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A 3500 ^{14}C yr High-Resolution Record of Water-Level Changes in Lake Titicaca, Bolivia/Peru

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Sediment cores collected from the southern basin of Lake Titicaca (Bolivia/Peru) on a transect from 4.6 m above overflow level to 15.1 m below overflow level are used to identify a new century-scale chronology of Holocene lake-level variations. The results indicate that lithologic and geochemical analyses on a transect of cores can be used to identify and date century-scale lake-level changes. Detailed sedimentary analyses of subfacies and radiocarbon dating were conducted on four representative cores. A chronology based on 60 accelerator mass spectrometer radiocarbon measurements constrains the timing of water-level fluctuations. Two methods were used to estimate the ^{14}C reservoir age. Both indicate that it has remained nearly constant at ∼250 ^{14}C yr during the late Holocene. Core studies based on lithology and geochemistry establish the timing and magnitude of five periods of low lake level, implying negative moisture balance for the northern Andean altiplano over the last 3500 cal yr. Between 3500 and 3350 cal yr B.P., a transition from massive, inorganic-clay facies to laminated organic-matter-rich silts in each of the four cores signals a water-level rise after a prolonged mid-Holocene dry phase. Evidence of other significant low lake levels occurs 2900–2800, 2400–2200, 2000–1700, and 900–500 cal yr B.P. Several of the low lake levels coincided with cultural changes in the region, including the collapse of the Tiwanaku civilization.

INTRODUCTION

Highly resolved lacustrine records are useful for studying the mechanisms and effects of climate change. Spatial and temporal resolution must be both sufficiently extensive and fine-scaled to describe patterns that appear at the scale of the processes of interest. When the affected processes are certain human activities, this criterion for fine-scale resolution can be achieved by spatially defining the unit of study as a lake and its drainage basin and temporally as the period of habitation by humans. Furthermore, the measurement and description of paleoclimate at a lake basin point will be even more valuable if it is imbedded in a spatially extensive web of other point descriptions.

South America has a scarcity of sites with century-scale paleoclimate data sets, yet is extremely important because El Niño/Southern Oscillation events (ENSO) cause major economic hardships, the intertropical convergence zone (ITCZ) migrates over two-thirds of the surface area annually, the vast Amazon basin is the largest remaining forested area in the world (with important climatic and paleoclimatic implications), and several civilizations have developed and collapsed on the continent. The Lake Titicaca drainage basin and associated altiplano in the Peruvian and Bolivian Andes is an endorheic system that was also the site of the Tiwanaku civilization. Nearby alpine glaciers, and the lake itself, contain paleoclimate records. Several previous studies have been done in the Titicaca watershed (Thompson *et al.*, 1985; Wirrmann and Mourguiart, 1995; Abbott *et al.*, 1997). In this paper we describe a finely resolved record of lake-level change driven by climatic variability over the past 3500 yr, and in a compan-

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ion paper Binford *et al.* (1997) describe the effects of climate variation on civilization.

Low lake stands during the middle to late Holocene have been postulated for Lake Titicaca (Wirrmann and Mourguiart, 1995; Wirrmann *et al.*, 1992; Wirrmann and Oliveira Almeida, 1987), but the timing, rate, and mechanism for declines and returns to higher levels remains poorly described. Here we report evidence that suggests a rapid lake-level rise of 15 to 20 m about 3500 yr B.P. and several century-scale low stands at 2900–2800, 2400–2200, 2000–1700, and 900–500 cal yr B.P. These findings substantially improve our knowledge of the timing, duration, and magnitude of variations in the precipitation–evaporation balance of the South American altiplano during the late Holocene. This study also provides the first accurate AMS radiocarbon chronologies required to resolve century-scale dynamics of precipitation–evaporation variations on the altiplano.

This paper has four objectives: (1) to determine lake-level changes by identifying sediment unconformities from detailed core descriptions, smear-slide mineralogy, and the geochemical properties of sediment cores; (2) to define the magnitude of lake-level changes in the Lake Titicaca system based on a transect of cores from shallow to deeper water (0.7, 4.2, 6.0, and 12.6 m below overflow level); (3) to determine a reservoir age model for lake Titicaca to correct ^{14}C dates prior to calibration and assess whether the age has shifted during the past ca. 3500 ^{14}C yr; and (4) to determine a high-resolution chronology for lake-level changes based on 61 AMS radiocarbon dates.

STUDY AREA

Lake Titicaca has an area of ca. 8500 km^2, a drainage of ca. 57,000 km^2, and includes the connected Lago Grande and Lago Wiñaymarka basins (Fig. 1). Lake Titicaca has undergone measurable lake-level changes during the historic period (1914–present) ranging from 3806.2 m in 1943 to 3812.6 m in 1986, with an average annual fluctuation of 0.8 m (Roche *et al.*, 1992). Although Lake Titicaca has varied between a hydrologically open and closed system during the Holocene, it lies in the upper part of a much larger endorheic system that includes Lago Poopo and the vast *salares* in central and southern Bolivia, respectively. Today the lake drains over a 3804-m sill down the Río Desaguadero from the southwest corner of Lago Wiñaymarka (Wirrmann, 1992). We use the elevation of the sill as the base datum for reporting lake-level changes as meters BOL (below overflow level) because of the strong interannual variability of lake levels. This index horizon facilitates description of core boundary depths and lake-level changes inferred from the cored transect. The sill separating the eastern and western basins of Lago Wiñaymarka lies at 10 m BOL. When the water level of Lake Titicaca falls >10 m BOL to 3794 m two separate subbasin lakes are formed. The eastern basin remains connected to Lake Titicaca proper (Lago Grande) by the Tiquina Strait until lake level falls below 16 m BOL (3788 m), and then the Titicaca system separates into three separate lake basins. The four cores from shallow regions of Lago Wiñaymarka are assumed to represent changes in Lake Titicaca as a whole. This is defensible given the morphology of the connections to the main lake and local stream sources.

The Lake Titicaca basin is particularly sensitive to shifts in the precipitation–evaporation balance because even with the overflowing conditions that prevail today, only 1 to 3% of the lake water is lost by overflow. During the recorded period, lake level has remained above the overflow level, although most of the water is removed by evaporation. Estimates of the amount of water lost historically by evaporation range from a mean of 91% from 1968 to 1987 to 99% from 1956 to 1978. Estimates for the average residence time of water in Lake Titicaca range from 60 to 175 yr (Carmouze, 1992; Roche *et al.*, 1992; Han, 1995).

