Quaternary Research **56**, 181–190 (2001)
doi:10.1006/qres.2001.2263, available online at http://www.idealibrary.com on IDEAL®

Holocene Lake-Level Fluctuations of Lake Aricota, Southern Peru

Christa Placzek and Jay Quade

Department of Geosciences and Desert Laboratory, University of Arizona, Tucson, Arizona 85721

E-mail: cplaczek@geo.arizona.edu

and

Julio L. Betancourt

U.S. Geological Survey, Desert Laboratory, 1675 West Anklam Road, Tucson, Arizona 85745

Received November 2, 2000

Lacustrine deposits exposed around Lake Aricota, Peru (17° 22′S), a 7.5-km^2 lake dammed by debris flows, provide a middle to late Holocene record of lake-level fluctuations. Chronological context for shoreline deposits was obtained from radiocarbon dating of vascular plant remains and other datable material with minimal ^{14}C reservoir effects (<350 yr). Diatomites associated with highstands several meters above the modern lake level indicate wet episodes. Maximum Holocene lake level was attained before 6100 ^{14}C yr B.P. and ended ∼2700 ^{14}C yr B.P. Moderately high lake levels occurred at 1700 and 1300 ^{14}C yr B.P. The highstand at Lake Aricota during the middle Holocene is coeval with a major lowstand at Lake Titicaca (16°S), which is only 130 km to the northeast and shares a similar climatology. Comparisons with other marine and terrestrial records highlight emerging contradictions over the nature of mid-Holocene climate in the central Andes. © 2001 University of Washington.

INTRODUCTION

Recently, there has been considerable interest in the possible influence of the precessional cycle and seasonal insolation variations on the South American Summer Monsoon and precipitation over the central Andes (Abbott *et al.*, 1997b; Baker *et al.*, 2001a, 2001b; Betancourt *et al.*, 2000; Cross *et al.*, 2000; Kull and Grosjean, 1998; Seltzer *et al.*, 2000; and http://wwwpaztcn.wr.usgs.gov/pcaw). The evolution of tropical circulation patterns can be best tracked with well-dated paleoclimate records along the fringes of the tropical rainfall belt. The scarcity of such records from the central Andes leaves open many questions about the evolution of Holocene climate in this critical region.

One of the best dated Holocene records in the region comes from Lake Titicaca (16°S) and features a major lowstand 8000–3200 ^{14}C yr B.P. (Wirrmann and Alameida, 1987; Abbott *et al.*, 1997a; Mourguiart *et al.*, 1998; Seltzer *et al.*, 1998; Baker *et al.*, 2001a; Cross *et al.*, 2000). There remain questions about the cause, magnitude, and regional extent of the climatic event responsible for this lowstand. For example, in the highlands of the central Atacama Desert (22–24°N), several lake records seem to indicate mid-Holocene drying (Grosjean *et al.*, 2000), while slightly wetter conditions than today are inferred from playa cores (Bobst *et al.*, in press), spring deposits, and fossil rodent middens (Betancourt *et al.*, 2000). Here, we document lake-level changes during the Holocene at Lake Aricota, southern Peru. Lake Aricota is 700 km north of the Salar de Atacama but only 130 km southeast of Lake Titicaca (Fig. 1).

CLIMATE

The Atacama Desert is among the driest regions on Earth. The Andes largely block moisture originating in the Amazon Basin, forming an extreme rainshadow on the Pacific slope. To the west, sinking air of the South Pacific Anticyclone effectively excludes Pacific moisture from the Atacama Desert (Trewartha, 1981). The scant precipitation that reaches the northern and central Atacama falls in the austral summer, when moisture from the Amazon Basin spills over the Andes. The western flank of the Andes (>2500 m; Fig. 1b) and high Altiplano (>3700 m; Fig. 1a) receive considerably more precipitation than the coastal desert (<1000 m, Figs. 1c, 1d).

Heating over the Altiplano drives summer rainfall in this region, a precipitation regime that has been termed the South American summer monsoon (Zhou and Lau, 1998). During summertime heating, a warm-cored, closed anticyclone (the Bolivian High) develops in the upper troposphere over the Altiplano, and moisture-bearing trade winds intensify (Zhou and Lau, 1998). The strength and position of the Bolivian High modulates rainfall anomalies, in part tracking the Southern Oscillation (Lenters and Cook, 1999; Vuille, 1999). El Niño Southern Oscillation (ENSO) warm (cool) phases are correlated with dry (wet) summers. The Bolivian High decreases in strength and shifts southward during El Niño episodes, whereas the opposite occurs during La Niña events. Weakened easterly winds in the troposphere accompany this displacement of the Bolivian High and further

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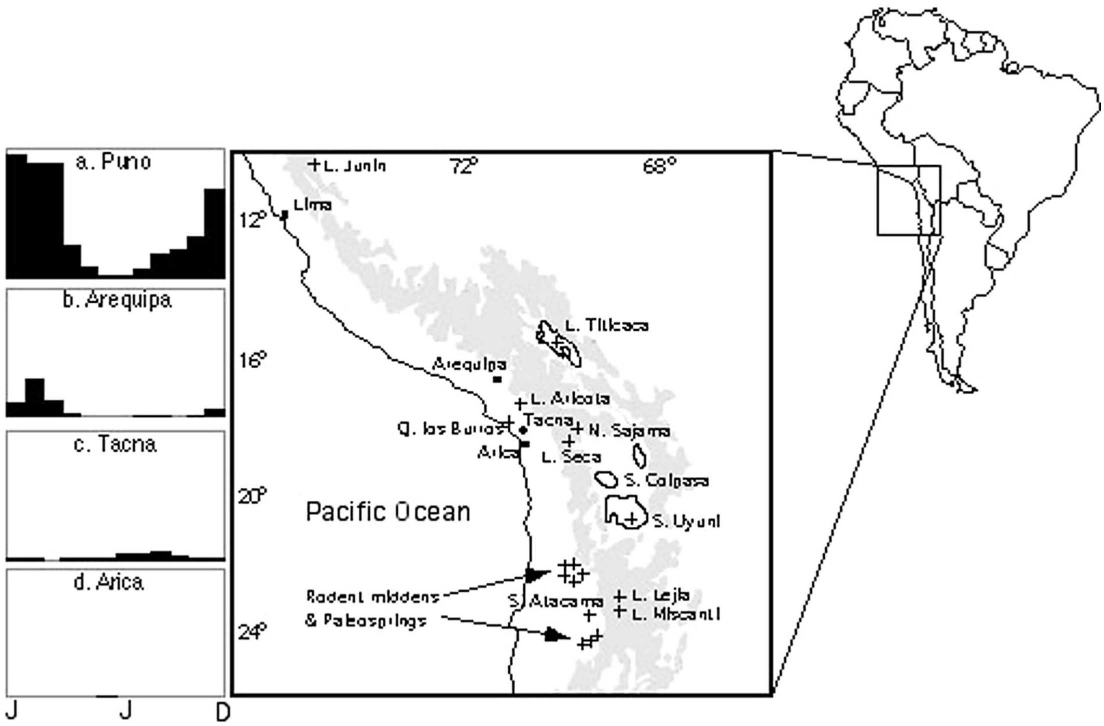

