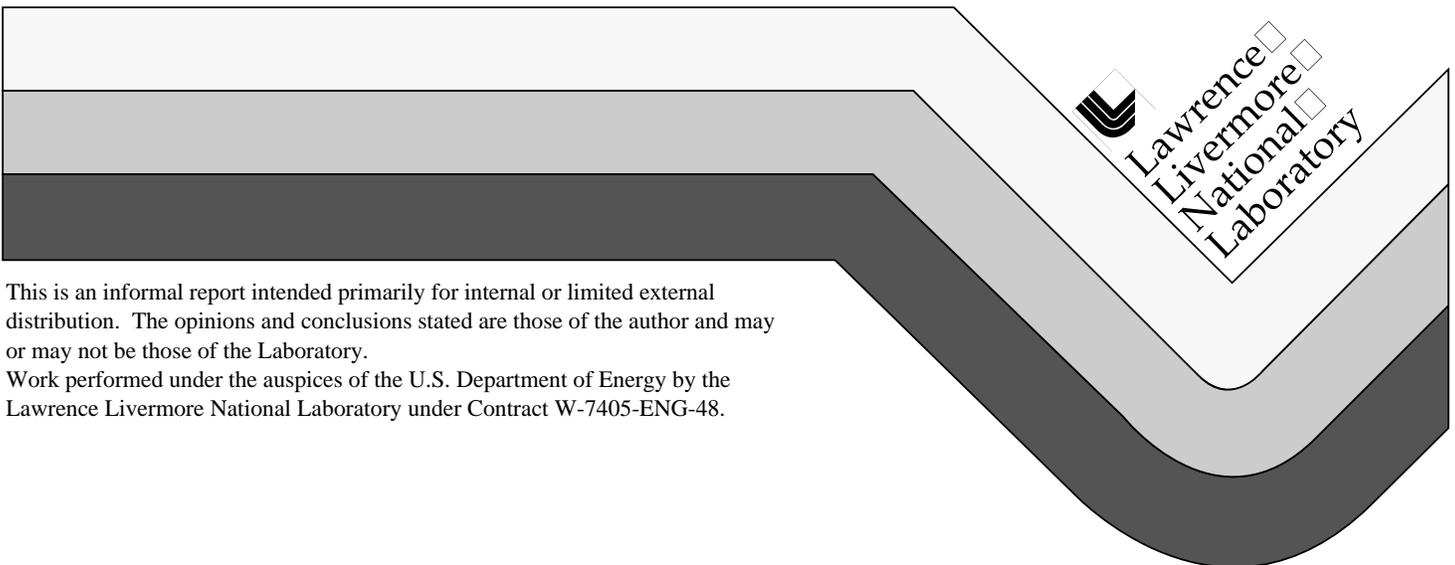


Holocene Paleohydrology of the Tropical Andes from Lake Records

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Two century-scale time series in northern Bolivia constrain the ages of abrupt changes in the physical, geochemical, and biological characteristics of sediments obtained from lakes that formed during deglaciation from the late Pleistocene glacial maximum. The watersheds of Laguna Viscachani (16°12'S, 68°07'W, 3780 m) and Lago Taypi Chaka Kkota (16°13'S, 68°21'W, 4300 m), located on the eastern and western slopes of the Cordillera Real, respectively, contain small cirque glaciers. A high-resolution chronology of the lake sediments is provided by 23 AMS ¹⁴C dates of discrete macrofossils. Late Pleistocene glaciers retreated rapidly, exposing the lake basins between 10,700 and 9700 ¹⁴C yr B.P. The sedimentary facies suggest that after 8900 ¹⁴C yr B.P. glaciers were absent from the watersheds and remained so during the middle Holocene. An increase in the precipitation–evaporation balance is indicated above unconformities dated to ~2300 ¹⁴C yr B.P. in both Lago Taypi Chaka Kkota and Laguna Viscachani. An abrupt increase in sediment accumulation rates after 1400 ¹⁴C yr B.P. signals the onset of Neoglaciation. A possible link exists between the observed millennial-scale shifts in the regional precipitation–evaporation balance and seasonal shifts in tropical insolation. © 1997 University of Washington.

INTRODUCTION

Lake-sediment records from both sides of the Cordillera Real, Bolivia, were analyzed to investigate the Holocene environmental dynamics of the Bolivian Andes (Fig. 1). These time series also extend the 3500-yr record of changes in the precipitation–evaporation balance for the region established by dating water-level fluctuations in Lake Titicaca (Abbott *et al.*, in press; Binford *et al.*, in press). The shallow

southern basin of Lake Titicaca (Lago Wiñaymarka) contains an incomplete Holocene record because it was almost completely desiccated prior to about 3500 ¹⁴C yr B.P. (Wirrmann *et al.*, 1990; Wirrmann and Mourguiart, 1995; Abbott, 1995). Also, all of the closed basin lakes in the cordillera are ephemeral lakes lacking a complete Holocene record that extends through the proposed mid-Holocene dry phase. Therefore, we targeted glacier-fed lakes with a positive water balance to obtain continuous Holocene paleoclimate sequences. Although the glacial lakes in this study maintain overflowing stages throughout the dry season (May–November), the erosion and deposition histories of Lago Taypi Chaka Kkota and Laguna Viscachani provide strong evidence for a dry middle Holocene. We suggest that cirque glaciers were absent from the watersheds during the middle Holocene, and without ice to provide a meltwater buffer during the dry season, a lake would have been seasonally lower or become desiccated. The absence of a meltwater buffer also rendered these high-altitude lake systems more susceptible to annual to century-scale droughts during the middle Holocene.

Previous water-level studies in Lake Titicaca imply a negative trend in the regional precipitation–evaporation balance from the latest Pleistocene to the middle Holocene (Servant and Fontes, 1978; Wirrmann and De Oliveira Almeida, 1987; Mourguiart, 1990). Studies of glacier retreat and higher snowlines for this period provide further evidence supporting a negative water balance in the region (Gouze *et al.*, 1986; Seltzer, 1992).