The water balance of the altiplano is affected by many factors including ENSO events, fluctuations in the seasonal location of the ITCZ, and changes in the strength of summer monsoon circulation. Strong ENSO years correlate with drought on the altiplano (Roche *et al.*, 1992). There are strong seasonal contrasts in precipitation, with more than 78% of the average annual precipitation (760 mm/yr basin-wide) occurring during the summer wet season (December–February), when the ITCZ reaches its southernmost extent. Maximum precipitation in the Lake Titicaca watershed occurs on the high mountains in the northeast corner, reaching totals of >1000 mm/yr, and on the southern shore of Lago Grande, where precipitation totals of ~1100 mm/yr are enhanced by lake-effect moisture (Roche *et al.*, 1992).

METHODS

A transect of sediment cores was collected to identify and map the major sediment transitions. Although 15 cores were described, we focused on four representative cores for detailed sediment analysis and high-resolution dating. 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). Organic matter was measured by weight loss on ignition (LOI) at 550°C (Håkanson and Jansson, 1983) and carbonate content was assessed from the weight loss between 550° and 1000°C (Dean, 1974). Calcium, magnesium, iron, and potassium in bulk-sediment samples were measured on a Jarrell-Ash 9000 Inductively Coupled Argon Plasma Spectrophotometer, following ashing at 550°C and digestion for 1 hr

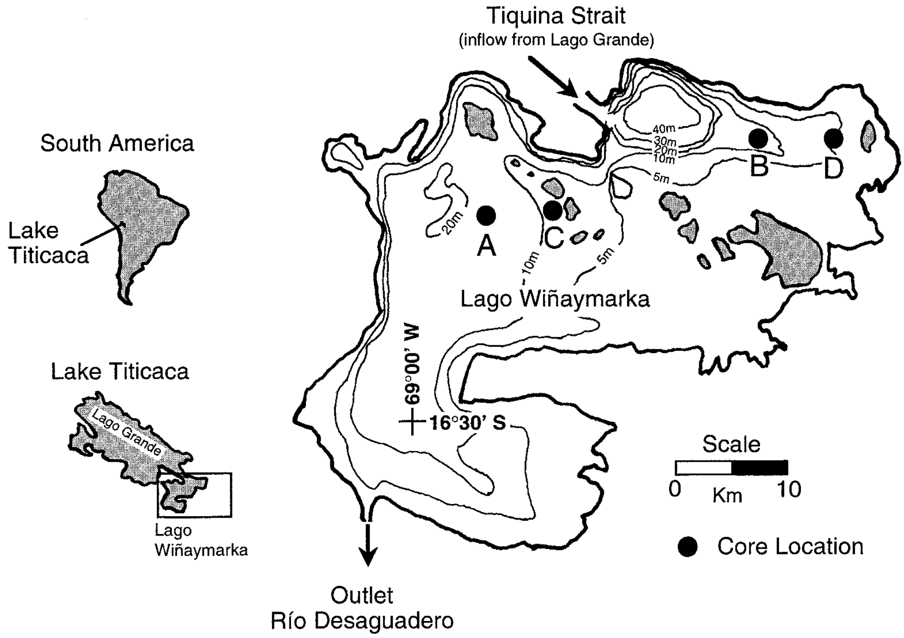

FIG. 1. Map showing the location of Lake Titicaca in South America including Lago Grande and the two subbasins of Lago Wiñaymarka. The bathymetric map shows core sites A and C in the western basin and B and D in the eastern basin. Water drains from Lago Grande through the Tiquina Strait into Lago Wiñaymarka and out of Lake Titicaca down the Río Desaguadero.

in boiling 1 *N* HCl. Lithology was determined from smear-slide mineralogy and detailed inspection of sediments, noting Munsel color, texture, sedimentary structures, and biogenic features.

Most stratigraphic levels contained insufficient terrestrial organic material for AMS ^{14}C measurements. Therefore we used calcite shells from the abundant aquatic gastropods (*Littoridina andecola* and *Littoridina* sp.). All sample material for ^{14}C measurements was wet-sieved through nested screens (500, 250, and 125 μm), microscopically inspected, sonically cleaned, and archived in precombusted glass containers. Carbonate samples were pretreated with 10% dissolution using HCl. Radiocarbon dates were measured at the Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory (CAMS).

Radiocarbon ages are reported either as ^{14}C yr B.P. (uncalibrated) or cal yr B.P. if corrected and calibrated according to the methods outlined for CALIB 3.0 by Stuiver and Reimer (1993). Abrupt sediment transitions interpreted as erosion surfaces were ^{14}C dated by taking samples 1 cm above and below the disturbed contact to avoid reworked material. Where an abrupt transition was interpreted as an unconformity, a ^{14}C measurement from the upper surface was interpreted as an estimate of the age of transgression. A date from just below the unconformity defines a maximum age for the low lake stand because the amount of eroded sediment is unknown. In some cases, these desiccation surfaces show little or no evidence of erosion.

Although sediment transitions associated with subaerial exposure can be identified in a single core, the rate and magnitude of water-level change was resolved with a transect of cores from shallow to deep water. This core series was used to identify subfacies related to increasing water depths (Binford *et al.*, 1992). Surface sediments yielded information that was used to calibrate sediment subfacies formed in particular depth ranges in Lake Titicaca. Water-level reconstructions are based on these criteria.

Exposure surfaces were identified by (1) scour marks, (2) mud cracks, (3) abrupt transitions ($<$1 cm) characterized by coarser grained (fine sand) sediments with high bulk density ($>$1 g/cm^3) overlying fine-grained organic-rich muds ($>$20% organic matter), (4) an abrupt increase in iron and potassium concentration associated with the reducing conditions in water-saturated soils, and (5) highly fragmented shell material in the overlying muds. The presence of one or more of these characteristics combined with an abrupt change in the radiocarbon activity of adjacent strata indicate erosion or nondepositional surfaces. We used detailed core descriptions, a smear-slide mineralogy, and radiocarbon stratigraphy to delimit water-saturated soils and erosion surfaces formed during low water stands and subaerial exposure.

Shallow-water subfacies ($<$2 m water depth) were identified by (1) the presence of high concentrations of achenes (seeds) of the littoral sedge *Schoenoplectus tatora* in a coarse-grained matrix (silt to sand), (2) large amounts of aquatic plant macrofossils (*Myriophyllum*, *Chara*, and *Potamogeton*), and (3) sediments containing >90% $CaCO_3$ composed of calcified macrophyte coatings and fragmented mollusk shells. During prolonged low stands, water-saturated soil formation is more intense, as indicated by order-of-magnitude increases in iron and potassium.