FIG. 1. Map of the region and mean monthly precipitation. Puno (a): annual precipitation is 670 mm/yr, $n = 16$ years. Arequipa (b): 90 mm/yr, $n = 76$. Tacna (c): 30 mm/yr, $n = 33$. Arica (d): 9 mm/yr, $n = 59$. All stations have the same scale (maximum precipitation for any month is 150 mm). + = study sites referred to in text. L. = Lake; Q. = Quebrada; and S = Salar.

reduce movement of moisture onto the Altiplano (Vuille, 1999; Vuille *et al.*, 2000).

Winter precipitation embedded in the westerlies has little impact on the northern Atacama (Vuille and Ammann, 1997). Winter storms do not penetrate onto the Andean flank but are responsible for the scant rains falling in some localities on the coastal plain (e.g., Tacna, Fig. 1c). Other coastal sites (e.g., Arica, Fig. 1d) receive virtually no rainfall but experience frequent fogs as a result of a permanent temperature inversion (Trewartha, 1981).

STUDY AREA

Lake Aricota is 2800 m above sea level on the western flank of the Andes (Fig. 1). Elevation and precipitation gradients are steep in the 620-km^2 catchment. Volcán Yucamane (5400 m) and the Altiplano are less than 25 km from Lake Aricota and are climatically most similar to Puno (Fig. 1a). Summer precipitation from these highlands feeds the perennial Río Callazas and the ephemeral Río Jaruma (Fig. 2).

Lake Aricota formed when debris flows from steep canyon walls blocked the Río Callazas (Figs. 2 and 3). The main debris flow dam ($\sim$4.5 km^2) is overlain by a smaller ($\sim$1.5 km^2) debris flow (Figs. 2 and 3). The debris flows are derived from ignimbrites and metasedimentary rocks. The lowest points within the dam are at least 75 m above the modern lake level, and the dam is several kilometers wide. The age of the debris-flow dam is much greater than the paleoclimate record documented in this study. The pre-Holocene age of the debris flows is indicated by (1) extensive incision of the southwest side of the debris flow, (2) the generally smooth topography on the original debris flow surface, (3) weathering and spalling of boulders within the debris flow, and (4) radiocarbon dates from the main delta.

Other paleolake systems in the region preserve evidence of major late glacial age highstands (Grosjean *et al.*, 1995; Sylvestre *et al.*, 1999; Seltzer *et al.*, 2000; Baker *et al.*, 2001a, 2001b; Bobst *et al.*, in press), and the mid-Holocene highstand at Lake Aricota is likely small compared with these wetter episodes. The lack of highstand diatomites from older events at Lake Aricota is probably due to the erodibility of diatomite and steep topography surrounding most of the lake. Modern and Holocene diatomites are found only on lower gradient slopes ($<20°$). These shallow slopes exist primarily on the alluvial fans formed where small catchments drain into Lake Aricota (Figs. 2 and 3). These fans may themselves be the products of increased sedimentation during major wet episodes or may have been too active in glacial times to preserve shorelines or diatomite deposits.

A hydroelectric project currently siphons water from Lake Aricota to provide power for the cities of Ilo, Moquegua, Cuajone, Toquepala, and Tacna. Hydroelectric use has artificially lowered the lake from an original volume of $\sim$800,000 m^3 in 1967, when the hydroelectric plant was completed, to an

