QUATERNARY RESEARCH **47,** 235–248 (1997)
ARTICLE NO. QR971882

Climate Variation and the Rise and Fall of an Andean Civilization

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Received May 7, 1996

Paleolimnological and archaeological records that span 3500 years from Lake Titicaca and the surrounding Bolivian–Peruvian altiplano demonstrate that the emergence of agriculture (ca. 1500 B.C.) and the collapse of the Tiwanaku civilization (ca. A.D. 1100) coincided with periods of abrupt, profound climate change. The timing and magnitude of climate changes are inferred from stratigraphic evidence of lake-level variation recorded in ^{14}C-dated lake-sediment cores. Paleolake levels provide estimates of drainage basin water balance. Archaeological evidence establishes spatial and temporal patterns of agricultural field use and abandonment. Prior to 1500 B.C., aridity in the altiplano precluded intensive agriculture. During a wetter period from 1500 B.C. to A.D. 1100, the Tiwanaku civilization and its immediate predecessors developed specialized agricultural methods that stimulated population growth and sustained large human settlements. A prolonged drier period (ca. A.D. 1100–1400) caused declining agricultural production, field abandonment, and cultural collapse.

INTRODUCTION

Precolumbian Andean civilizations offer exceptional insights into human–environment interactions. These civilizations developed irrigated agriculture that sustained dense human populations in apparently arduous environments. The emergence, persistence, and subsequent collapse of the Tiwanaku civilization (300 B.C.–A.D. 1100) in the Andean altiplano illustrates remarkable cultural adaptability within a seemingly harsh environment, as well as the existence of a critical environmental threshold.

Environmental thresholds vary through time as climate changes, populations grow, cultures and their technologies evolve, and resources are depleted or substituted. Here we address an environmental threshold defined as climatic extremes that limit the complexity of cultural development. Our study demonstrates that (1) initiation of agriculture and the emergence of complex pre-Tiwanaku societies near Lake Titicaca coincided with increased available moisture ca. 1500 B.C. that caused a >20-m rise in lake level and (2) the collapse of the Tiwanaku civilization ca. A.D. 1100 coincided with a protracted drier period that lowered lake level 12–17 m. An environmental threshold was exceeded prior to 1500 B.C., when arid conditions precluded intensive agriculture. The decline in available moisture after A.D. 1150 was less severe. However, by this time Tiwanaku was sustained by a highly productive, water-dependent form of intensive cultivation on raised agricultural fields. The environmental threshold was exceeded because the raised-field system had stimulated dense human populations that could not be supported during drier conditions.

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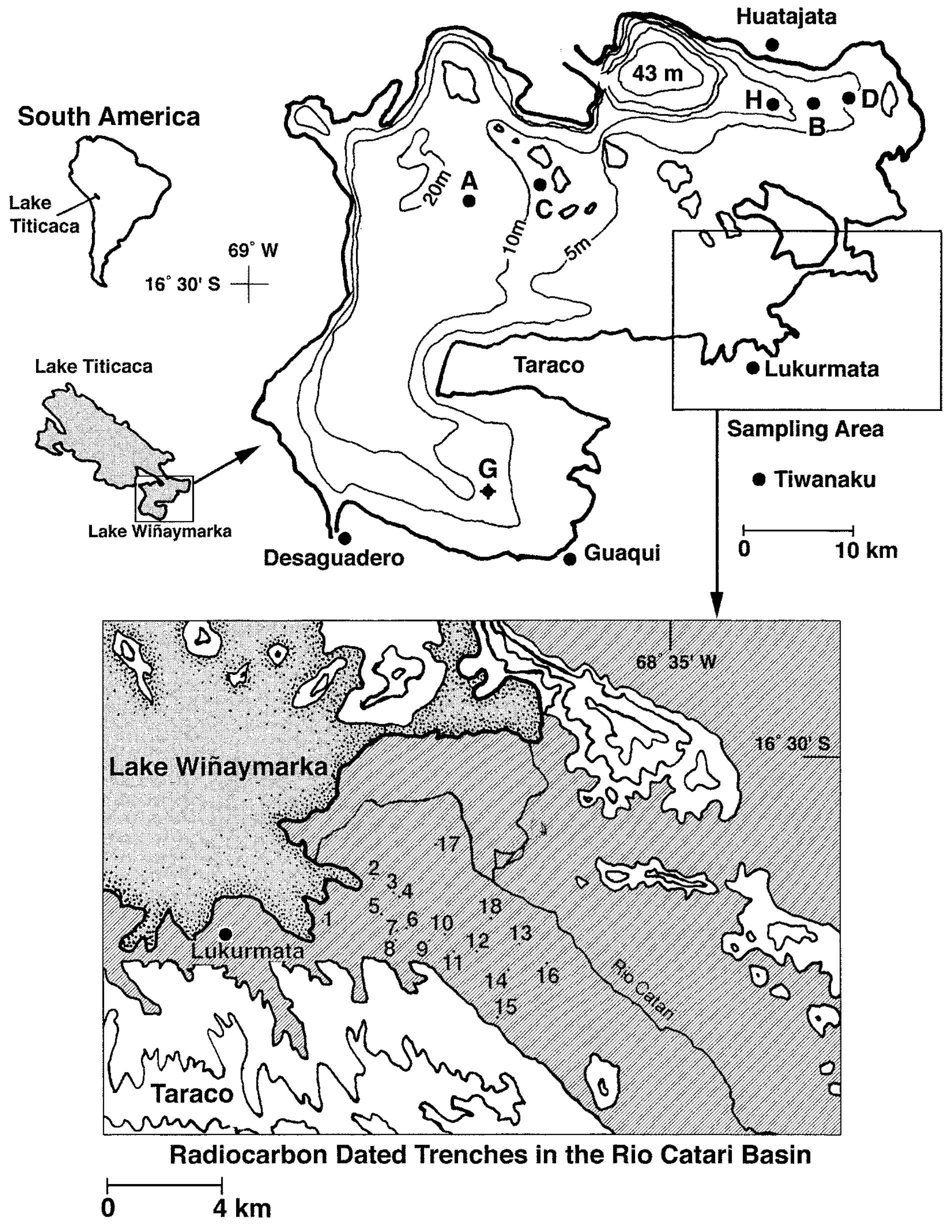