RESULTS

Reservoir Age Measurements and Calibration

Radiocarbon dates derived from aquatic organisms may be significantly older than their true age of deposition because of the long residence time of the lake water and the presence of limestone in the drainage basin that is a source of ^{14}C-depleted carbonate. The contemporary reservoir age of Lake Titicaca was estimated by measuring the ^{14}C activity of aquatic gastropods (*L. andecola*) taken from the A.D. 1900 stratigraphic level (identified by ^{210}Pb dating) to avoid younger samples contaminated by fossil fuels and nuclear-weapons testing (Levin *et al.*, 1989). The measured fraction Modern was corrected for radioactive decay since A.D. 1950 and compared with the value expected from Stuiver and Pearson (1993). The result is a 250-yr offset, which is subtracted from the measured ^{14}C ages prior to calibration (Stuiver and Reimer, 1993).

When lake level falls below 3804 m, Lake Titicaca has no surface outflow and residence time increases. It was thus critical to check whether the ^{14}C reservoir age of Lake Titicaca varied over past centuries. We assessed changes in the ^{14}C reservoir effect for the past 3500 yr by measuring the ^{14}C activity of paired samples formed of carbon from aquatic and atmospheric sources, respectively, collected from the same stratigraphic level. Radiocarbon measurements of *L. andecola* shells and *S. tatora* achenes from five nearly equivalent levels at four core sites indicate that the 250-yr offset has been consistent through time (compare CAMS −17006 to −17048, −16995 to −4981, −16998 to −4978, −11976 to −13601, and −13608 to −13609 in Table 1).

Sediment Cores

Detailed descriptions of sediment cores A, B, and D are included as examples of sedimentary facies from shallow water (<5 m BOL), intermediate water (5–10 m BOL), and deeper water (>10 m BOL) sites, respectively. Radiocarbon dating focused on cores A, B, C, and D to develop century-scale chronologies. The stratigraphy and water depth of core C are similar to core B described below and are therefore not discussed here. Sediment boundaries labeled ES-1 through ES-5 are interpreted as erosion surfaces (ES) and were identified by changes in color, texture, grain size, mineralogy, organic content, biogenic features, and bulk-sediment geochemistry (Figs. 2 and 3). If these surfaces are interpreted as intervals of continuous sedimentation then the units are labeled S-1 through S-4. The radiocarbon dates from stratigraphic levels above and below the erosion surfaces are used as supporting evidence for periods of erosion or nondeposition. Table 1 lists the radiocarbon dates and Table 2 summarizes the age interpretations of the upper and lower boundaries. The radiocarbon dates on ES-5 are variable partly because the samples were arranged to provide an even spread along the length of the core. The dates bracket the unconformities, but do not define them exactly.

Core A was collected in the western basin of Lago Wiñaymarka from 12.6 m BOL (16.6 m water depth when the core was collected in August 1993). The core is 6.6 m long and contains one abrupt sediment transition at 14.2 m BOL (ES-1) and two layers of nearly pure gastropod shell material at 13.7 (S-3) and 13.1 m BOL (S-5) (Fig. 2). Fourteen radiocarbon dates define the abrupt ES-1 boundary and two shell layers S-3 and S-5 that coincide with erosion surfaces ES-3 and ES-5 in cores B, C, and D. Analyses of smear-slide mineralogy show that the sediments immediately below the ES-1 contact contain a higher concentration of clastic component, coarser grain size (silt to fine sand), and decreased organic matter compared with the sediments directly overlying the boundaries. We interpret the shell layers at the S-3 and S-5 contacts as lag deposits formed during a period of lowered lake level, although water still covered the core site and no erosion occurred.

The sediments below 14.2 m BOL are massive, coarse-grained (silt to fine sand), and contain terrestrial sedge seeds suggesting subaerial exposure. Sedimentary structures at the ES-1 boundary are typical erosion scour marks. Aquatic gastropods are absent from the lower boundary. Weakly laminated, fine-grained (clayey-silt) lacustrine muds above ES-1 are dated 3510 + 120/−40 cal yr B.P. (CAMS-11976), documenting the age of lake-level rise.

There is no evidence for the S-2 and S-4 contacts in core A, either because the lake did not drop sufficiently or because the accumulation rate of this core is slow relative to cores from the eastern basin. Between 3510 +120/−40 and 2270 +50/−150 cal yr B.P. (CAMS-11973) calcium carbonate content increased (~40 to 50%), organic matter decreased (~40 to 30%), and clastic material remained relatively constant (~20%).

The S-3 contact is marked by a 1-cm-thick layer of gastropod shells (*L. andecola*). Coincident increases in grain size (silt), clastic material (~50%), and accumulation rate are consistent with a shallow-water environment. The S-3 contact is interpreted as a lag deposit formed during a low lake stand, during which material was transported from recently exposed sites. Likewise, sediments forming the S-5 contact show high concentrations of gastropod shells and an increase

TABLE 1
AMS Radiocarbon Dates and Calibrated Ages[a] from Lake Titicaca Sediment Cores

