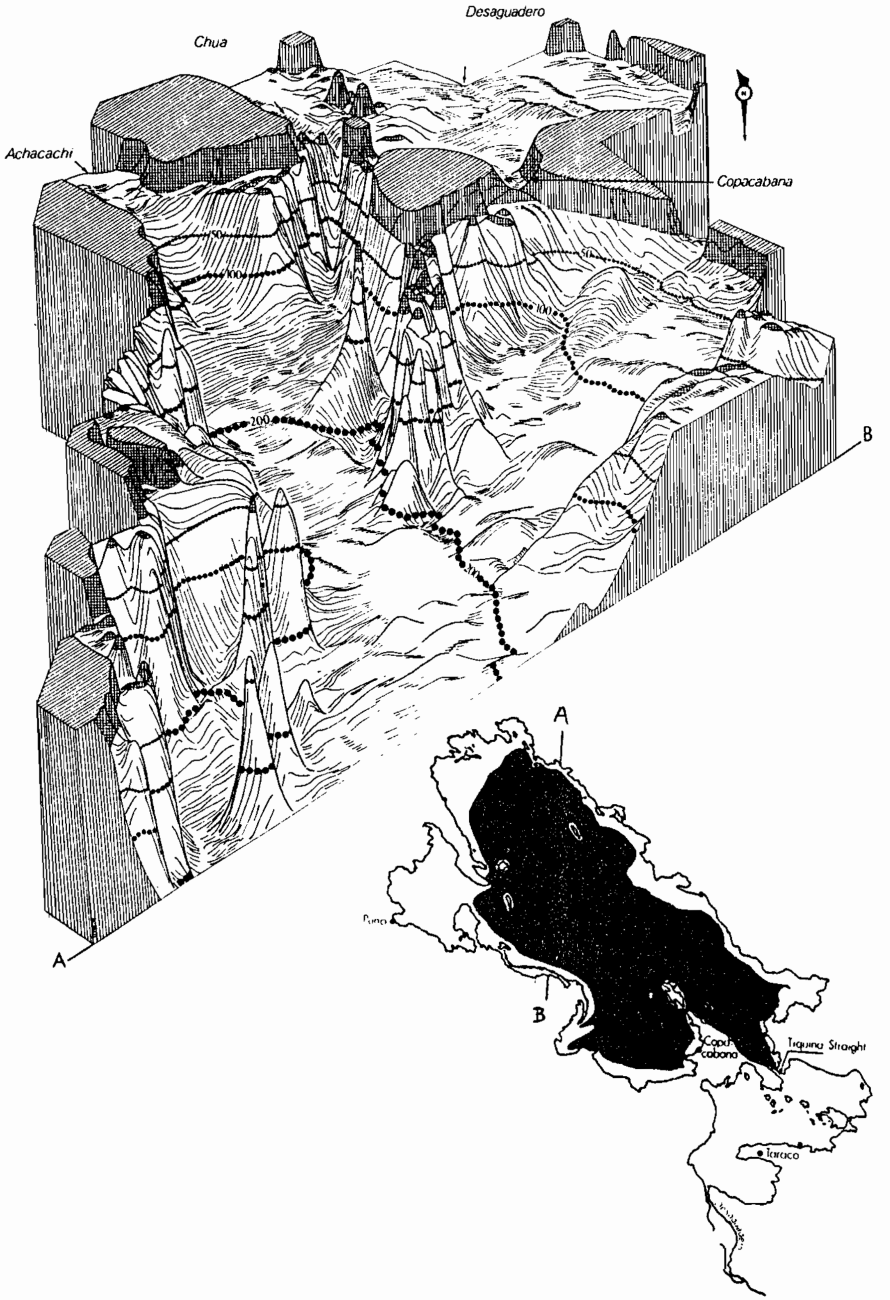

Figure 4. Block diagram of the present Titicaca basin showing the emerged land (hatched), the state of water level during the maximum lowering (50) and the corresponding water area (after Wirrmann, 1987 and Wirrmann *et al.*, 1988).

- after 2000 BP and before 1000 BP, Lake Titicaca assumed its present state and the Desaguadero became an effective outlet. Lake level oscillations of 5–10 metres amplitude are noted. According to historical chroniclers (Ramos Gavilán, 1621) a slight rise in level occurred around 350 BP. This event is not recorded in all the Mackereth cores, because the majority of them have been sampled beyond the water depth which allows the recording of such interannual lake level fluctuations. It is only in four cores (TC, TC1, TE and TF) and also in two Züllig cores (B1 and D4) that this event is recognisable.

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YBERT (J.P.), Sédimentation palynologique actuelle dans les lacs d'altitude de Bolivie. Relations avec la bathymétrie et avec l'altitude. (en préparation).
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C. DEJOUX and A. ILTIS / Editors

Lake Titicaca

A Synthesis of Limnological Knowledge

Kluwer Academic Publishers

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A Synthesis of Limnological Knowledge

Edited by

C. DEJOUX and A. ILTIS

KLUWER ACADEMIC PUBLISHERS

DORDRECHT / BOSTON / LONDON

Library of Congress Cataloging-in-Publication Data

Lake Titicaca : a synthesis of limnological knowledge / edited by C.
Dejoux and A. Iltis.
p. cm. -- (Monographiae biologicae ; v. 68)
Includes indexes.
ISBN 0-7923-1663-0 (HB : alk. paper)
1. Limnology--Titicaca Lake (Peru and Bolivia) 2. Aquatic
resources--Titicaca Lake (Peru and Bolivia) I. Dejoux, Claude.
II. Iltis, A. III. Series.
QP1.P37 vol. 68
[QH128]
574 s--dc20
[574.5'26322'098412] 92-7958

ISBN 0-7923-1663-0

Published by Kluwer Academic Publishers,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

Kluwer Academic Publishers incorporates
the publishing programmes of
D. Reidel, Martinus Nijhoff, Dr W. Junk and MTP Press.

Sold and distributed in the U.S.A. and Canada
by Kluwer Academic Publishers,
101 Philip Drive, Norwell, MA 02061, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers Group,
P.O. Box 322, 3300 AH Dordrecht, The Netherlands.

Printed on acid-free paper

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Printed in the Netherlands