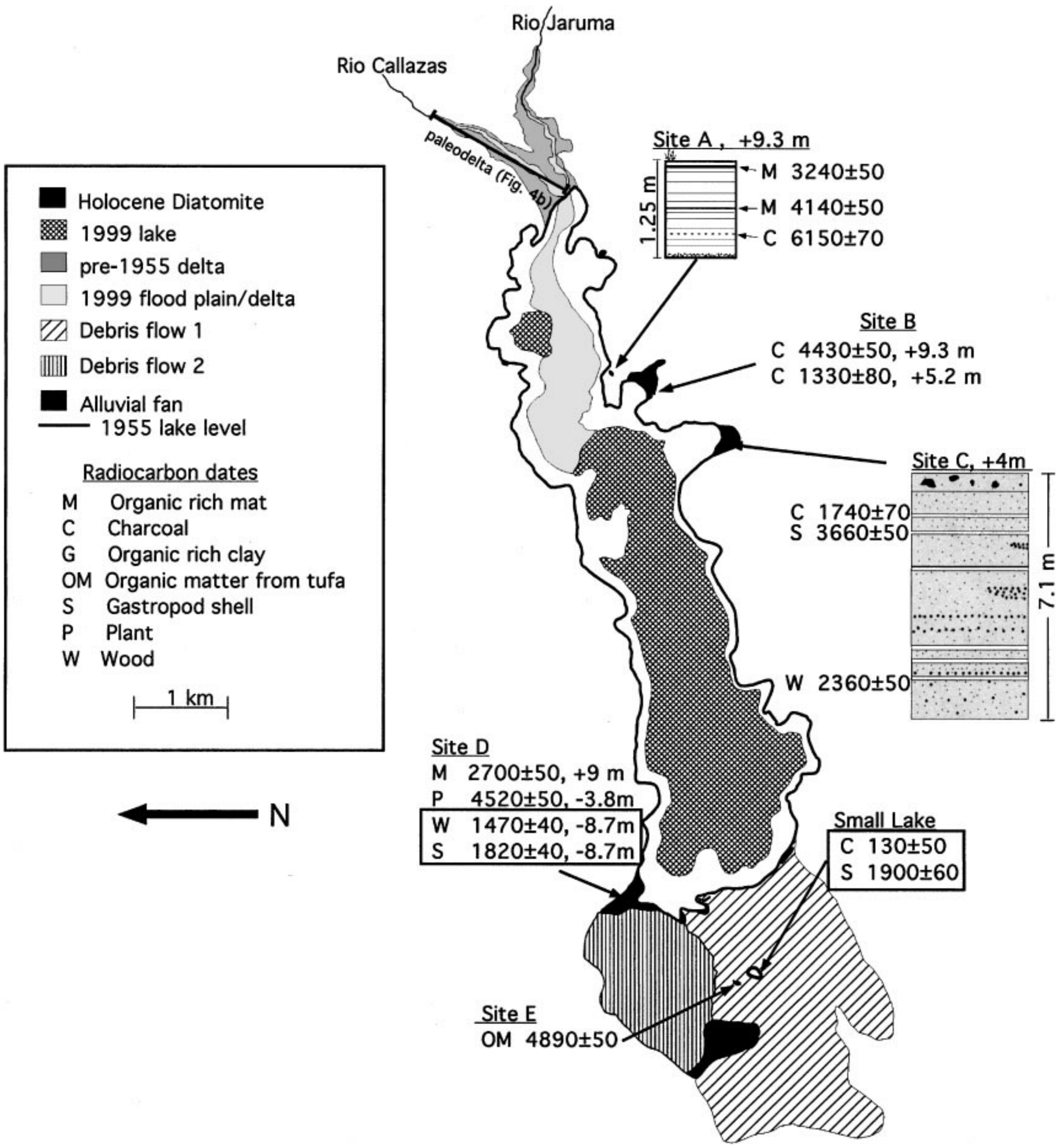

FIG. 2. Lake Aricota study sites and m above modern lake level for the tops of sample pits. Radiocarbon dates are ^{14}C yr B.P. Boxed radiocarbon dates are from the same sample pit and stratigraphic level.

average monthly volume of ~140,000 m^3 in 2000, when we visited the site (http://www.lamolina.edu.pe/facultad/economia/sociologia/aguasperdidas.htm; http://www.rcp.net.pe/E-M). Lake volume has been as low as 33,000 m^3 in 1992. All references to modern lake level refer to 1955, when we can actually map the prehydroelectric lake levels from aerial photographs (Fig. 3). Diatomite located above this modern level marks highstands of Lake Aricota. Most diatoms live in perennial standing water, and we take the presence of diatomite as an indicator of minimum lake level at the time of deposition.

Our study assumes that Aricota lake levels are responding mainly to changes in local precipitation–evaporation balance. Lake-fed groundwater now seeps from the base of the debris flow dam and presumably did so in the past. Many lakes lose moisture by seepage, and the assumption, unstated in most studies, is that this loss remains a constant proportion of lake level. Our assumption is that changes in seepage rates result from changes in lake level, with increased seepage rates during highstands. There is both modern and prehistoric evidence for this. First, before construction of the hydroelectric plant, seepage from the higher lake watered the Curibaya Valley downstream of the debris flow; this valley has since been desertified due to less seepage with the reduction of lake volume (http://www.lamolina.edu.pe/facultad/economia/sociologia/aguasperdidas). Second, deposits from a now-inactive spring within the debris flow argue for increased seepage during formation of this deposit, and radiocarbon dates

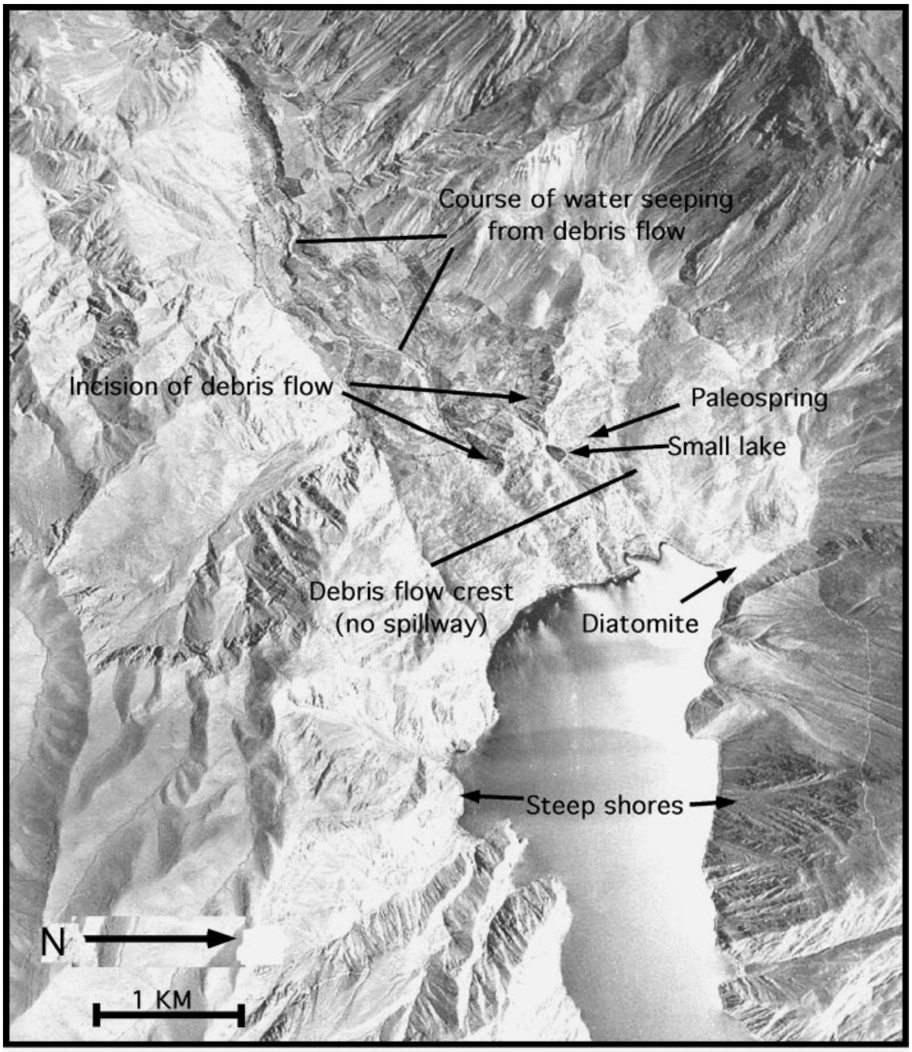

FIG. 3. 1955 aerial photograph of the east end of Lake Aricota.

indicate that this spring was likely concurrent with high lake levels. Therefore, Lake Aricota's response to increasing inflow is offset, at least in part, by higher seepage rates. This head-dependent seepage would tend to amplify the climate signal inferred from higher lake levels.