Here we present new proxy climate data from two sites in tropical South America indicating a middle Holocene dry

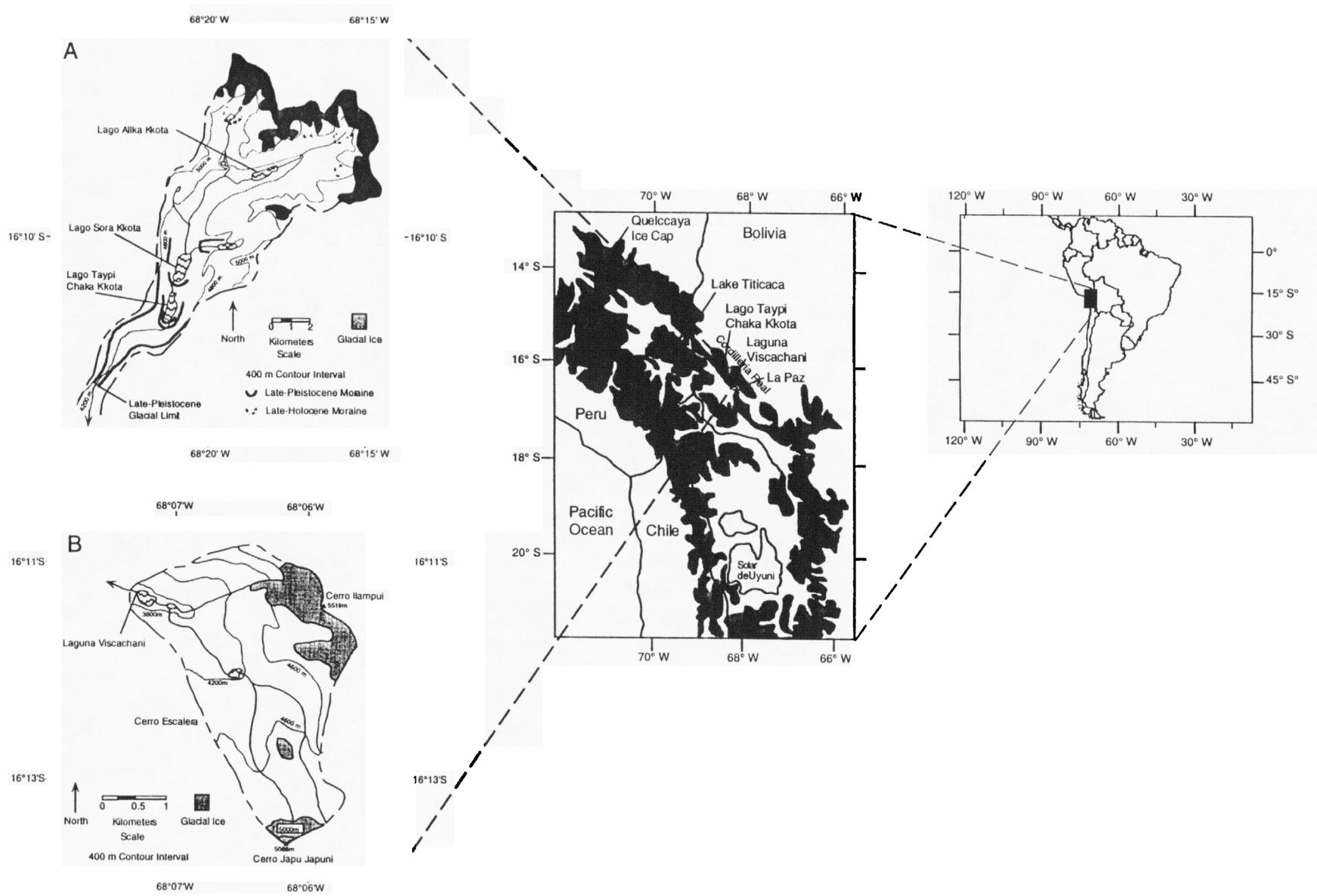


FIG. 1. Map showing the Cordillera Real and the Altiplano region in the northern Bolivian Andes (modified from Seltzer, 1994). Detailed maps of the Lago Taypi Chaka Kkota (A) and Laguna Viscachani (B) watersheds show the locations of the lakes and modern cirque glaciers.

phase, resulting in the nearly complete melting of glaciers between 8900 and 2300 ^{14}C yr B.P. in watersheds with headwalls of 5500 m altitude and lower in the Cordillera Real, Bolivia. Terrestrial records of Holocene deglaciation based on radiocarbon dates of peat downvalley from terminal moraines indicate that the glaciers had receded to within 200 m of their modern extent by 9700–8600 ^{14}C yr B.P. (Seltzer, 1992; Seltzer *et al.*, 1995). Late Holocene glacier advances appear to have obliterated evidence of any moraines that may have formed during the middle Holocene. Therefore, only by investigating lacustrine sediment records can we determine if glaciers melted completely during the early and middle Holocene. We also discuss a possible link between observed millennial-scale shifts in the regional precipitation–evaporation balance and seasonal shifts in insolation incident in the tropics of the Southern Hemisphere.

CLIMATE SETTING OF STUDY AREA

Pronounced seasonal contrasts in precipitation are characteristic of the Andean Altiplano (14–21°S). During the Austral summer, a heat-induced low-pressure cell forms over the center of South America that draws moisture from the South Atlantic. At the same time, convective activity over the Altiplano associated with the “Bolivian High” (Aceituno and Montecinos, 1993) produces precipitation in the Andes. As a result, most precipitation falls between December and March in this region. Periodic blocking of the easterly atmospheric circulation by the westerlies (Aceituno and Montecinos, 1993; Kessler, 1988) and perturbations caused by El Niño Southern Oscillation (ENSO) events (Thompson *et al.*, 1984; Ribstein *et al.*, 1995; Francou *et al.*, 1995) can produce dry phases on the Altiplano during the normal wet season. We contend that the synoptic climatic conditions that lead to seasonal and intra-seasonal variations in effective moisture today on the Altiplano serve as reasonable analogs for changes that may have occurred over longer periods during the Holocene.

This study uses sediment records collected from both sides of the Cordillera Real, Bolivia, to investigate changes in effective moisture. The two study sites are separated by 25 km: Lago Taypi Chaka Kkota (16°13'S, 68°21'W, 4300 m altitude) is located in the Río Palcoco valley on the western side of the cordillera (Fig. 1A). Laguna Viscachani (16°12'S, 68°07'W, 3740 m) is situated in the Río Zongo valley on the eastern side of the divide (Fig. 1B). Both watersheds contain small cirque glaciers, with headwalls at 5500 m altitude.

The eastern cordillera of the northern Bolivian Andes is a zone of steep climatic gradients resulting from a relief of >600 m above the Amazon Basin. The result is a pronounced rain shadow, with precipitation decreasing east to west from >1400 mm/yr in the lowlands to <700 mm/yr

in the Altiplano (Hoffman, 1975). Roche *et al.* (1992) estimated that the highest peaks of the Cordillera Real receive >800 mm/yr precipitation; 50 km to the west over the Altiplano this decreases to <500 mm/yr. Ribstein *et al.* (1995) measured ~900 mm of precipitation during the 1992–1993 hydrological year on Zongo Glacier, located on the continental divide 10 km from Laguna Viscachani and 20 km from Lago Taypi Chaka Kkota. Summer precipitation (December–March) accounts for 65 to 78% of the annual total, and winter precipitation accounts (June–September) for only 3 to 8% of the annual total (Roche *et al.*, 1992).

METHODS

Cores were taken with a square-rod piston corer (Wright *et al.*, 1984) and a piston corer designed to collect undisturbed sediment-water interface profiles (Fisher *et al.*, 1992). Total carbon (TC) and total inorganic carbon (TIC) were measured with a UIC Coulometric System. Total organic carbon (TOC) was calculated by the difference of TC–TIC. Biogenic-silica was analyzed by a time-series dissolution experiment (DeMaster, 1979; DeMaster, 1981). Core lithology was determined from smear-slide mineralogy and detailed inspection of sediments noting Munsel color, texture, sedimentary structures, and biogenic features. Magnetic susceptibility was measured with a Bartington Susceptibility Bridge at low frequency. Values were corrected for mass differences with bulk density measurements.