FIG. 1. Map of Lake Wiñaymarka (Titicaca) and the Rio Catari Basin showing 1977 bathymetry, coring locations, archaeological sites, extent of abandoned raised fields (shaded area in lower map), and excavation sites (numbered points).

SITE DESCRIPTION

The ecosystems of the Tiwanaku and Catari River drainage basins near Lake Titicaca constitute the Tiwanaku civilization's core area (Fig. 1). The basins lie in the intermontane altiplano between 4200 and 3800 m altitude. The basin floors, or *pampas*, are perennially marshy and subject to seasonal inundation and are covered by large areas of abandoned raised fields and associated Tiwanaku-period drainage features (Kolata, 1993).

Raised fields were first described as ancient and pantropical agricultural systems by Denevan (1970) and Denevan and Turner (1974). Tiwanaku raised fields are elevated earthen platforms from 3 to 10 m wide and up to 200 m long. Seasonally flooded canals alternate with platform planting surfaces. Approximately 30–60% of the field area is planting surface. Water in canals is supplied mostly by springs, rivers, or groundwater, depending upon field location. We believe that these fields were first constructed to raise the root zone above water-saturated soils. Several advantageous physical, chemical, and biological consequences result from field morphology. Raised fields conserve heat (Kolata and Ortloff, 1989; Sanchez de Lozada, 1996), retain dissolved and particulate nutrients (Carney *et al.*, 1993), enhance nitrogen fixation (D. D. Biesboer, unpublished data), and may decrease soil salinity (Sanchez de Lozada, 1996), contributing to the productivity and sustainability of the cultivation system.

The Tiwanaku core area contains approximately 190 km^2 of abandoned raised fields (Kolata, 1993). Each hectare could have supported the minimum annual caloric requirements of 20–40 people, or a total of 380,000 to 760,000 people (Kolata, 1993). From archaeological evidence, Kolata (1993) extrapolates a core area population of about 365,000 people, which is at the lower end of the range of the potential population. About 40,000 people now inhabit the area, practicing dry farming on steep hillslopes with nutrient-poor soils subject to severe erosion.

Modern climate in the area is cool (9°C annual mean). Mean diurnal temperature fluctuations (±13°C) exceed the annual mean monthly variation (±3°C). Eighty-five percent of mean annual precipitation (ca. 750 mm) falls from December to March. Precipitation and potential evapotranspiration are approximately equal in January and February. Average monthly precipitation is less than mean monthly potential evapotranspiration from March to December. Lacking groundwater sources, soils will suffer a permanent moisture deficit and a consequent increase in salinity.