METHODS

A combination of aerial photography and a hand level was used to map highstand deposits and to survey elevations above modern lake level (aml ±2 m) at Lake Aricota. Samples for ^{14}C dating were collected from three highstand sites (Fig. 2; Sites A, B, and D), from spring deposits within the debris flow (Site E), from interbedded diatomite and alluvium within a small alluvial fan (Site C), and from the main paleodelta. Most organic samples were wood, vascular plants, or charcoal (Table 1) and were subjected to a standard acid-base pretreatment prior to dating. Some organic-rich diatomite layers contained organic fragments that were hand picked and pretreated as above. In a few cases, the organics in a mat were too small to be physically separated from sediment, and the humate (base-soluble) fraction of the layer was dated. Organic samples were converted to CO_2 by combustion and gastropod shells by reaction with phosphoric acid. This gas was purified cryogenically and converted to graphite at the Desert Laboratory (University of Arizona) and analyzed by the University of Arizona/National Science Foundation Tandem Accelerator Mass Spectrometer facility.

RESULTS AND DISCUSSION OF RADIOCARBON DATES

Vascular plants, wood, and charcoal provide reliable ^{14}C dates and are uncomplicated by ^{14}C reservoir effects. These dates constitute the main chronologic framework for the lake-level reconstruction. Organic mats with visible organic matter also provide dates close to the age of deposition. The organic mats consist of vascular plant fragments, small charcoal flakes, but possibly

TABLE 1
Radiocarbon Dates from Lake Aricota

Sample number	Material	$\delta^{13}C$	Site, elevation	Age (^{14}C yr B.P.)	Calibrated Age* (Cal yr B.P.)	Notes
AA34616	charcoal	−25	small lake	130 ± 50	260	associated with AA34965
AA34618	organic clay	−21.7	upper delta	4690 ± 60	5450	
AA34619	charcoal	−21.6	upper delta	2130 ± 50	2130	
AA34620	wood	−26.5	lower delta	140 ± 50	270	
AA34621	wood	−24.4	lower delta	110 ± 50	250	
AA34622	plant	−25.8	upper delta	3540 ± 60	3830	
AA34623	wood	−26.5	far upper delta	postbomb		
AA34965	gastropod	−6.4	small lake	1900 ± 60	1880	associated with AA34616
GX25848	wood	−23.9	upper delta	1940 ± 70	1880	conventional date
AA36685	humate	−22.8	Site D, +7.8 m	1890 ± 60	1860	
AA36686	humate	−23.4	Site D, +7.8 m	1740 ± 50	1690	
AA36687	organic mat	−19.8	Site D, +9 m	2700 ± 50	2780	
AA36688	humate	−23.5	Site D, +5.4 m	1790 ± 50	1710	
AA36689	humate	−19	Site D, +1.4 m	2580 ± 50	2740	
AA36690	plant	−16.9	Site D, −3.8 m	4520 ± 50	5280	
AA36691	wood	−20.5	Site D, −8.7 m	1470 ± 40	1350	associated with AA36692
AA36692	gastropod	−6.29	Site D, −8.7 m	1820 ± 40	1730	associated with AA36691
AA36694	humate	−24.6	paleospring	3180 ± 50	3380	
AA36695	organics from tufa	−19.4	paleospring	4890 ± 50	5600	
AA36696	wood	−23.8	Site C	2360 ± 50	2350	
AA36697	gastropod	−0.77	Site C	3660 ± 50	3980	
AA36698	charcoal	−16.1	Site C	1740 ± 70	1690	
AA36700	charcoal	−24.6	Site B, +9 m	4430 ± 50	5030	
AA36701	charcoal	−23.8	Site B, +5.2 m	1330 ± 80	1280	
AA36702	charcoal	−21.7	Site A	6150 ± 70	7140	
AA36703	organic mat	−22.8	Site A	4140 ± 50	4790	associated with AA36704
AA36704	humate	−24.1	Site A	2500 ± 40	2710	associated with AA36703
AA36705	organic mat	−23.2	Site A	3240 ± 50	3470	
AA36706	wood	−26.5	upper delta	280 ± 40	310	

* Dates converted to cal yr B.P. with Calib 4.0 (Stuiver and Reimer, 1993); dates listed have highest probability.

nonvascular plant or algal material subject to ^{14}C reservoir effects as well. Carbon-14 from an aquatic gastropod (1820 ± 40 ^{14}C yr B.P., AA36692) and associated wood (1470 ± 40 ^{14}C yr B.P., AA36691), however, show ^{14}C reservoir effects to be less than 350 years at Lake Aricota (Table 1).

In contrast, the humate fraction of organic mats yields minimum ages due to contamination by younger humic acids. This contamination is apparent from a sample in which humates produced a ^{14}C age 1640 years younger than that of coexisting coarse organic matter (Table 1: AA36704 and AA36703). Thus, humate dates must be considered minimum dates and are not used to construct the lake-level history.

Diatomite

White, unconsolidated deposits composed primarily of diatom tests are consistently found on shallow slopes at elevations 10 to 11 m aml down to the current elevation of the lake (Fig. 3a). The maximum elevation of the diatomites is consistently at the same level, and we interpret this elevation (10–11 m aml) to be the maximum Holocene lake level. Highstand diatomite was sampled and described at four sites (Fig. 2; Sites A through D). Site A is a small, closed topographic depression (<90 m^2) that was once an embayment of the paleolake. The area draining into the site is <500 m^2, and rilling or erosional features were not observed. The highest diatomites are 2.1 m above the flat center of this depression and at 10–11 m aml. A 1.25-m sample pit exposed bedded diatomite underlain by coarse, angular gravel (Fig. 2). A discontinuous organic mat with charcoal fragments occurs in diatomite 15 cm above this gravel base. Charcoal from this layer yielded a date of 6150 ± 70 ^{14}C yr B.P. (AA36702). A second organic-rich mat, located 36 cm above the gravel, contained plant material that was hand picked for radiocarbon dating. It returned a date of 4140 ± 50 ^{14}C yr B.P. (AA36703). A third layer located 3 cm below the top of the section was also hand picked for plant material and dated to 3240 ± 50 ^{14}C yr B.P. (AA36705).

The small embayment was filled only when the level of Lake Aricota was 8–10 m aml. This sample site is at the bottom of a partially vegetated, closed depression, and therefore significant loss of section due to fluvial erosion or deflation is unlikely. We conclude that the lake was within a few meters of its maximum highstand by 6100 ^{14}C yr B.P. and receded from this highstand shortly after 3200 ^{14}C yr B.P. There were probably no subsequent incursions of Lake Aricota into this embayment.

Site B consists of two sample pits in highstand diatomite (Fig. 2). Diatomite is again exposed 10–11 m aml at this site. Diatomite at this site is generally massive but contains occasional charcoal fragments. Charcoal from a pit 9.3 m aml dated at 4430 ± 50 ^{14}C yr B.P. (AA36700). Charcoal from a second pit 5.3 m aml yielded an age of 1330 ± 80 ^{14}C yr B.P. (AA36701).