Terrestrial macrofossils were not present in sufficient quantities for AMS ^{14}C measurements at most stratigraphic levels. Therefore, we used *Isoetes* macrofossils for AMS ^{14}C measurements from Lago Taypi Chaka Kkota and *Myriophyllum* macrofossils from Laguna Viscachani. The contemporary radiocarbon reservoir was assessed by measuring the ^{14}C activity of live samples of these submerged macrophytes from each lake. The results of radiocarbon measurements of living aquatic vegetation are 114 and 111% Modern for the years A.D. 1992 and 1994, respectively, indicating that the lake reservoir effects are minimal in these systems; however, it is possible that the reservoir age has changed with time.

The radiocarbon ages were measured at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory. Radiocarbon ages are reported either as ^{14}C yr B.P. (uncalibrated) or cal ^{14}C yr B.P. if corrected and calibrated according to the methods outlined for CALIB 3.0 by Stuiver and Reimer (1993). Accumulation rates ($\text{g}/\text{cm}^2/100$ yr) were calculated using calibrated dates as products of sediment accumulation rates (cm/yr) and bulk density (g/cm^3) without considering errors associated with radiocarbon measurements or calibration.

RESULTS

Lago Taypi Chaka Kkota

AMS ^{14}C dates indicate that the transition from glacial silt to organic-rich lacustrine sediments occurred at 10,790

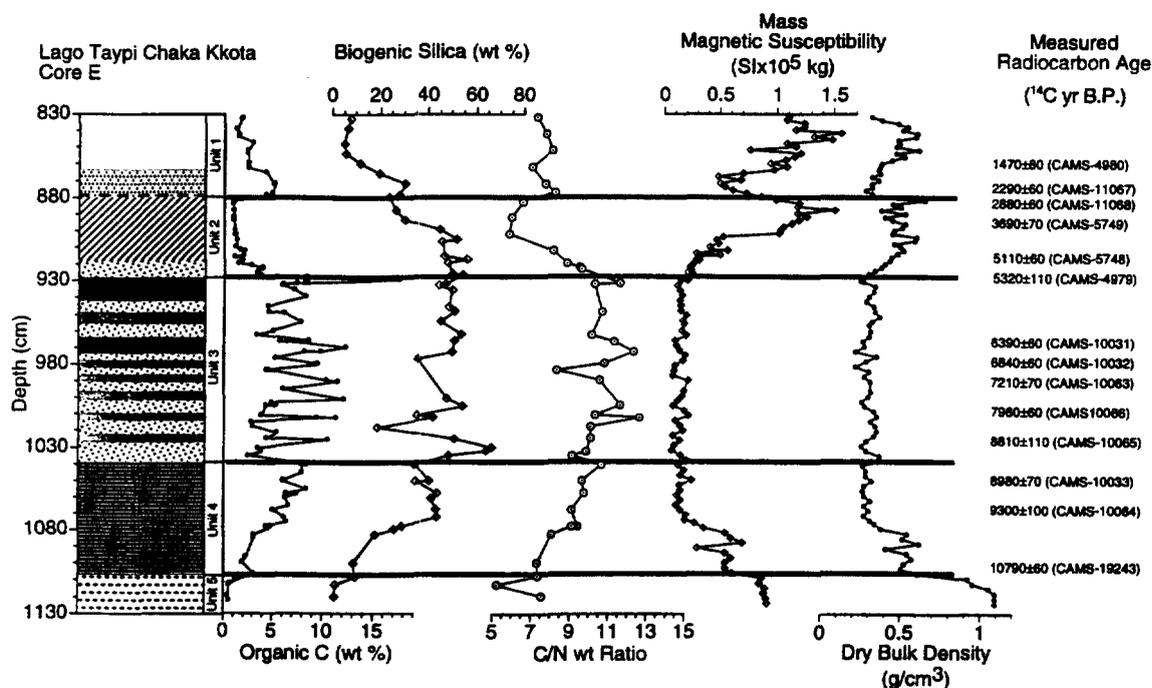


FIG. 2. Radiocarbon ages and sediment properties, including organic carbon, biogenic silica, C/N ratio, mass magnetic susceptibility, and dry bulk density, from core E collected from Lago Taypi Chaka Kkota.

± 60 ¹⁴C yr B.P. (CAMS-19243) in the Lago Taypi Chaka Kkota lake basin (4300 m), which is located more than 10 km downvalley and 1200 m below the catchment headwall (5500 m) (Fig. 2, Table 1). Seltzer (1992) estimated that the time of maximum late Pleistocene glaciation in Bolivia (Choqueyapu II Glaciation) was about 14,000 ¹⁴C yr B.P. based on glacial-geologic studies in the Bolivian-Peruvian Andes. Gouze *et al.* (1986) obtained a maximum limiting age for the Choqueyapu II glaciation of 16,600 ± 130 ¹⁴C yr B.P. on the western side of the Cordillera Real. In the Río Palcoco valley, the terminal moraine assumed to have formed during the Choqueyapu II glaciation is ~5 km downvalley from Lago Taypi Chaka Kkota. Seltzer (1991) described rapid deglaciation of the Río Palcoco valley on the basis of bulk radiocarbon dates obtained from the base of the organic-rich lacustrine deposits in Lago Taypi Chaka Kkota and Lago Allka Kkota, situated less than 3 km from the headwall. These dates are 10,460 ± 140 (Beta-35071) and 9980 ± 90 ¹⁴C yr (Beta-35069), respectively. Furthermore, the glaciers receded to within their Neoglacial limit by 8640 ± 80 ¹⁴C yr (Beta-35052) as indicated by a date from the transition of glacial silt to fibrous peat in a bog 200 m from the present glacier front at 4670 m (Seltzer, 1991). Glacier advances during the late Holocene extended less than 200 m from the present glacier fronts in the Cordillera Real (Gouze *et al.*, 1986; Seltzer, 1990).

The sediments that accumulated in Lago Taypi Chaka

Kkota between 9300 ± 100 (CAMS-10064) and 8810 ± 110 ¹⁴C yr (CAMS-10065) have higher concentrations of organic matter and biogenic silica, and a fourfold increase in accumulation rate compared to sedimentation between 10,790 and 9300 ± 100 ¹⁴C yr B.P. (Figs. 2 and 3). Between 10,790 ± 60 and 9300 ± 100 ¹⁴C yr B.P. the inorganic content of the sediments decreased from >80 to <40%, indicating that the glacial sediment source was greatly reduced or absent. Biogenic silica increased from <20 to >60% just prior to 9300 ± 100 ¹⁴C yr. This shift signals a marked increase in lake productivity and corresponds with a continued increase in accumulation rate. Well-preserved *Isoetes* plant fragments occur above the 1080 cm level, suggesting a reduction in the concentration of glacial silt in the water column, allowing light transmission to the lake bottom. The higher lake productivity is consistent with increased nutrient input into the lake system during the initial stages of soil stabilization in a recently deglaciated watershed.