CAMS No.	Core	Material	Core depth (cm BOL)	Measured radiocarbon age (^{14}C yr B.P.)	Measured error (^{14}C yr)	Median calibrated age (cal yr B.P.)	Calibrated (+) error	Calibrated (−) error
16055	A	Gastropod shell	1307	1150	50	785	120	50
16056	A	Gastropod shell	1315	1500	60	1170	95	100
16058	A	Gastropod shell	1315	250	60			
16057	A	Gastropod shell	1325	1960	60	1590	110	55
11971	A	Gastroped shell	1337	1350	80	980	90	45
11972	A	Gastropod shell	1345	1540	70	1200	90	40
11973	A	Gastropod shell	1367	2450	70	2270	50	150
11974	A	Gastropod shell	1388	2730	70	2640	90	280
11975	A	Gastropod shell	1408	3290	50	3230	100	70
13600	A	Fish scale	1414	3050	100	2870	125	90
11978	A	Fish scale	1414	3180	60	3070	130	110
11976	A	Gastropod shell	1418	3570	60	3510	120	40
13601	A	*S. tatora achenes*	1422	3410	50	3620	60	140
11977	A	Gastropod shell	1423	3540	60	3470	105	10
13596	B	Gastropod shell	647	430	80	150	150	150
13597	B	Gastropod shell	670	850	70	585	70	50
13598	B	Gastropod shell	673	1720	70	1340	70	40
13599	B	Gastropod shell	704	1930	70	1550	140	30
13602	B	Gastropod shell	765	2020	60	1650	80	70
13603	B	Gastropod shell	805	2270	80	1950	30	10
13604	B	Gastropod shell	814	2340	50	2030	95	40
13605	B	Gastropod shell	859	2500	90	2230	110	90
13606	B	Gastropod shell	868	3040	70	2870	80	80
13607	B	Gastropod shell	914	3410	70	3370	90	95
13609	B	Gastropod shell	919	3610	60	3610	75	130
13608	B	*S. tatora achenes*	919	3440	60	3630	65	60
13610	B	*S. tatora achenes*	923	3720	60	3980	110	80
16999	C	Gastropod shell	577	480	70	290	20	290
17000	C	Gastropod shell	590	1020	70	670	60	10
17001	C	Gastropod shell	615	1280	60	940	30	20
17045	C	Gastropod shell	674	2050	50	1710	95	85
17002	C	Gastropod shell	714	2460	50	2260	50	130
17046	C	Gastropod shell	719	2470	60	2250	75	110
17003	C	Gastropod shell	721	2570	50	2340	10	20
17047	C	Gastropod shell	734	2750	100	2560	185	200
17004	C	Gastropod shell	767	3220	60	3120	95	110
17005	C	Gastropod shell	772	3360	60	3350	25	95
17006	C	Gastropod shell	802	3820	60	3840	85	110
17048	C	*S. tatora achenes*	802	3560	70	3770	110	80
17007	C	Gastropod shell	812	3500	100	3470	105	105
5743	D	Gastropod shell	131	680	60	500	20	160
5744	D	Gastropod shell	151	760	60	520	30	20
5745	D	Gastropod shell	169	790	60	540	80	25
16992	D	Gastropod shell	173	660	70	490	20	170
16993	D	Gastropod shell	183	870	70	600	55	60
16994	D	Gastropod shell	203	1020	70	670	60	10
5762	D	Gastropod shell	221	2080	60	1730	100	90
5746	D	Gastropod shell	271	2230	60	1910	80	70
5760	D	Gastropod shell	301	2310	60	2000	110	60
16995	D	Gastropod shell	373	2480	60	2240	90	100
4981	D	*S. tatora achenes*	375	2240	70	2270	50	150
5747	D	Gastropod shell	381	2700	60	2470	240	115
5761	D	Gastropod shell	421	2870	60	2750	20	15
16996	D	Gastropod shell	428	2890	70	2760	20	20
16997	D	Gastropod shell	439	3040	70	2870	80	80
5763	D	Gastropod shell	451	3400	70	3360	95	90
16998	D	Gastropod shell	479	3420	70	3370	95	95
4978	D	*S. tatora achenes*	486	3210	80	3370	95	95
5741	D	Gastropod shell	491	6600	60	7220	60	20
5742	D	Gastropod shell	501	6790	60	7390	80	50

[a] Dates were calibrated by first subtracting the reservoir age (see text) and then calculating the age by using the computer program CALIB 3.0 (Stuiver and Reimer, 1993).

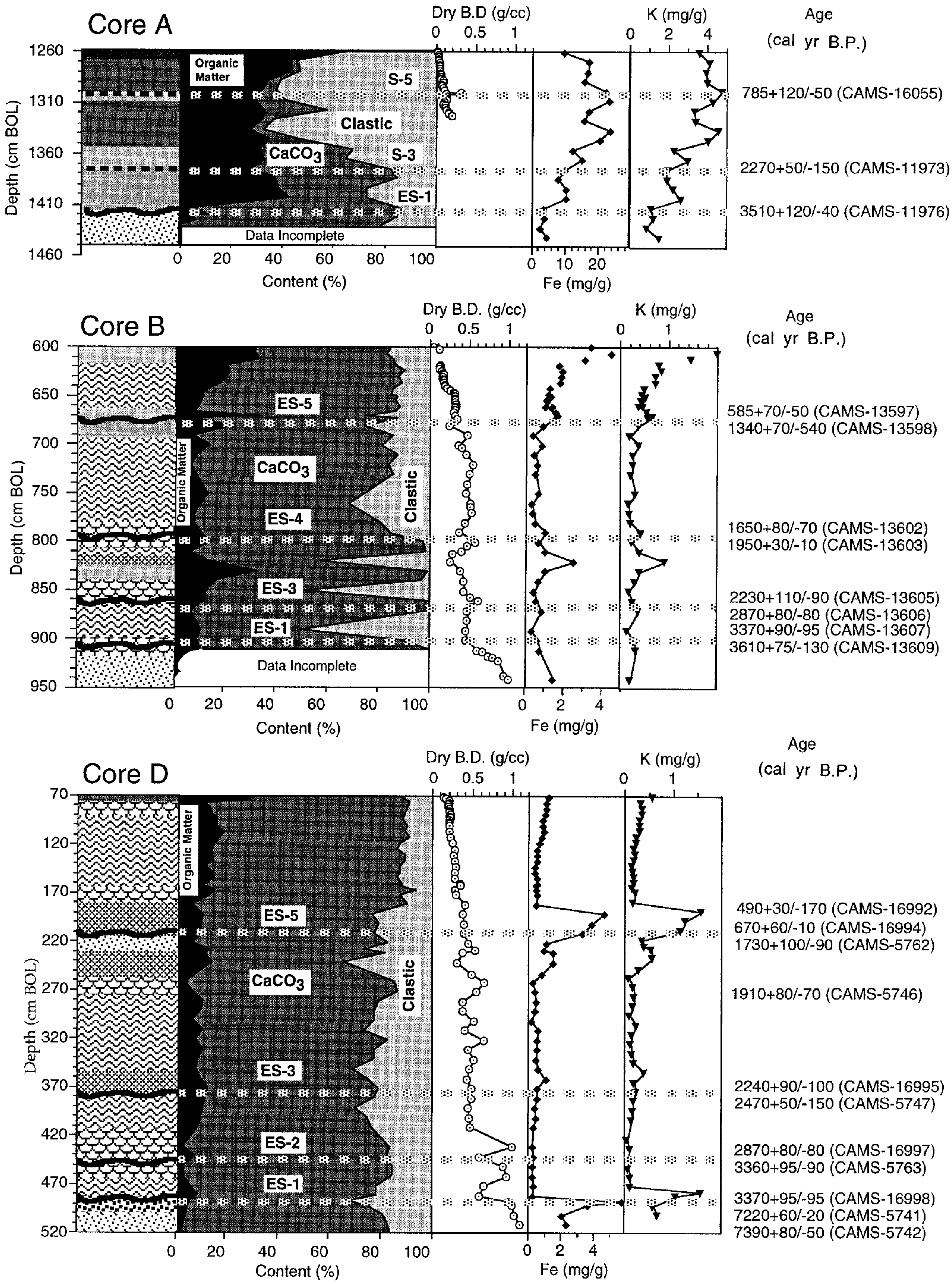

FIG. 2. Stratigraphy and sediment properties for cores A, B, and D. Note the abrupt shifts in core properties across the disconformable surfaces, as indicated by results from smear-slide mineralogy, loss on ignition at 550° and 900°C, dry bulk density measurements, and bulk-sediment geochemistry.