Results from deposits at least 8 m above the modern lake level at both Sites A and B point to attainment of maximum lake level during the mid-Holocene (Fig. 3a). The date of 1330 ^{14}C yr B.P. from Site B demonstrates that the lake was at least 5.3 m aml at that time.

Interbedded alluvial gravels and diatomite are exposed above the modern lake level at Site C (Fig. 2). The uppermost diatomite in this section contains charcoal (4 m aml) with an age of 1740 ± 70 ^{14}C yr B.P. (AA36698). A date of 3660 ± 50 ^{14}C yr B.P. (AA36697) was obtained on a gastropod (3.5 m aml), and wood from just below modern lake level yields an age of 2360 ± 50 ^{14}C yr B.P. (AA36696).

We regard the charcoal and wood dates as more reliable, and the charcoal date of 1700 ^{14}C yr B.P. shows that the lake was at least 4 m above modern lake level at that time. The gastropod date is too old for its stratigraphic position for one of two reasons: either it was reworked from older deposits or it reflects a ∼1900 yr ^{14}C reservoir effect in the lake. We prefer the reworking explanation, because other paired organic/mollusk samples in a lower energy setting (Table 1, Site D) at roughly the same time indicate a much a smaller reservoir (∼350 years) effect.

Diatomite is again exposed 10–11 meters above modern lake level at Site D, and several sample pits exposed dateable layers. An organic mat from a pit located ∼9 m aml yielded a date of 2700 ± 50 ^{14}C yr B.P. (AA36687). A vascular plant macrofossil found in diatomite −3.8 m aml has an age of 4520 ± 50 ^{14}C yr B.P. (AA36690). Four humate samples from organic-rich diatomite between 1.4 and 7.8 m aml date to the late Holocene (Table 1).

The date of 2700 ^{14}C yr B.P. from Site D shows that the lake was slightly below the high lake level at that time. The date of 4500 ^{14}C yr B.P. at site D shows that the lake did not drop below −3.7 m aml during the mid-Holocene. Humate dates from this section are minimum ages and support evidence already presented that the lake was above the modern level at certain intervals during the Holocene.

Site E consists of spring deposits on an east-facing slope within the main debris flow (Fig. 2). This spring was once fed by seepage from Lake Aricota but is now inactive. Tufa from this paleospring forms a prominent bench. Downslope from the tufa, interbedded diatomite and organic layers blanket the hillside. The organic fraction of this tufa (residue after acid treatment) returned an age of 4890 ± 50 ^{14}C yr B.P. (AA36695). The dated material may be terrestrial plant fragments or algal tissue. Humates from organic-rich diatomites yielded a date of 3180 ± 50 ^{14}C yr B.P. (AA36694).

A small lake within the debris flow was also sampled. The lake is now dry but contained water in 1955 aerial photographs. There are no diatomite deposits above the lake level in 1955 photographs. A mollusk from the lake deposits produced an age of 1900 ± 55 ^{14}C yr B.P. (AA34965), and associated charcoal dated to 125 ± 50 ^{14}C yr B.P. (AA34965). This age discrepancy indicates long travel times and/or perhaps significant water–rock interaction for debris-flow seepage.

A rise in the saturated zone and increased seepage within the debris flow probably activated the spring at Site E during lake highstands. Unlike Lake Aricota, potential reservoir effects on aquatic samples from the debris flow are >1000 yr. The organic residue from tufa with a date of 4900 ^{14}C yr B.P. probably represents a maximum date due to this reservoir effect. The humate date from this site may also have been subjected to both contamination by younger organic material and aquatic reservoir effects.

Deltaic Deposits

The sediments of Lake Aricota's main delta are exposed by the anthropogenically induced drop in base level, revealing ∼40 m of foreset beds overlain in places by ∼8 m of topset beds along a sharp truncation. The top of these topset beds is a few meters above the modern lake. Dates from organic-rich clay, wood, plants, and charcoal in the foreset beds are between 4700 and 1900 ^{14}C yr B.P. and <200 ^{14}C yr B.P. (Fig. 4b). Exposed foreset beds steepen downstream and are commonly truncated and laterally discontinuous. Sediment generally consists of poorly sorted medium gravel but also includes local clay-rich strata and boulders. A pervasive paleoerosion surface is cut into the foreset system on the upper delta and is capped by a coarse, horizontal gravel dated at 280 ± 40 (AA36706)) ^{14}C yr B.P. (Fig. 4b). This gravel bed is overlain by a thin layer of fine sediment in the upper reaches of the delta. Charcoal from the fine sediment yielded a postbomb date (AA34622).

The exposed section of Lake Aricota's paleodelta contain the upper units of a Gilbert-type delta sequence (Gilbert, 1890). Bottomset deposits are not observed at Lake Aricota, and it is likely that a substantial portion of the delta lies below the visible, young delta. Radiocarbon dates indicate that Lake Aricota's upper delta was active during the middle and late Holocene. The pervasive nature of the erosion surface between topset and foreset beds may be a result of varied water depth and is bracketed by dates on wood between 1940 ± 70 (GX25848) and 280 ± 40 (AA36706) ^{14}C yr B.P. (Fig. 4b). The paleoclimatic implications of this surface are, however, unclear, but we suggest that it may represent a late Holocene lowstand.

In summary, sections from Lake Aricota contain strong evidence for a mid-Holocene highstand and indicators of moderate changes in lake level since that time (Fig. 5a). Lake Aricota attained a high level no later than 6100 ^{14}C yr B.P., and this high lake level persisted until approximately 2700 ^{14}C yr B.P. Moderate highstands developed at 1700 and 1300 ^{14}C yr B.P.