A marked shift in the sedimentation pattern occurred after 8810 ± 110 yr B.P., based on a change from mm-scale laminations to cm-scale bands. The cm-scale bands that formed between 8810 ± 110 and 5320 ± 110 ¹⁴C yr B.P. (CAMS-4979) alternate between dark-brown laminae containing aquatic macrophytes and megaspores and light-gray laminae with lower organic carbon content and lacking well-preserved macrofossils. Two hypotheses are proposed to explain the cm-scale bands. One is that variations in glacier

TABLE 1
AMS Radiocarbon Dates from Lago Taypi Chaka Kkota and Laguna Viscachani

Lake	Depth (cm)	Material	Measured ^{14}C age (^{14}C yr B.P.)	Median calibrated ^{14}C age (Cal ^{14}C yr B.P.)	CAMS-#
Lago Taypi Chaka Kkota	860.5	aquatic macrofossil	1470 \pm 80	1310	4980*
Lago Taypi Chaka Kkota	879.5	aquatic macrofossil	2290 \pm 60	2230	11,067
Lago Taypi Chaka Kkota	882.5	aquatic macrofossil	2880 \pm 60	2940	11,068
Lago Taypi Chaka Kkota	893.5	aquatic macrofossil	3690 \pm 70	3950	5749
Lago Taypi Chaka Kkota	919.5	aquatic macrofossil	5110 \pm 60	5820	5748
Lago Taypi Chaka Kkota	928.5	aquatic macrofossil	5320 \pm 110	6030	4979
Lago Taypi Chaka Kkota	971	aquatic macrofossil	6390 \pm 60	7223	10,031
Lago Taypi Chaka Kkota	981	aquatic macrofossil	6840 \pm 60	7580	10,032
Lago Taypi Chaka Kkota	988.5	aquatic macrofossil	7210 \pm 70	7940	10,063
Lago Taypi Chaka Kkota	1011.5	aquatic macrofossil	7960 \pm 60	8680	10,066
Lago Taypi Chaka Kkota	1028	aquatic macrofossil	8810 \pm 110	9730	10,065
Lago Taypi Chaka Kkota	1054	aquatic macrofossil	8980 \pm 70	9950	10,033
Lago Taypi Chaka Kkota	1069.5	aquatic macrofossil	9300 \pm 100	10,260	10,064
Lago Taypi Chaka Kkota	1104.5	aquatic macrofossil	10,790 \pm 60	12,680	19,243
Laguna Viscachani	523	aquatic macrofossil	1220 \pm 80	1070	17,011
Laguna Viscachani	527	aquatic macrofossil	1380 \pm 90	1290	17,012
Laguna Viscachani	580	aquatic macrofossil	2480 \pm 60	2420	17,010*
Laguna Viscachani	574	aquatic macrofossil	2510 \pm 80	2650	17,013
Laguna Viscachani	619.5	aquatic macrofossil	5450 \pm 90	6250	16,063
Laguna Viscachani	638	aquatic macrofossil	6080 \pm 60	6880	17,014
Laguna Viscachani	697	aquatic macrofossil	8550 \pm 70	9480	17,015
Laguna Viscachani	725.5	aquatic macrofossil	9590 \pm 70	10,760	16,064
Laguna Viscachani	737	aquatic macrofossil	9790 \pm 70	10,970	17,016

* Not used in sedimentation rate calculations.

activity drove century-scale changes in sediment input to the lake basin; the other is that variable lake level occurred during the middle Holocene, caused by the disappearance of glaciers from the watershed and the loss of glacial meltwater as a buffer during the dry season.

In the first hypothesis, increased glacier activity may explain the formation of the light-gray cm-scale bands. Although a small increase in the mineral content of the light bands is noted, the inorganic accumulation rate is decreased in these intervals. This is not consistent with the inference of increased glacier activity. Furthermore, the biogenic-silica content of the light cm-scale bands remains $>40\%$, in contrast to values of $<5\%$ at present and $<2\%$ during the early Holocene. Therefore, this hypothesis is considered unlikely.

In the second hypothesis, modern analogs are offered to aid the interpretation of the past system. *Isoetes* is found only in very shallow water (<1 m deep) in the contemporary system. Assuming this was also true in the past, the dark cm-scale laminae that contain well-preserved *Isoetes* plant matter could only be formed during century-scale periods when the lake level was seasonally below its overflowing stage. This implies that glaciers were greatly reduced or absent from the watershed after 8810 ± 110 ^{14}C yr B.P. and is consistent with sedimentological evidence provided above. Low lake levels are unlikely in the modern system because glacial meltwater maintains the water level at its

overflowing stage even during the dry season. A modern example of a similar lake system without glaciers in its watershed is Laguna Kollpa Kkota ($17^{\circ}26'S$, $67^{\circ}88'W$, 4400 m). In this system, lake level is seasonally lower and the lake often is desiccated during the dry season because the catchment lacks glaciers to buffer water level (Seltzer, 1994).

A marked decrease in the organic carbon content occurs at 5320 ± 110 ^{14}C yr B.P. This suggests lower lake productivity or increased decomposition of organic matter during the period between 5320 ± 110 and 2880 ± 60 yr B.P. (CAMS-11068). Furthermore, increases in the inorganic matter content, mass magnetic susceptibility, and bulk density occur with little change in the rate of inorganic sedimentation. Again, two hypotheses could explain this interval. Either the lake system returned to overflowing conditions after 5320 ± 110 ^{14}C yr B.P. or the lake was seasonally lower and occasionally desiccated after this time.

If the first hypothesis is correct, decreased lake productivity signals the return of year-round overflowing conditions driven by the return of cirque glaciers to the Lago Taypi Chaka Kkota watershed. However, this is inconsistent with the erosion history of the catchment, as recorded in the lake sediments. Increased glacier activity would have resulted in greater input of fine-grained glacial sediment, producing higher accumulation rates and lower lake productivity. Although trends in sediment analyses are consistent with lower