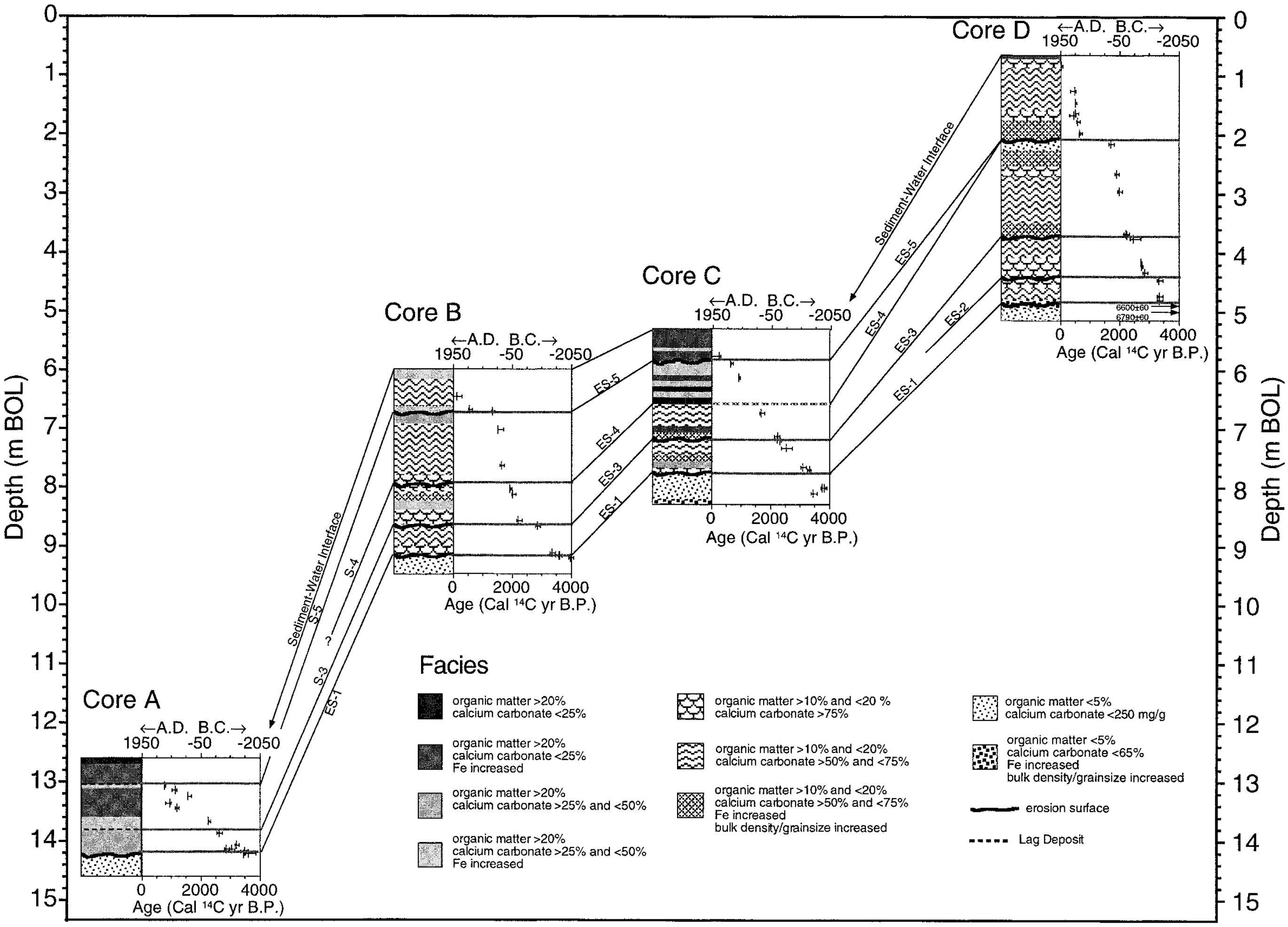

FIG. 3. Transect of cores and age-depth plots showing the location and magnitude of the unconformities. The elevations of cores A, B, C, and D are shown with respect to the overflow level of the lake into Río Desaguadero. The western basin is isolated from the eastern basin when the water falls >10 m BOL (below overflow level). Likewise, the eastern basin is isolated from Lago Grande when the water level falls >15 m BOL.

in clastic material from ~10% to nearly 40%. Above the S-5 contact the organic matter content of the sediments increases to >60% and fine-grained carbonate precipitates comprise <10% of the sediments, consistent with deeper-water sediment facies.

Core B was collected in the eastern basin of Lago Wiñaymarka from 6.0 m BOL (11.1 m water depth in August 1992). The core is 5.4 m long and contains four abrupt sediment transitions at 6.7 m (ES-5), 7.9 m (ES-4), 8.6 m (ES-3), and 9.1 m (ES-1) BOL (Fig. 2) within a 3.5-m-thick late Holocene section. Thirteen radiocarbon dates show that the four abrupt transitions coincide with major shifts in the age plots of the sediments.

Figure 2 illustrates the massive sediments below the ES-1 transition that are dominated by fine-grained calcareous mud (silty clay). This subfacies is characterized by high bulk density (>1 g/cm^3), low organic matter (<10%), and increased iron content, consistent with subaerial exposure. The sediments overlying the ES-1 contact include gastropod shell debris, silt-sized mineral clastics, *S. tatora* achenes, and aquatic macrophytes, indicating a shallow-water facies. This facies is equivalent to ES-2 at core site D.

The sediments overlying the ES-3 contact are characterized by increased grain size (from clayey silt to silt), clastic content (from <10 to 45%), and bulk density (from <0.3 to >0.5 g/cm^3). This is consistent with a shallow-water environment. The sediments overlying the erosion surface contain increased gastropod shell content.

The sediments overlying the ES-4 contact are characterized by increased bulk density (0.4 to >0.6 g/cm^3), increased Fe content, and increased grain size (clayey silt to silt). The overlying sediments exhibit high concentrations of gastropod shells and aquatic macrophytes, consistent with a shallow-water environment.