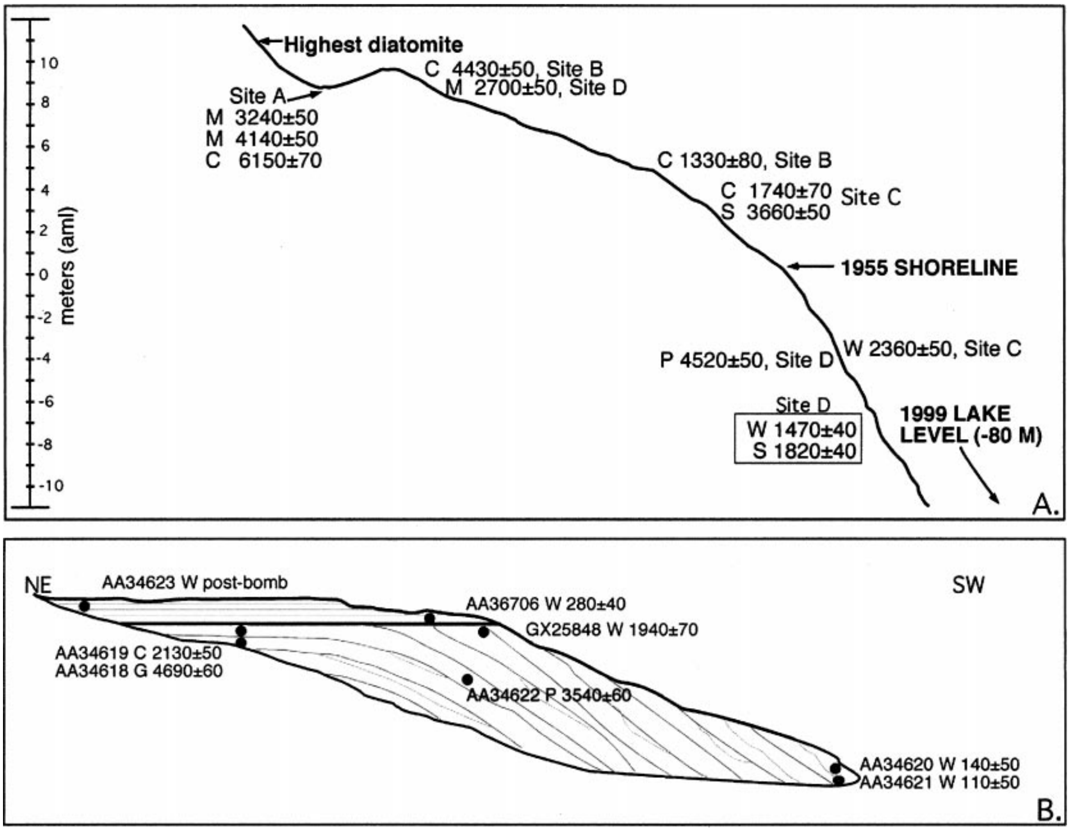

FIG. 4. Composite diagrams of radiocarbon results (^{14}C yr B.P.). Letters preceding dates indicate the type of material dated (see Fig. 2 for key) and boxed samples are from the same stratigraphic level. (A) Composite diagram of the relationship between diatomite samples and elevation (meters above modern lake level). (B) Main paleodelta at Lake Aricota. Diagram is ~40 m high and 3.5 km long; see Fig. 1 for location.

REGIONAL HOLOCENE CLIMATE RECORDS

Evidence for greater effective moisture during the mid-Holocene agrees with some records in the region but contrasts strongly with others. Playa cores, rodent middens, and paleospring deposits provide evidence for a mid-Holocene wet phase in the central Atacama (Fig. 5a). The wet phase observed in these records is, however, only moderately wetter than modern climate at these sites (Bobst *et al.*, in press; Betancourt *et al.*, 2000). Facies analysis of a playa core dated by U/Th disequilibria

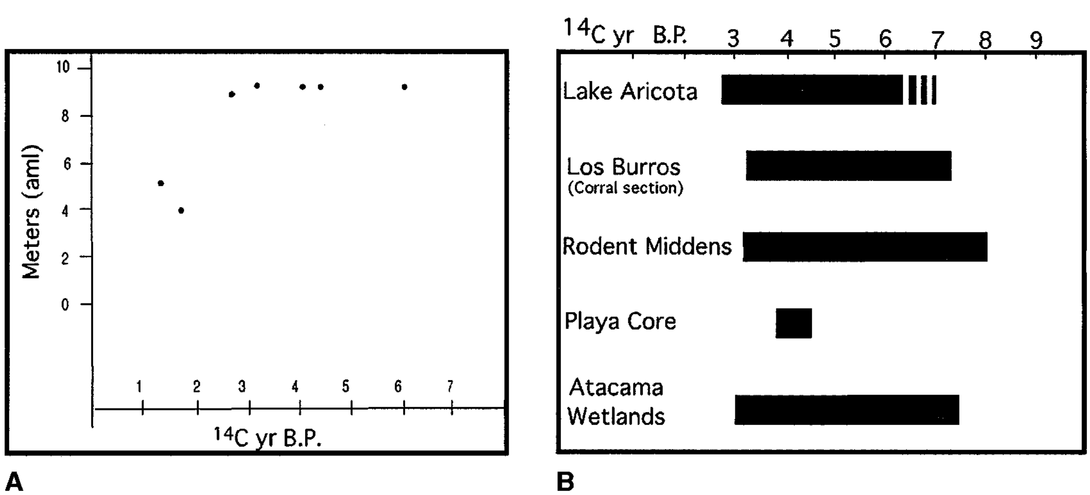

FIG. 5. (A) Holocene lake levels for Aricota. (B) Timing of mid-Holocene wet episodes discussed in text.

from the Salar de Atacama shows a moist interval between 5300 and 3200 cal yr B.P. (∼4500 to 3800 ^{14}C yr B.P.; Bobst *et al.*, in press). Precipitation-induced changes in vegetation are reflected in rodent middens from the central Atacama, which contain higher elevation grasses and shrubs between 8000 and 3000 ^{14}C yr B.P. (Betancourt *et al.*, 2000; see also Latorre *et al.* abstract in http://www.paztcn.wr.usgs.gov). Wetland deposits associated with springs in the Calama/Salar de Atacama basins accumulated during periods of high water tables and were dissected during a subsequent drop in groundwater levels. These wetland deposits date between 7400 and 3000 ^{14}C yr B.P. (Betancourt *et al.*, 2000; see also Rech *et al.* abstract in http://www.paztcn.wr.usgs.gov). A fossil rodent midden series spanning the last 9500 calendar yr B.P. near Arequipa, Peru, shows that mid-Holocene vegetation was relatively stable, if not slightly more mesophytic than today, at the same elevation and only 100 km northwest of Lake Aricota (Holmgren *et al.*, 2001).

Fontugne *et al.* (1999) reported wetland deposits interbedded with eolian sands at Quebrada de los Burros (18°S; 150 m) on the coast of southern Peru. These deposits are attributed to episodes of higher water table and date between 7320 and 3220 ^{14}C yr B.P. at their "corral" section. Groundwater at Quebrada de los Burros is believed to originate in the coastal cordillera (1000 m) and flat plains of Pampa de Lintay (600 m), a few kilometers to the north (Fontugne *et al.*, 1999). The hydrology of these coastal aquifers is not well known, particularly the extent to which variability in groundwater levels reflects variability in coastal fog intensity, actual winter rains, or other inputs, including Andean aquifers. The agreement between coastal and highland groundwater levels would seem inconsistent and requires further investigation.