Lago Taypi Chaka Kkota
Core E

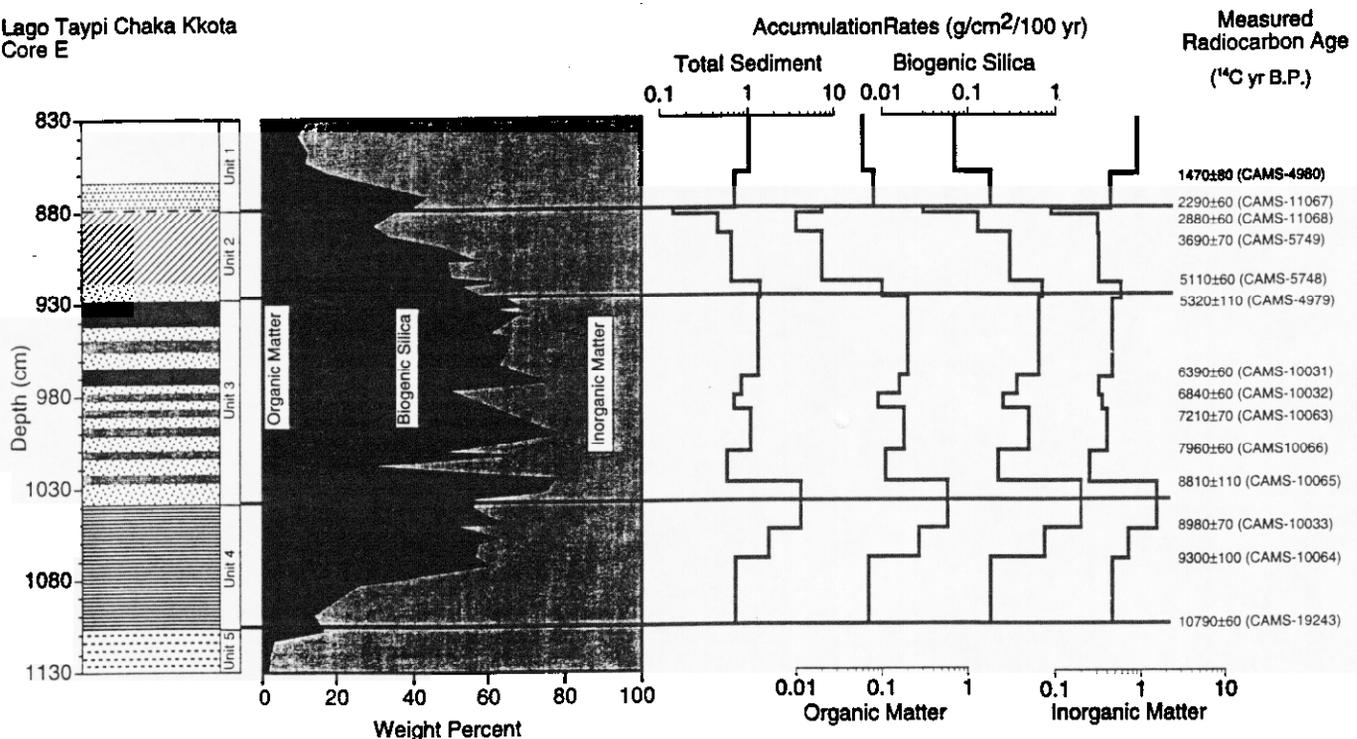


FIG. 3. Comparison of organic matter, biogenic-silica, and inorganic matter content and their respective accumulation rates plotted on a log scale from core E in Lago Taypi Chaka Kkota.

productivity, the total accumulation rate decreased in the interval from 5320 ± 110 to 2290 ± 60 ^{14}C yr B.P. (CAMS-11067). The average inorganic accumulation rate for this period ($0.4 \text{ g/cm}^2/100 \text{ yr}$) dropped to less than half the rate calculated for the modern system ($0.9 \text{ g/cm}^2/100 \text{ yr}$). This suggests that if glaciers were present, they were less extensive than now.

If the second hypothesis is correct, the lake would have been seasonally lower or desiccated during the dry season for the period from 5320 ± 110 to 2290 ± 60 ^{14}C yr B.P. Accumulation rates reach the lowest Holocene values during this phase, suggesting that sediments could have been partially lost by deflation when the lake was desiccated. Seasonal exposure of organic sediments may have resulted in higher rates of organic matter oxidation (Killops and Killops, 1993) and increased bulk density. Progressive decreases in organic carbon and biogenic-silica combined with increases in bulk density, inorganic matter content, and mass magnetic susceptibility are consistent with desiccation surfaces. The decreases in accumulation rates described above and the apparent unconformity from 2880 ± 60 to 2290 ± 60 ^{14}C yr B.P. (880 cm) suggest that the lake was seasonally dry or desiccated for an extended period prior to 2290 ± 60 ^{14}C yr B.P. Peaks in mass magnetic susceptibility and ARM magnetization occur at the 887 cm level. Water levels in Lake Titicaca dropped

10 to 12 m between 2450 and 2250 ^{14}C yr B.P. before rising abruptly after 2250 ^{14}C yr B.P., supporting the hypothesis of a dry phase at this time (Abbott, 1995).

Above the 2290 ± 60 ^{14}C yr B.P. level in the sediment core, abrupt increases in organic carbon and biogenic-silica, combined with decreases in mass magnetic susceptibility and bulk density, indicate a return to more humid environmental conditions and higher lake productivity. These conditions were temporary, as organic carbon and biogenic-silica content decreased rapidly to near late Pleistocene values by 1470 ± 80 ^{14}C yr B.P. (CAMS-4980). After this time, inorganic content, mass magnetic susceptibility, and bulk density increased rapidly. Organic carbon accumulation rates fell abruptly to the lowest Holocene values ($<0.1 \text{ g/cm}^2/100 \text{ yr}$) and the inorganic accumulation rates increased to the highest values since the early Holocene ($>0.9 \text{ g/cm}^2/100 \text{ yr}$), when the glaciers were in the final stages of recession.

Laguna Viscachani

The transition from glacial silts to organic-rich lacustrine sediments occurred at 9790 ± 70 yr B.P. (CAMS-17016) in Laguna Viscachani (3740 m). This contact is 1000 ^{14}C yr younger than the $10,790 \pm 60$ ^{14}C yr B.P. age obtained from Lago Taypi Chaka Kkota (4300 m) on the western side of the range. The latest Pleistocene ice limit in the Lago Taypi