During the 20th century, on average, the lake rose 80 cm in the rainy season and fell 78 cm in the dry season. Since 1912, lake level has fluctuated 6.4 m from a low of 3805.2 m in 1943 to a high of 3811.6 in 1986. When the level is lower than the outlet sill in Desaguadero (3804 m), the lake is closed. Even at higher levels, $<1\%$ of the water entering the lake exits via the outflow, so that the lake behaves hydrologically as if it were a closed basin when at levels measured in the 20th century (Roche *et al.*, 1992). Lake level is correlated with annual precipitation, which tends to be lower during El Niño–Southern Oscillation (ENSO) years (Roche *et al.*, 1992; Binford and Kolata, 1996).

CULTURE AND CLIMATE HISTORY

The earliest agricultural communities in the southern Titicaca basin belonged to the Chiripa culture (1500 to 200 B.C.). Chiripa agriculture appears to have consisted primarily of dryland farming with low total production relative to subsequent raised-field cultivation. Dryland cultivation continued after the emergence of Tiwanaku about 400 B.C. In the Tiwanaku core area, raised-field cultivation on wetlands emerged after A.D. 600 and expanded to a regional scale by A.D. 800–1000 (Seddon, 1994). Raised-field farming was the principal method of local food production until the disintegration of Tiwanaku ca. A.D. 1100. Other methods of intensive agriculture such as irrigated and dry-farmed terracing replaced raised fields by A.D. 1450 (Kolata, 1993).

The altiplano climate and the level of Lake Titicaca have varied greatly during the Holocene. Between A.D. 350 and ~500, the lake level was higher than today, coincident with early construction of raised fields (Binford *et al.*, 1996; Binford and Kolata, 1996). The paleoclimate record from the Quelccaya ice cap in Peru indicates wetter periods from A.D. 610 to 650 and 760 to 1040 and drier periods from A.D. 540 to 610, 650 to 760, and ca. 1100 to 1500 (Thompson *et al.*, 1985; Thompson and Mosley-Thompson, 1987; Thompson, 1992). Expansion of raised fields coincided with several centuries of high average ice accumulation at Quelccaya. Long-term average ice accumulation at Quelccaya declined by about 15% (from 1.44 to 1.22 m yr^{-1}) between A.D. 1000 and 1100 and remained low for 300–400 yr (Thompson *et al.*, 1985; Ortloff and Kolata, 1993). Reduction of net precipitation may have affected the entire central Andean region and possibly the western portions of South America (Ortloff and Kolata, 1993; Stine, 1994). Ortloff and Kolata (1993) and Ortloff (1996) infer that decreased rainfall severely reduced ground water recharge and spring and river flows.

Application of the Quelccaya record may not accurately describe conditions in Lake Titicaca 200 km to the south and >2000 m lower. Nonetheless, our independent archaeological and paleolimnological data from the Tiwanaku area provide evidence that climate extremes dramatically affected cultural developments in the altiplano.

METHODS

Paleolimnological Field Methods

Sediment cores were collected at six sites along a transect in water depths of 5.8 to 16.6 m (Fig. 1). Sediment–water interface sections were taken with a 7.5-cm diameter plastic-barrel corer (Fisher *et al.*, 1992) and deeper sections were taken in 1-m segments with a square-rod piston corer (Wright *et al.*, 1984). We depict core stratigraphies relative to a 0 datum at the depth of the lake outflow at 3804 m altitude. Core sample and lake elevations are described as meters below outlet level (BOL) or above outlet level (AOL). Twentieth-century mean dry-season lake level is 3808 m altitude, or 4 m AOL.

Gross stratigraphy of sediment cores was described and photographed in the field. Cores were wrapped in plastic and aluminum foil and stored in PVC pipe for shipment to the laboratory, where they were described in detail. Cores were then subsampled in 1-cm contiguous segments. Subsamples at 10-cm or smaller intervals were selected for analyses.

Archaeological Field Excavations

We selected excavation sites by a stratified random sample design, with strata defined as all points in the Catari basin between 3811–3815, 3816–3820, 3821–3823, and 3824–3825 m altitude inclusive. These four strata represented approximately equal areas in the zone of known distribution of raised fields. This sampling design was appropriate because elevation above the lake level strongly controls the relationship between groundwater and surface water, and the location of raised fields should be dependent on altitude (Kolata, 1993). We designated 150 points for sampling within each stratum by randomly selecting Universal Transverse Mercator (UTM) coordinates defined in a geographic information system (GIS) data base with a 30-m ground cell resolution.