TABLE 2
Radiocarbon Dates Bracketing Erosion Surfaces ES-1 through ES-5 and Sediment Units S-1 through S-4

Boundary	Core	Elevation of erosion surface (cm BOL)	Elevation of upper age (cm BOL)	Upper age (cal yr B.P.)	Elevation of lower age (cm BOL)	Lower age (cal yr B.P.)
S-5	A	No erosion				
ES-5	B	671	670	585	673	1340
ES-5	C	591	590	670	615	940
ES-5	D	204	203	670		See ES-4
S-4	A	No erosion				
ES-4	B	790	765	1650	805	1950
ES-4	C	670		No date	674	1710
ES-4	D	Eroded		See ES-5	221	1730
S-3	A	No erosion				
ES-3	B	859	859	2230	868	2870
ES-3	C	719	719	2250	721	2340
ES-3	D	374	373	2240	381	2470
S-2	A	No erosion				
S-2	B	Shallow water				
S-2	C	Shallow water				
ES-2	D	440	439	2870	451	3360
ES-1	A	1419	1418	3510	1422	3620
ES-1	B	915	914	3370	919	3610
ES-1	C	774	772	3350	802	3840
ES-1	D	480	479	3370	491	7220

The sediments overlying the ES-5 contact are characterized by coarser grain sizes (from clayey silt to silt), clastic content (from <20 to 35%), and bulk density (from <0.3 to >0.5 g/cm^3). Coincident increases in Fe and K are consistent with the shallow-water oxidizing facies overlying the ES-5 boundary in core D. The thickness of this interval is less in core B, consistent with an increasing water level from 6.7 to 2.1 m BOL. The muds overlying the ES-5 boundary have increased organic content and decreased concentrations of gastropod shells, consistent with deeper-water facies.

Core D was collected in the eastern basin of Lago Wiñaymarka from 0.7 m BOL (5.8 m water depth in August 1992). The core is 4.4 m long and contains four abrupt sediment transitions (<1 cm thick) at 2.0 (ES-5), 3.8 (ES-3), 4.4 (ES-2), and 4.8 m (ES-1) BOL in the late Holocene section. Twenty radiocarbon measurements reveal that the four abrupt contacts coincide with shifts in the radiocarbon age of *L. andecola* shells, suggesting periods of erosion or nondeposition.

The ES-1 boundary at 4.9 m BOL is marked by a shift from massive-gray clays to weakly laminated, organic silts. The sediments below the ES-1 transition contain <5% organic matter, >70% fine-grained calcite (silty clay), elevated Fe (>2 mg/g), and high wet bulk density (>1 g/cm^3) (Fig. 2). They also contain less organic matter, fragmented highly weathered gastropod shells, and *S. tatora* achenes, consistent with a facies formed by reworking of exposed older shallow-water sediments. A 10-cm-thick bed overlying the ES-1 layer is marked by increased organic matter (from <5 to >8%), clastic material (from ~20 to >30%), Fe (from ~2 to 4 mg/g), and K (from ~1 to >1.3 mg/g). This weakly laminated section contains fragmented *L. andecola* shells, *S. tatora* achenes, and fibrous organic matter characteristic of shallow-water environments (<2 m deep). The calculated accumulation rate for this interval is an order of magnitude higher than that measured for the equivalent stratigraphic zone at other sites in the lake. This suggests that material from higher in the lake basin was eroded and redeposited during a transgression. The upper and lower contacts of the ES-1 layer are dated at 3370 ± 95 (CAMS-16998) and 7220 +60/−20 cal yr (CAMS-5741), respectively, implying a 3850-yr hiatus.

Figure 2 shows that sediments overlying the ES-2 transition at 4.4 m BOL are characterized by decreased organic matter (from 8 to <5%), increased grain size (from clayey silt to silt), and higher bulk density (from ~0.6 to ~1.0 g/cm^3). This facies is consistent with a near-shore environment formed during a transgression. The zone between 4.6 and 4.1 m BOL contains two layers of increased bulk density and gastropod shell content, consistent with lower lake stands. The upper and lower contacts of the ES-2 boundary are dated at 2870 ± 80 (CAMS-16997) and 3360 + 95/−90 cal yr (CAMS-5763), respectively, indicating a 490-yr hiatus. This implies that the water level was at least 5 m BOL during this period.

Sediments overlying the ES-3 contact are coarser (from silty clay to clayey silt) and with Fe content to >1 mg/g. The lower sediment unit at the ES-3 contact contains *S. tatora* achenes that suggest a near-shore shallow-water environment (<2 m water depth) for this subfacies. The radiocarbon age of the upper sediment contact is 2240 +90/−100 cal yr B.P. (CAMS-16995).

The sediment subfacies underlying the ES-5 contact is characterized by increased grain size (silt to fine sand) and increased Fe and K content. Sediments immediately overlying the ES-5 boundary exhibit an order-of-magnitude increase in Fe and K content. This facies has lower $CaCO_3$ (<70%) and coarser grain size (clayey silt), consistent with shallow-water oxidizing conditions. Based on accumulation rates, an estimated 150 cm is missing at the ES-5 boundary, representing more than 1000 cal yr. This missing section spans the period that should have contained the ES-4 contact. The sediments in the upper meter of the core show increased organic and carbonate content implying higher water levels at this site beginning 500 yr ago. The upper section of the core contains >80% $CaCO_3$, >15% organic matter, and well-preserved gastropod shells.

LAKE-LEVEL HISTORY

A water-level history for Lake Titicaca is based on calibrated core chronologies for the past 3500 cal yr B.P. Five periods of significant lake-level depression are documented by five erosion surfaces (Fig. 3: ES-1 through ES-5) defined by the criteria discussed above and supported by significant age differences between adjacent strata (Table 2). The lake was probably no more stable during the periods of high and low water than it has been during the 20th century. Therefore, the lake-level curve is represented as a broad band to indicate the level of variability constrained either by radiocarbon dates or by observations over the past century (~6 m) (Fig. 4).

Prior to 3500 cal yr B.P. the lake level was lower than 15 m BOL based on ages of basal sediments in six cores, four of which are discussed in this paper. Lake level rose rapidly after 3500 cal yr B.P., nearing the overflow stage by 3350 cal yr B.P. High accumulation rates in core D around 3350 cal yr B.P. suggest large-scale erosion and reworking of shorelines. Hiatuses in core D between 3300 and 2900 cal yr B.P. and variations in shallow-water facies in cores B and D suggest that water level was variable at this time, fluctuating between the overflow stage and 8 m BOL. The age of the upper boundary of the ES-2 surface in core D indicates that lake level rose after 2900 cal yr B.P. to within 2 m of, and possibly above, the overflow stage.