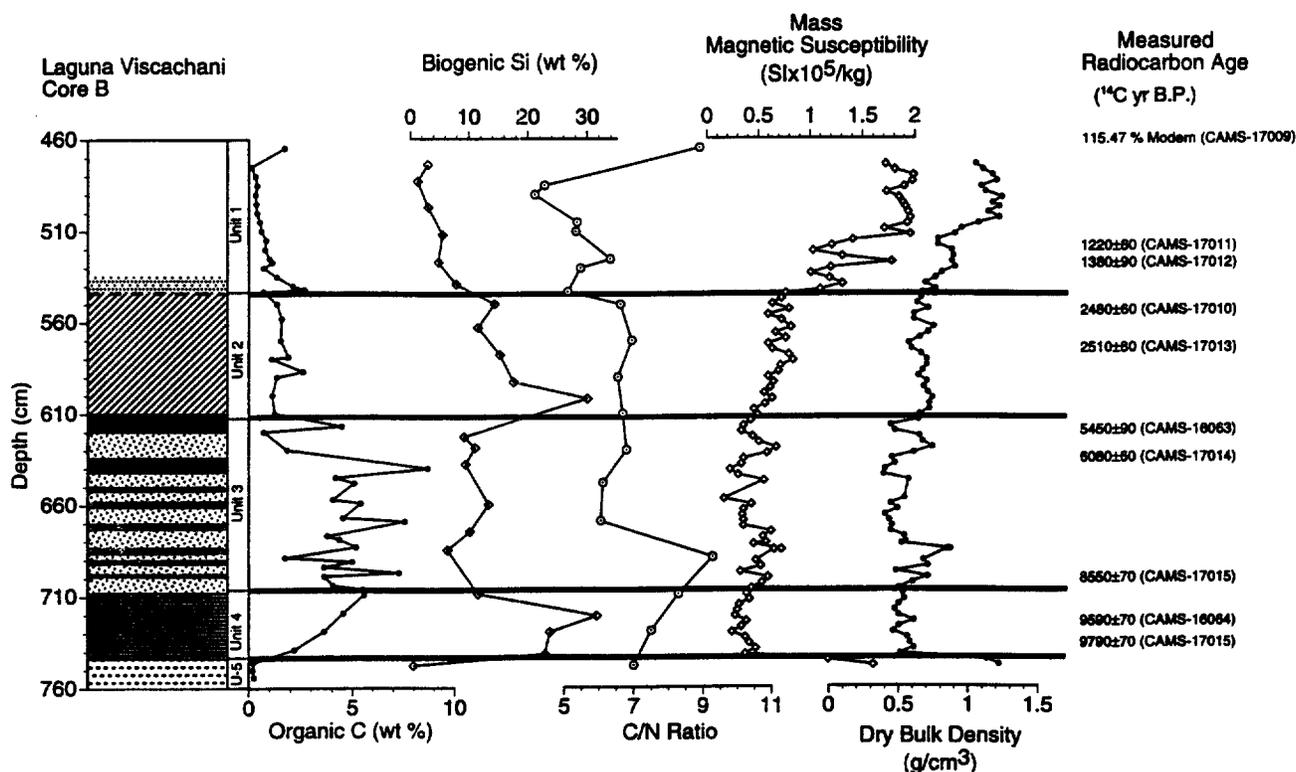


FIG. 4. Radiocarbon ages and sediment properties, including organic carbon, biogenic silica, C/N ratio, mass magnetic susceptibility, and dry bulk density, from core B collected from Laguna Viscachani.

Chaka Kkota watershed is at ~ 4200 m altitude, indicating that glaciers on the eastern side of the mountains advanced at least 460 m lower than those on the west. This supports modern observations of a pronounced rain shadow across the Cordillera Real (Seltzer, 1990). Therefore, the Laguna Viscachani watershed should receive higher average annual precipitation and be more prone to the regeneration of cirque glaciers after the middle Holocene dry phase than the Lago Taypi Chaka Kkota catchment. Furthermore, the higher precipitation on the eastern side of the Cordillera Real renders Laguna Viscachani less susceptible to periods of prolonged dry-season desiccation.

After 9790 ± 70 ^{14}C yr B.P., abrupt increases in organic matter and biogenic-silica content signal higher lake productivity. Figures 4 and 5 show that organic matter (>0.2 $\text{g}/\text{cm}^2/100$ yr) and biogenic-silica (>0.7 $\text{g}/\text{cm}^2/100$ yr) accumulation rates were at their highest Holocene levels. Organic matter sedimentation decreased from 9790 ± 70 to 5450 ± 90 ^{14}C yr B.P. (CAMS-16063), when it reached its lowest Holocene level of 0.03 $\text{g}/\text{cm}^2/100$ yr. The biogenic-silica accumulation rate decreased before stabilizing after 8550 ± 70 ^{14}C yr B.P. (CAMS-17015). The inorganic accumulation rate was stable after 9590 ± 70 ^{14}C yr B.P. (CAMS-16064) until 5450 ± 90 ^{14}C yr B.P. The subfacies formed during the middle Holocene vary from organic-rich laminae containing

well-preserved macrophytes to lower organic sediments without macrofossils. These deposits are consistent with a lake system that shifted between overflowing conditions and seasonally lower water levels.

Decreased accumulation rates between 5450 ± 90 and 2510 ± 80 ^{14}C yr B.P. (CAMS-17013) were synchronous with a similar trend in Lago Taypi Chaka Kkota. This supports the hypothesis that water levels were seasonally lower. Furthermore, the inorganic accumulation rate is the lowest of any period during the Holocene (0.5 $\text{g}/\text{cm}^2/100$ yr), suggesting that cirque glaciers were not present in these watersheds. An initial increase in the biogenic-silica content followed by a steady decline from 5450 ± 90 to 2510 ± 80 ^{14}C yr B.P. is the same trend observed in the Lago Taypi Chaka Kkota core during this period.

After 2510 ± 80 ^{14}C yr B.P., accumulation rates of organic matter, biogenic-silica, and inorganic matter increased. The largest increase was in the inorganic matter accumulation rate from ~ 1.0 to 2.2 $\text{g}/\text{cm}^2/100$ yr. An abrupt increase in the mass magnetic susceptibility after 2480 ± 60 ^{14}C yr B.P. (CAMS-17010) and inorganic matter content are consistent with the return of cirque glaciers in the Laguna Viscachani catchment. After 1220 ± 80 ^{14}C yr B.P. (CAMS-17011), the accumulation rate of inorganic matter doubled. This is coincident with the stabilization of increased values of mass