Of the 600 points in the *pampas* of the Catari basin, the 300 points in the area south of the Rio Catari were designated the sampling universe. We eliminated 107 points because they were located in rocky streambeds, on tops of hills too small to appear on the topographic quadrangle, or on private land to which we were denied access. The 193 remaining sites were located in the field with a Garmin GPS 100 Survey II global positioning system, with a mean horizontal position error of ±30 m, equivalent to the resolution of the GIS. Sites were excavated whether or not they fell in areas with preserved raised fields. A test trench 1 m deep by 3 m long was opened perpendicular to the long axis of raised fields, or in alternating N–S or E–W alignments if no raised fields were visible on the surface. If the trench encountered surface-expressed or buried raised fields, the long axis was elongated to 6 m. The trench was then deepened to either the water table or at least 25 cm below any anthropogenic feature. Trench depths ranged from 1 to 2.6 m below the ground surface. Surface and subsurface features in each trench were profiled and photographed. Samples of organic material and mollusc shells were collected for radiocarbon dating.

Laboratory Methods

Core sediment samples were dried at 105°C and combusted at 550°C to determine water and organic matter content, respectively (Dean, 1974). Total and inorganic carbon were measured coulometrically (Engleman *et al.*, 1985). Nitrogen was measured by autoanalyzer following sediment digestion (Parkinson and Allen, 1975).

Radiocarbon Dating

AMS radiocarbon dates for lake sediment cores were determined at the Lawrence Livermore Laboratory for gastropod shells (*Littoridina andecola* and *Littoridina* sp.), sedge achenes of *Schoenoplectus tatora,* and fish scales (Abbott *et al.*, 1997). We estimated the contemporary reservoir age of carbon in lake water, or the ‘‘hard-water error’’ (Deevey and Stuiver, 1964), by dating gastropods deposited ca. A.D. 1890 as determined by ^{210}Pb dating. Paired dates from sedge achenes and aquatic gastropods from deeper core sections suggest that the reservoir age has been about 250 yr since 3400 ^{14}C yr B.P. (Abbott *et al.*, 1997). We interpolated the dates of sediment horizons between ^{14}C dates by assuming a constant annual accumulation rate of dry sediment mass.

AMS radiocarbon dates of freshwater gastropod shells (*Taphius montanus*), charcoal, and organic matter from archaeological contexts were determined at the National Ocean Science AMS Facility at Woods Hole Oceanographic Institution. Calibrated dates for both archaeological and core sediments were calculated, after reservoir-age correction, with CALIB 3.0 (Stuiver and Reimer, 1993).

Stable Isotopes

Eighty-eight samples of the ostracod *Limnocythere* were taken at 2- or 5-cm intervals for measurement of δ^{18}O in core D. Sediment samples were disaggregated in 2–3% H_2O_2 and washed through a 106-μm sieve. Individual ostracod valves were picked, dried, ultrasonically cleaned in distilled water, soaked in H_2O_2, and rinsed with methanol. Aggregate samples of about 40 carapaces, weighing about 400 mg, were reacted in 100% orthophosphoric acid at 70°C using a VG Isogas autocarbonate preparation system. The δ^{18}O of purified CO_2 gas was measured with a triple-collector VG Isogas PRISM mass spectrometer. All δ^{18}O measurements are reported as deviation from the PDB standard. Analytical precision for δ^{18}O is ±0.14‰.

Water Budget Modeling

We used an existing surface heat-budget and water-budget model for the Lake Titicaca basin to estimate paleoprecipitation (Hastenrath and Kutzbach, 1985). The hypsographic curve relating lake surface area to water depth was developed from the 1977 bathymetric map published by the joint Bolivian–Peruvian commission (Comisión Mixta Peru-Bolivia, 1977) and refined by Wirrmann (1992).

The nonlinear, steady-state model is

$$1 = 1/(1 + B_l)*(R_l/\mathrm{LP})*a_l + (1 - e^{-(Rb/\mathrm{LP})})*(1 - a_l),$$

where B is the Bowen ratio (ratio of the flux of sensible heat to the flux of latent heat), R_1 and R_b are the net radiation at the surface (W m^{-2}) of the lake and drainage basin, respectively, LP is the precipitation-heat equivalent (1 W m^{-2} = 12.97 mm precipitation yr^{-1}), and a_1 is the fractional area of the basin occupied by the lake. We used the parameter values in Table 1, which were defined by Hastenrath and Kutzbach (1985) and assumed constant insolation (G and G_0), surface albedo (a), surface emissivity (e), and Angstrom ratio (A) of the land surface to solve for LP.