Erosion surfaces preserved in all cores penetrating 10 m BOL and a lag deposit at 13.8 m BOL in core A indicate that lake level dropped between 10 and 12 m BOL by ~2400 cal yr B.P. Shallow-water lacustrine facies in core D indicate lake level increased abruptly to at least 2 m BOL by 2200 Cal yr B.P. Sediments at sites B and D experienced marked erosion during this low stand and have ^{14}C ages that are similar to those for sediments overlying the ES-3 contact (Table 2).

Lake level fell between 10 and 12 m BOL after 1900 cal yr B.P., as indicated by the ES-4 surface in core B. Deposits covering this period are absent in core D because they were eroded during a subsequent low stand when the ES-5 surface formed. Further supporting evidence for this low stand is found in shallow-water subfacies in core C from the western basin. Shallow-water subfacies in core B indicate lake level rose after 1650 cal yr B.P. to near the overflow level.

The latest prolonged low stand culminated after 700 cal yr B.P., as indicated by the age of the sediments immediately overlying the ES-5 surface in cores B, C, and D. Massive erosion occurred at core sites D and B, making it difficult to estimate the timing of the onset of lower water levels. Shallow-water facies formed in cores B and D at ~600 cal yr B.P. These subfacies have characteristics consistent with deeper water sediments deposited after 500 cal yr B.P. The collapse of the Tiwanaku civilization, which relied on high lake levels for raised-field agriculture, occurred about 800 cal yr B.P. (Binford *et al.*, 1997), which is coincident with shallow-water sediment facies formed during a period of low lake level.

DISCUSSION

Thompson *et al.* (1985) described a 1500-yr record of snow accumulation on the Quelccaya ice cap, located ~200 km to the north at the limit of the Lake Titicaca watershed. This precipitation record shows four periods of prolonged drought during A.D. 540–610, 650–730, 1040–1490, and 1720–1860 and two marked wet intervals at A.D. 760–1040 and 1500–1720 (Thompson, 1992). The first two dry periods recorded in the ice core range from 70 to 80 yr long and do not coincide with low lake stands determined in this study. This implies that snow accumulation on the Quelccaya ice cap is not a perfect proxy for water levels in Lake Titicaca, because the 57,000-km^2 watershed integrates climate over a large area compared to the summit of the Quelccaya ice cap. However, the third dry period identified in the Quelccaya record occurred over a prolonged period of 450 yr and coincides with a low stand of 7–12 m BOL, marked as ES-5 in the core stratigraphies (Fig. 4). The age of the lake-level rise is consistent with high accumulation on the Quelccaya ice cap at the end of this 450-yr period. The two wet periods in the ice core record are between 200 and 300 yr long and coincide with lake levels at or above the overflow level (Fig. 4).

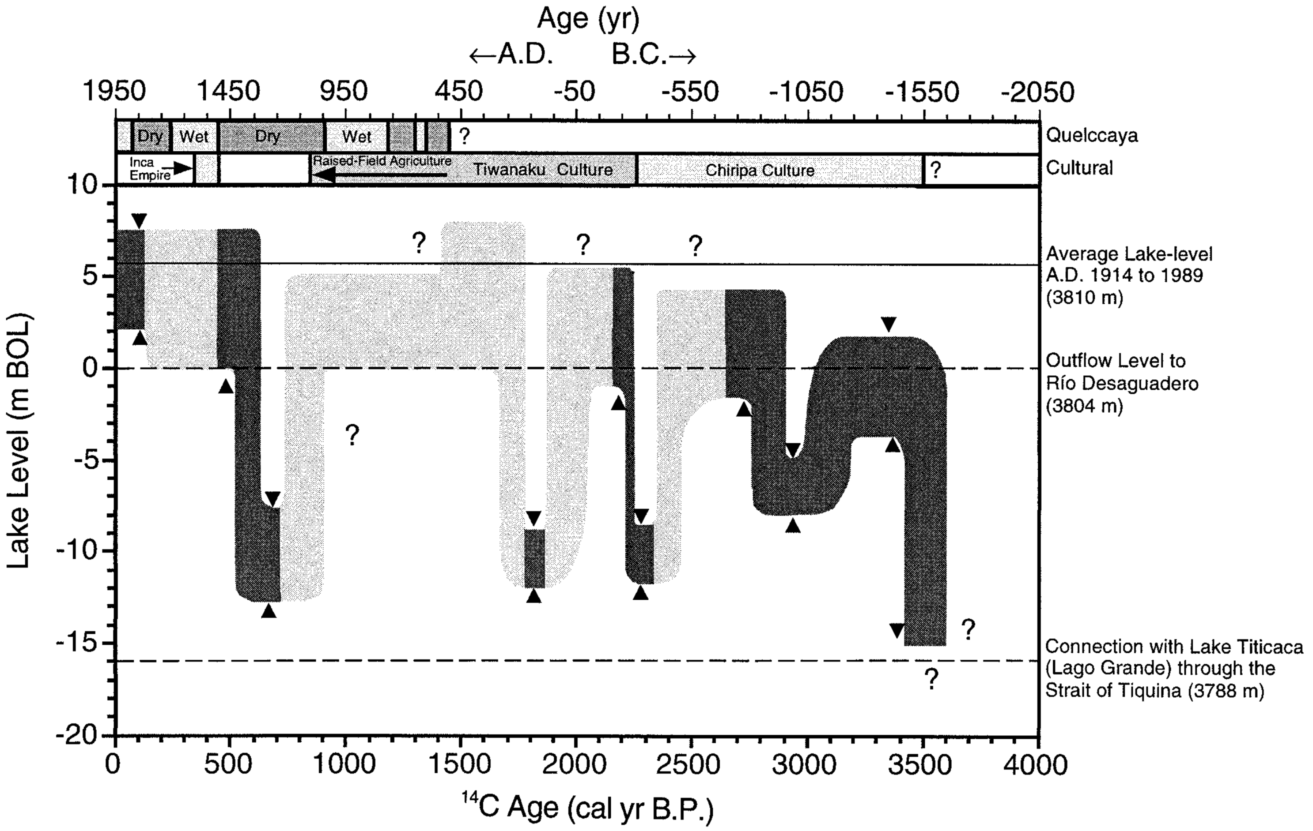

FIG. 4. Water level history of Lake Titicaca based on lithostratigraphy from four cores and 60 AMS ^{14}C measurements. The ▼ symbol signifies the lowest stratigraphic level in cores A–D where an erosion surface occurs suggesting lake level was below this point at the time indicated. Likewise, the ▲ symbol indicates the highest stratigraphic level where lacustrine sediments are preserved, implying water level was above this point. The areas of darker shading represent times where lake level is know with a higher degree of confidence. The broad band represents lake-level variability during a period, either assumed to be equivalent to the 20th century amplitude of fluctuation (6 m) or actually constrained by ^{14}C dates. Question marks signify periods where lake level is not well defined. Interpretations from the Quelccaya ice core record (Thompson *et al.*, 1985) and the cultural record (Ortloff and Kolata, 1993) are shown for comparison (Binford *et al.* (1997).