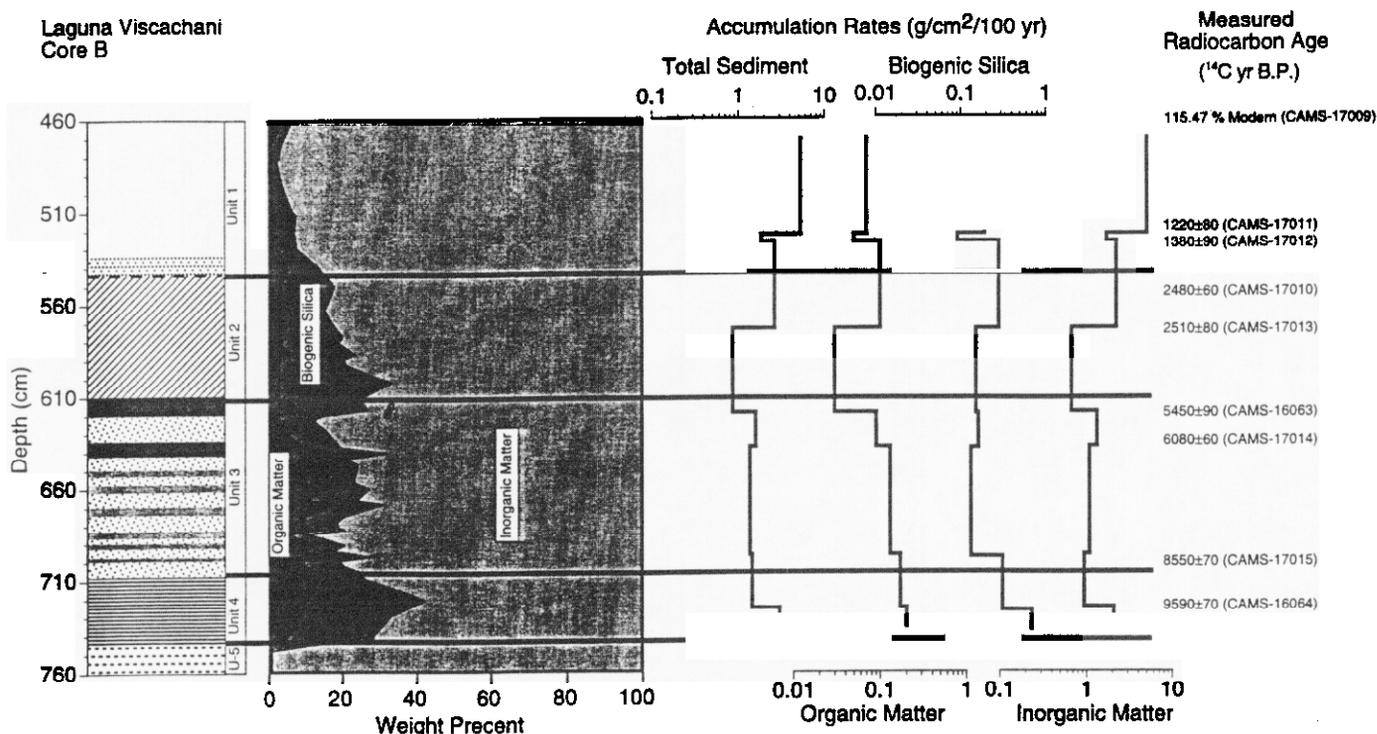


FIG. 5. Comparison of organic matter, biogenic-silica, and inorganic matter content and their respective accumulation rates plotted on a log scale from core B in Laguna Viscachani.

magnetic susceptibility and bulk density, suggesting Neoglaciation. Furthermore, organic matter and biogenic-silica content returned to pre-Holocene values.

CLIMATIC CONTROLS ON REGIONAL GLACIATION

Little information exists on the mid-Holocene activity of glaciers in the tropical Andes. In northern Bolivia we can say with certainty that deglaciation at the end of the Pleistocene proceeded rapidly, so that by $\sim 10,000$ ^{14}C yr B.P. many glaciers were near or within their modern limits. In the late Holocene Neoglaciation is evidenced by extensive, sparsely vegetated moraines only within 200 m of modern glaciers. However, there is little geomorphic record of mid-Holocene glacier activity in this area.

We suggest that glaciers are critical for maintaining the perennial lakes in the Cordillera Real. During the extensive dry period that occurs every year in the austral winter, meltwater generation from glaciers in these watersheds appears to maintain the overflowing condition of the lakes. This is supported by the observation that ephemeral lakes in the cordillera occur in basins that are not linked to modern glaciers. Thus, factors that influence glacier mass balance may also indirectly influence the hydrologic mass balance of the lakes.

Francou *et al.* (1995) assessed the mass balance of Zongo

Glacier ($16^{\circ}17'S$, $68^{\circ}09'W$, 6000–4890 m) and measured water discharge, temperature, and precipitation from September 1991 through August 1993 to determine the response of modern tropical glaciers to climatic variability. Zongo Glacier is on the eastern side of the Huayna Potosi massif <10 km from Laguna Viscachani. The study period spanned a strong ENSO event that occurred during the summer of 1991–1992. Francou *et al.* (1995) compared the “normal” 1992–1993 hydrological year with the 1991–1992 ENSO event and concluded that (1) there was a marked negative water balance during the ENSO event year, with water loss amounting to twice the precipitation gain, (2) the equilibrium-line altitude of the glacier rose 200 m, (3) the glacier accumulation-area ratio (AAR) decreased from 86 to 58%, and (4) a very low accumulation rate occurred at high elevations. These effects are directly related to increased radiation receipt at the glacier surface, which causes warmer summer temperatures and results in a higher rate of ablation. Furthermore, the summer wet season lasted only 2 months during the 1991–1992 ENSO event instead of the 4 months of a “normal” hydrological year.

Francou *et al.* (1995) concluded that factors controlling the mass balance of glaciers in the tropics include the duration of the wet season, and the temperature during the periods that precede and follow the rainy season. Temperature and precipitation during the months of October–December and March–

May appear to be critical for determining the mass balance of tropical glaciers. The association of ENSO events with low accumulation or negative mass balance reported by Francou *et al.* is paralleled by ice-core evidence of decreased precipitation on the Quelccaya ice cap (Thompson *et al.*, 1985).

Ribstein *et al.* (1995) observed that during the 1991–1992 ENSO event, Zongo Glacier produced increased runoff despite lower precipitation values compared with the 1992–1993 “normal” hydrological year. The decrease in precipitation corresponded to decreased cloud cover, which allowed more solar radiation to reach the glacier surface. Thus, extended periods of low precipitation would first lead to increased meltwater production by the glaciers followed by desiccation of these valleys after the glaciers had completely ablated.

Wetter conditions on the northern Altiplano are associated with the Bolivian High, which develops as a result of convective precipitation over this region in the austral summer (J. Lenters and K. Cook, unpub. data). We assume here that any decrease in summer insolation would be related to a decrease in precipitation on the Altiplano, thereby having the effect of decreasing cloudiness and increasing the receipt of solar radiation at the glacier surface. Given the conceptual model above, the glaciers would ablate and eventually disappear if these phases lasted long enough. Also, an increase in insolation in the austral winter would lead to increased glacier ablation during that season.

GCM simulations by Kutzbach and Guetter (1986) showed that at 9000 yr B.P. (~8450 ¹⁴C yr B.P.) when perihelion occurred in July the seasonality of solar radiation was decreased in the Southern Hemisphere. Climate model simulations, predicted that incident solar radiation was decreased in January by 28 W/m² (6%) and increased in July by 11 W/m² (5%) relative to the A.D. 1950 value (Fig. 6A). These changes caused (1) decreased seasonality, resulting in cooler summers and warmer winters, (2) decreased sea-level pressure over the ocean and increased sea-level pressure over land, resulting in a lower pressure gradient and decreased transport of water vapor over the continent, and (3) a decrease in the net precipitation–evaporation balance, with the decreased precipitation being more significant than the decreased evaporation. The summer and winter average insolation values returned to near-modern levels and the rate of change slowed about 3000 yr B.P. (~2900 ¹⁴C yr B.P.) which generally corresponds with wetter conditions on the Altiplano (Fig. 6A). Figure 6B illustrates a plot of monthly insolation at 20°S for the Austral summer and transitional months for the past 20,000 yr. For the months of December–February which are the peak of the wet season, insolation values were at their lowest between 12,000 and 8000 yr B.P. (~10,000–7600 ¹⁴C yr B.P.) (Edwards *et al.*, 1993), which corresponds with deglaciation and the beginning of the mid-Holocene dry phase observed at the sites in this study. Insol-