The mid-Holocene highstand at Lake Aricota occurs at the same time as a pronounced lowstand at Lake Titicaca. Dated evidence of Lake Titicaca's mid-Holocene lowstand includes an erosional unconformity, a rooted macrophyte, and a shell lag (Cross *et al.*, 2000). The physical evidence for lowstands of Lake Titicaca is reinforced by biological and sedimentological proxies (Mourguiart *et al.*, 1998; Baker *et al.*, 2001a), which indicate minimum lake levels between 5000 and 6000 cal yr B.P. (Baker *et al.*, 2001a). The pronounced mid-Holocene lowstand observed at Lake Titicaca is not noted at Lake Junin, another of the region's well-dated lake records (Seltzer *et al.*, 2000). Stable isotope evidence from Lake Junin, in Peru's wet Cordilleras Oriental and Occidental (11°S, ∼875 mm rain/year), argues for increasingly wetter conditions since a dry late glacial/early Holocene (Seltzer *et al.*, 2000). Lake cores from 10 alpine watersheds in the central Andes (14–20°S) indicate general aridity during the mid-Holocene. These cores also indicate that climate was unstable over century to millennial time scales during the entire Holocene. Glacier-fed lakes were not always in phase with Titicaca and other lakes not fed by glaciers (Abbott *et al.*, 2000).

Low lake levels during the mid-Holocene also have been inferred from sedimentological and isotopic analysis of cores from Lakes Lejia, Miscanti, and Seca (Grosjean *et al.*, 1995; Valero-Garcés *et al.*, 1996; Schwalb *et al.*, 1999) in the southern Altiplano. Establishing an accurate chronology for these lakes is greatly complicated by large ^{14}C reservoir effects. The reservoir correction at Laguna Lejia is as much as 11,000 years (Geyh *et al.*, 1999). Calcareous sediments at Laguna Miscanti were dated to >8000 ^{14}C yr B.P., but a reservoir correction of 3000–4000 yr instead suggests a mid-Holocene age for maximum aridity (Valero-Garcés *et al.*, 1996).

Rates of ice accumulation on the Nevado Sajama ice sheet decreased during the mid-Holocene and are interpreted to indicate less precipitation. High dust and anion concentrations in this ice core during the Holocene provide additional evidence of regional lake desiccation (Thompson *et al.*, 1998). Glacial retreats and advances in the central Andes are assumed to be coupled with variability in precipitation more than changes in temperature. Thus, regional glacial retreat during the mid-Holocene is taken as additional evidence of aridity (Seltzer, 1990). Inability to discriminate between temperature and precipitation effects, however, confounds paleoclimatic interpretation of both glacial and lake records.

CONCLUDING REMARKS

Results from Lake Aricota suggest that the mid-Holocene wet episode documented in the central Atacama (22–24°S; Betancourt *et al.*, 2000; Bobst *et al.*, in press) extended well into the northern Atacama (17°N). The likely cause of mid-Holocene wetness in both areas is an increase in summer precipitation. Lake Aricota is too high to be affected by coastal precipitation and too far north to be influenced by the southern westerlies. Records indicating a wet mid-Holocene, however, are on the western fringe of the South American summer monsoon (Fig. 1). These records indicate that the mid-Holocene was only moderately wetter than today. Precipitation variability is more pronounced on the western side of the Altiplano and Pacific slope of the Andes. During wet years the regional east–west precipitation gradient shallows, and drier localities receive a relatively greater increase in precipitation (Vuille *et al.*, 2000). It is possible that the slightly wetter conditions observed in records such as Lake Aricota are undetectable in more humid settings that may be less variable temporally. We recognize the need for empirical studies of modern weather data and mesoscale modeling of climate responses to changing boundary conditions in the central Andes and northern Atacama Desert.

Physiographic differences and chronological uncertainties may also play a role in the apparently contrasting fluctuations of this region's lakes. Lake Aricota, with its small surface-area to depth ratio and outflow via seepage, should be principally responsive to changes in precipitation and less sensitive to changes in rates of evaporation. Thus, a temperature change will have little effect on the level of Lake Arictoa. Thermal effects may, however, overwhelm small changes in precipitation in records from large and/or shallow lakes. Chronological uncertainties and varying response times further hinder correlation of the region's climate records. Studies of additional lakes coupled with comparative modeling are required to reconcile the contrasting mid-Holocene histories of lakes in the region.

Finally, we note that there is a general inconsistency between purported aridity in the central Andes and marine and other evidence for suppressed El Niño strength and frequency during the middle Holocene (e.g., Cole, 2001; see also Clement *et al.*, 2000 and Liu *et al.*, 2000) and indicators of aridity at Lake Titicaca and the central Andes. Today, the transport of moisture across the Altiplano to the Pacific slope of the Andes is at least partly regulated by Pacific influence on the strength of the easterlies, with stronger (weaker) easterlies and wetter (drier) conditions during La Niñas (El Niños). These inconsistencies among ocean and terrestrial paleorecords suggest that there is room for improving our understanding of mid-Holocene climates in the South American tropics.

ACKNOWLEDGMENTS

We thank Claudio Latorre, John Dohrenwend, and Nathan English for assistance in the field and Kate Rylander for assistance in the lab. Permission to collect in Peru was granted by the Instituto Nacional de Recursons Naturales (INRENA). This paper greatly benefited from discussions with Judy Parrish, Julia Cole, Camille Holmgren, and Jason Rech. We also acknowledge the University of Arizona NSF Accelerator Facility. This study was supported by NSF Grant EAR-9904838 to J. Q. and J. L. B.

REFERENCES

Abbott, M. B., Binford, M. W., Brenner, M., and Kelts, K. R. (1997a). A 3500 ^{14}C yr high-resolution record of water-level changes in Lake Titicaca, Bolivia/Peru. *Quaternary Research* **47,** 169–180.

Abbott, M., Seltzer, G. O., Kelts, K. R., and Southon, J. (1997b). Holocene paleohydrology of the tropical Andes from lake records. *Quaternary Research* **47,** 70–80.

Abbott, M. B., Wolfe, B., Aravena, R., Wolfe, A. P., and Seltzer, G. O. (2000). Holocene hydrological reconstructions from stable isotopes and paleolimnology, Cordillera Real, Bolivia. *Quaternary Sciences Reviews* **19,** 1801–1820.

Baker, P. A., Seltzer, G. O., Fritz, S. C., Dunbar, R. B., Grove, M. J., Tapia, P. M., Cross, S. L., Rowe, H. D., and Broda, J. P. (2001a). The history of South American tropical precipitation for the past 25,000 years. *Science* **291,** 640–643.