Thompson *et al.* (1988) observed two major dust events during which particles $\geqslant$0.63 and $<$16.0 μm increase by an order of magnitude, reaching maximum intensity at A.D. 600 and 920. Each lasted ~130 yr. They note that the dust could have been produced by the combination of extensive use of agricultural raised fields and the exposure of large areas of silty lake sediment during low lake stands. These peaks in dust content do not correspond with lake-level decreases interpreted in this study, although they do correspond with periods of major raised-field activity by the Tiwanaku civilization (Kolata, 1993). During field trips in the years 1995 and 1996 we observed a several-meter decline in lake level that exposed very large areas of totora beds and lake sediment that were quickly colonized and used for agricultural purposes. Although the lake level did not reach the elevation of core D by September 1996, which would require an additional 4-m decline, the newly exposed land increased the area available for agriculture by a third (M. W. Binford, unpublished data). Large dust clouds that we observed could be the source of the dust fallout at Quelccaya. A second ice core collected from Huascarán in the north-central Andes of Peru provides a longer record that shows a marked increase in dust concentration at ~2200 yr B.P. (Thompson *et al.*, 1995). This is coincident with a 10- to 12-m low stand identified in this study and with an erosion surface in Lago Taypi Chaka Kkota, a small glacial-fed lake at 4300 m in the southeast corner of the Titicaca Watershed (Abbott *et al.*, 1997). This was unexpected because Huascarán is located in northwestern Peru outside of the altiplano climate zone and therefore suggests a large-scale shift in the precipitation–evaporation balance of the tropical Andes.

Martin *et al.* (1993) used field evidence obtained from four locations in South America to propose long intervals dominated by the Southern Oscillation Low Phase. These century-scale phenomena are manifested either as prolonged periods of ENSO-like conditions or as high frequencies of individual ENSO-like events. Specifically, the field studies suggest that conditions on the altiplano were (1) drier prior to 3900 yr B.P., (2) wetter between 3900–3600 and 2800–2500 yr B.P., and (3) wetter ca. 2200, 1300 yr B.P., and in the recent past. Whereas the general directions and fluctuations proposed by Martin *et al.* (1993) are consistent with our results, we identify more events and estimate the magnitude of the water balance shifts by bracketing extent of lake-level changes with multiple radiocarbon dates on a series of cores. The possibility remains that a connection exists between the century-scale variations in the moisture balance of the altiplano region observed in this study and the long-term variations in the frequency of ENSO events. Although ENSO events have been reviewed and categorized over historic times (cf. Anderson, 1992; Quinn *et al.*, 1987), little is known about the changes in the longer term frequency of these events (Sandweiss *et al.*, 1996).

Mourguiart (1990) reconstructed water-level changes in Lake Titicaca based on a transfer function using the modern ostracod fauna. The results suggest the following lake level history: (1) >20 m lower prior to 7700 ^{14}C yr B.P., (2) dry or fluctuating ca. 20 m lower 7700–3900 yr B.P., (3) 3–5 m below present level 3900–1500 yr B.P., and (4) modern levels after 1500 yr B.P. (see also Wirrmann *et al.*, 1990). We show that the mid-Holocene dry phase ended abruptly between 3500 and 3350 cal yr B.P. We also note a 8- to 12-m decrease in lake level ending after 650 cal yr B.P., as well as three other fluctuations in water level. Wirrmann *et al.* (1990) noted a dry period at 2500–2300 yr B.P. in a core from 8 m of water depth from the western basin of Lago Wiñaymarka. We date a similar dry phase ending at 2200 cal yr B.P. Wirrmann and Mourguiart (1995) modified their original lake-level scenario, suggesting that the Lake Titicaca system rose gradually in two steps: (1) the lake level increased to 3797 m (7 m BOL) at 3800 yr B.P. and remained relatively constant until 2200 yr B.P. and (2) the water level stabilized at 3800 m (4 m BOL) at 2000 yr B.P. before rising to its present level at 1600 yr B.P. This is inconsistent with the results of our study, probably because of our closer dating and sampling resolution and because we include a carbon-reservoir correction and calibration.

CONCLUSIONS

This study demonstrates that the level of Lake Titicaca has fluctuated with an amplitude >22 m during the past 3500 cal yr and that four of the low stands were both profound and occurred abruptly over a period of 100–200 yr. The middle to late Holocene has been hydrologically eventful on the South American altiplano, with five periods of low water stands in Lake Titicaca. The earliest occurred during a prolonged mid-Holocene dry phase ending after 3500 cal yr B.P. All of the cores collected in Lago Wiñaymarka for this study penetrate previously exposed sediments, indicating that Lake Titicaca was >15 m BOL prior to 3500 cal yr B.P. A second low stand of 5–8 m BOL occurred between 2900 and 2800 cal yr B.P. Shallow-water subfacies dating between 3500 and 2900 cal yr B.P. suggest that the lake remained below the overflow stage during this period. The third low lake stand of 10–12 m BOL ended after 2200 cal yr B.P. The duration of this dry phase is estimated to have been 200 cal yr long. The fourth low stand of 10–12 m BOL ended after 1650 cal yr B.P. The duration of this phase remains unknown, but was likely ca. 200 yr based on sediment accumulation rates. The final low lake level of 7–12 m BOL began prior to 900 cal yr B.P. and ended after 700 cal yr B.P. Shallow-water subfacies suggest that water level probably remained low until 500 cal yr B.P. The final low lake stand is coincident with the decline of raised-field agriculture and the collapse of Tiwanaku culture. Even more provocatively, at least one other low stand was approximately coincident with the transition from the earlier Chiripa culture to the Tiwanaku. This dry period was severe enough to appear in Core A, the deep water core. We do not speculate on the relationships between climate fluctuation and the cultural transition because very little is known about the Chiripa culture.

The cause of the observed changes in the precipitation–evaporation balance remains uncertain. The abruptness (100–200 yr) of the shifts between high and low lake stands, however, suggests that changes in the mode of atmospheric circulation is a likely cause. However, our data shed no new light on the mechanism.

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