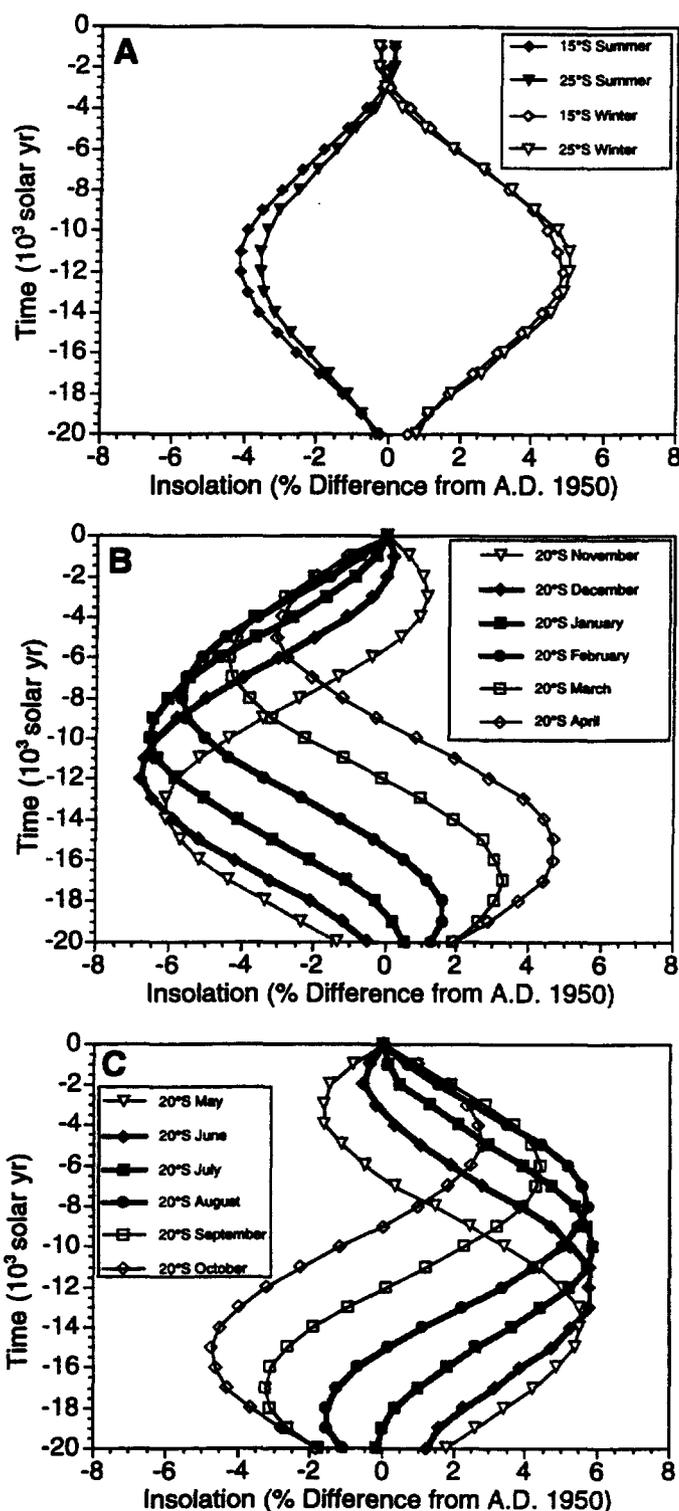


FIG. 6. Insolation changes for the past 20,000 yr B.P. as calculated from values given by Berger (1978a), Berger (1978b), and Berger and Loutre (1991). (A) Summer and winter insolation values for 15°S and 25°S showing seasonal insolation values reach present levels after 4000 yr B.P. (3700 ¹⁴C yr B.P.). Summer and winter values are defined as the 90 day period centered on the solstice. (B) Monthly insolation for the summer wet season and (C) for the winter dry season.

ation values for the months of June–August reached their highest between 13,000 and 7000 yr B.P. (11,000–6600 ^{14}C yr B.P.), likely resulting in increased ablation during the winter months (Fig. 6C). Thus, seasonality in the Southern Hemisphere was decreased over the past 20,000 yr, peaking at the Pleistocene/Holocene transition. Given the scenario above, a decrease in summer insolation may have resulted in lower summer precipitation; an increase in winter insolation may have resulted in enhanced ablation of the glaciers during the winter months. The combination of decreased summer precipitation and increased melting in the winter would contribute to the disappearance of cirque glaciers from watersheds with headwalls lower than 5500 m. Both factors would contribute to the prolonged dry phase in the middle Holocene documented in this study.

CONCLUSIONS

The sediment records from Lago Taypi Chaka Kkota and Laguna Viscachani contain striking similarities in the pattern and timing of geochemical, biological, and sedimentological changes, supporting the hypothesis that these systems are recording a regional climatic signal. Twenty-three AMS ^{14}C dates constrain the timing of the climatic shifts and yield sufficient time resolution to determine the Holocene erosion and deposition history of these catchments. Sediment core analyses showing abrupt shifts from nearly pure silt to increasingly organic-rich silt, suggest that glaciers receded above 4300 m altitude on the western side of the Cordillera Real by 10,700 ^{14}C yr B.P. and above 3740 m on the eastern side of the range by 9700 ^{14}C yr B.P. Increased accumulation rates of organic matter and biogenic silica, coupled with an abrupt decrease in the inorganic content of the sediments in both watersheds, suggests that the cirque glaciers disappeared between 9700 and 8900 ^{14}C yr B.P. High accumulation rates of organic carbon and biogenic silica from 9700 to 5400 ^{14}C yr indicate more favorable environmental conditions and higher lake productivity than today. Cm-scale bands of sediments deposited during this period bear shallow-water macrophytes indicating water levels of <1 m and alternate with laminae containing lower organic content and no macrofossils >0.5 μm in size. This suggests that there were century-scale periods of seasonally lower water levels. After 5400 ^{14}C yr B.P., macrophytes are absent from the sediments, but biogenic silica accumulation rates increase until the interval between 2900 and 2500 ^{14}C yr B.P. The Lago Taypi Chaka Kkota core shows an abrupt increase in inorganic content, bulk density, and mass magnetic susceptibility after 4000 ^{14}C yr B.P., which is most likely the result of prolonged droughts leading to low-water stands during this interval. No such changes are observed in the Laguna Viscachani core during this time, but accumulation rates in both lakes reached their lowest level between 5400 and 2300

^{14}C yr B.P. A desiccated surface forming an unconformity in the Lago Taypi Chaka Kkota core has an age of 2300 ^{14}C yr B.P., indicating that higher water levels were reached after this time. After 2300 ^{14}C yr B.P. sediment characteristics became increasingly similar to those of latest Pleistocene glacial sediments, indicating the return of cirque glaciers to watersheds with headwalls at 5500 m and intense Neoglacial activity after 1400 ^{14}C yr B.P.

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