Baker, P. A., Rigsby, C. A., Seltzer, G. O., Fritz, S. C., Lowenstein, T. K., Bacher, N. P., and Veliz, C. (2001b). Tropical climate changes at millennial and orbital timescales on the Bolivian Altiplano. *Nature* **409,** 698–701.

Betancourt, J. L., Latorre, C., Rech, J. A., Quade, J., and Rylander, K. A. (2000). A 22,000-yr record of monsoonal precipitation from northern Chile's Atacama Desert. *Science* **289,** 1542–1545.

Bobst, A., Lowenstein, T. K., Jordan, T. E., Godfrey, L. V., Hein, M. C., Ku, T.-L., and Luo, S. (in press). A 106 ka paleoclimate record from the Salar de Atacama, Northern Chile. *Palaeogeography, Palaeoclimatology, Palaeoecology*.

Clement, A. C., Seager, R., and Cane, M. A. (2000). Suppression of El Niño during the mid- Holocene by changes in the earth's orbit. *Palaeoceanography* **15,** 731–737.

Cole, J. E. (2001). A slow dance for El Niño. *Science* **291,** 1496–1497.

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,** 21–32.

Fontugne, M., Usselmann P., Lavallee, D., Julien, M., and Hatte, C. (1999). El Niño variability in the coastal desert of southern Peru during the Mid-Holocene. *Quaternary Research* **52,** 171–179.

Geyh, M. A., Grosjean, M., Nuñez, L., and Schotterer, U. (1999). Radiocarbon reservoir effect and the timing of the Late-Glacial/Early Holocene humid phase in the Atacama desert. *Quaternary Research* **52,** 143–153.

Gilbert, G. K. (1890). Lake Bonneville. *United States Geological Survey Monograph*, pp. 65–70.

Grosjean, M., Geyh, M. A., Messerli, B., and Schotterer, U. (1995). Late-glacial and early Holocene lake sediments, ground-water formation and climate in the Atacama Altiplano. *Journal of Paleolimnology* **14,** 241–252.

Grosjean, M., van Leeuwen, J. F. N., van der Knaap, W. O., Geyh, M. A., Ammann, B., Tanner, W., Messerli, B., Nuñez, L. A., Valero-Garces, B. L., and Veit, H. (2000). A 22,000 ^{14}C year B.P. sediment and pollen record of climate change from Laguna Miscanti (23°S), northern Chile. *Global and Planetary Change* **553,** 1–17.

Holmgren, C., Betancourt, J. L., Rylander, K. A., Roque, J., Tovar, O., Zeballos, H., Linares, E., and Quade, J. (2001). Holocene vegetation history from fossil rodent middens near Arequipa, Peru. *Quaternary Research* **56,** 242.

Kull, C., and Grosjean, M. (1998). Albedo changes, Milankovitch forcing, and late Quaternary climate changes in the central Andes. *Climate Dynamics* **14,** 871–881.

Lenters, J. D., and Cook, K. H. (1999). Summertime precipitation variability over South America: Role of the large-scale circulation. *Monthly Weather Review* **127,** 409–431.

Liu, Z., Kutzbach, J., and Wu, L. (2000). Modeling climate shift of El Niño variability in the Holocene. *Geophysical Research Letters* **27,** 2265–2268.

Mourguiart, P., Correge, T., Wirrmann, D., Argollo, J., Montenegro, M. E., Pourchet, M., and Carbonel, P. (1998). Holocene palaeohydrology of Lake Titicaca estimated from an ostracod-based transfer function. *Palaeogeography, Palaeoclimatology, Palaeoecology* **143,** 51–72.

Schwalb, A., Burns, S. J., and Kelts, K. (1999). Holocene environments from stable isotope stratigraphy of ostracods and authigenic carbonate in Chilean Altiplano Lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* **148,** 153–168.

Seltzer, G. (1990). Recent glacial history and paleoclimate of the Peruvian-Bolivian Andes. *Quaternary Science Reviews* **9,** 137–152.

Seltzer, G. O., Baker, P., Cross, S., Dunbar, R., and Fritz, S. (1998). High-resolution seismic reflection profiles from Lake Titicaca, Peru-Bolivia: Evidence for Holocene aridity in the tropical Andes. *Geology* **26,** 167–170.

Seltzer, G., Rodbell, D., and Burns, S. (2000). Isotopic evidence for late Quaternary climate change in tropical South America. *Geology* **28,** 35–38.

Stuiver, M., Reimer, P. J. (1993). Extended ^{14}C database and revised CALIB radiocarbon calibration program. *Radiocarbon* **35,** 215–230.

Sylvestre, F., Servant, M., Servant-Vildary, S., Causse, C., Fournier, M., and Ybert, J.-P. (1999). Lake-level chronology on the southern Bolivian Altiplano (18°–23° S) during Late-Glacial time and the early Holocene. *Quaternary Research* **51,** 54–66.

Thompson, L. G., Davis, M. E., Mosley-Tompson, E., Sowers, T. A., Henderson, K. A., Zagorodnov, V. S., Lin, P.-N., Mikhalenko, V. N., Campen, R. K., Bolzan, J. F., Cole-Dai, J., and Francou, B. (1998). A 25,000-year tropical climate history from Bolivian ice cores. *Science* **282,** 1858–1864.

Trewartha, G. (1981). The Earth's Problem Climates. Univ. of Wisconsin Press, Madison.

Valero-Garcés, B. L., Grosjean, M., Schwalb, A., Geyh, M., Messerli, B., and Kelts, K. (1996). Limnogeology of Laguna Miscanti: Evidence for mid to late Holocene moisture changes in the Atacama Altiplano (Northern Chile). *Journal of Paleolimnology* **16,** 1–21.

Vuille, M. (1999). Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the Southern Oscillation. *International Journal of Climatology* **19,** 1579–1600.

Vuille, M., and Ammann, C. (1997). Regional snowfall patterns in the high, arid Andes. *Climatic Change* **36,** 413–423.

Vuille, M., Bradley, R., and Keimig, F. (2000). Interannual climate variability in the Central Andes and its relation to tropical Pacific and Atlantic forcing. *Journal of Geophysical Research* **105,** 12,447–12,460.

Wirrmann, D., and Alameida, F. L. (1987). Low Holocene level (7700 to 3650 years ago) of Lake Titicaca (Bolivia). *Palaeogeography, Palaeoclimatology, Palaeoecology* **59,** 315–323.

Zhou, J., and Lau, K. M. (1998). Does a monsoon climate exist over South America? *Journal of Climate* **11,** 1020–1040.