RESULTS

Sediment Core Stratigraphy and Chronology

Core sediment stratigraphies are described in detail by Abbott *et al.* (1997). Three major stratigraphic units occur in every core (Fig. 2). The lowest unit is a gray clay that resembles gleyed wetland soil. The clay differs from the

TABLE 1
Parameters for Model of Lake Water Balance (Hastenrath and Kutzbach 1985)

Symbol	Quantity	Units	Lake value	Land value
a_1	Area of lake as proportion of basin	—	Solution	Solution
G_o	Global radiation (clear sky)	(W/m^2)	300	300
c	Fractional cloud cover	—	0.11	0.11
$G = (1 - c)G_0$	Global radiation (with clouds)	(W/m^2)	267	267
a	Surface albedo	—	0.06	0.3
$G(1 - a)$	Net shortwave radiation absorbed at the surface	(W/m^2)	251	187
e	Surface emissivity	—	0.96	0.9
T	Surface temperature	(°K)	285	284
A	Angstrom ratio	—	0.146	0.195
$\mathrm{LW} = \mathrm{A}e\ 5.7^{-8}\ T^4$	Net long-wave radiation emitted from surface	(W/m^2)	53	65
$R = G(1 - a) - \mathrm{LW}$	Net radiation at surface	(W/m^2)	198	122
B	Bowen ratio	—	0.2	3
$L_\mathrm{E} = R/(1 + B)$	Evaporation (latent heat equivalent)	(W/m^2)	165	30
$E = (L_\mathrm{E}/0.077)$	Evaporation	(mm)	2146	396

overlying organic sediment in having much lower organic content, higher bulk density, and lower Ca but higher Fe, K, and Mg concentrations (Abbott *et al.*, 1997). The clay appears similar to Pleistocene inorganic clays that underlie organic-rich sediments in many neotropical lakes (Bradbury *et al.*, 1981; Deevey *et al.*, 1983; Brenner *et al.*, 1994). Such clays may develop through a process of soil formation followed by flooding. When lake level rises, inundated mineral soils are saturated, creating reducing conditions that lead to gleyzation (Gambrell and Patrick, 1978; Reddy *et al.*, 1986). We interpret the gray clay as a mineral soil that developed prior to ca. 1500 B.C., indicating a period of lower lake level and drier climate, whereas the laminated, organic sediments were deposited during the higher stand after ca. 1500 B.C.

This interpretation is consistent with earlier results that the mid-Holocene dry period terminated 3650 yr B.P. (Mourguiart *et al.*, 1986; Wirrmann and Oliveira Almeida, 1987; Wirrmann *et al.*, 1992; Wirrmann and Mourguiart, 1995). Our more recent radiocarbon dates refine the previous chronology because (1) dates in the prior studies were based on analysis of mixed-origin, bulk organic matter from cores taken in water 15–20 m deep, (2) dates were not corrected for hard-water error, (3) samples were not taken as close to the gray clay–organic lake sediment transition, and (4) reported dates were not from cores taken at sites with significantly different water depths.

An erosion surface and an abrupt transition to laminated organic sediments occur at the top of the gray clay in all our Lake Titicaca cores (Abbott *et al.*, 1997). The organic, laminated zone ranges in thickness from less than 1 m in core A to nearly 5 m in core H. Laminations range from submillimeter thickness to several centimeters, with intermittent layers of large particulates that may be gypsum crystals. Preserved laminae suggest formation in deep anaerobic waters where they would have been protected from wind-driven mixing and bioturbation.

The uppermost stratigraphic unit in the cores is a section of homogeneous gyttja that ranges from a few centimeters to nearly 3 m thick. The transition between the laminated and homogeneous sediments is gradual, usually occurring over several centimeters.

The gray clay has a terminal age of ca. 3500–3200 ^{14}C yr B.P. (Fig. 2; Abbott *et al.*, 1997). Radiocarbon dates at the transition from gray clay to organic lake sediment are concordant in all cores, despite the fact that the contact ranges over 10 m in altitude and the cores were taken at sites more than 25 km apart (Figs. 1 and 2). The ^{14}C date at 15 m BOL in core A is 3540 ± 60 ^{14}C yr B.P. or 1420 ± 120 cal yr B.C. This date indicates that the lake was $>$19 m lower than today until about 3500 years ago but rose $>$10 m during the subsequent 200–400 years. Terminal dates of the laminated organic zone fall between 2080 and 1020 ^{14}C yr B.P.

Lacustrine deposition occurred at all sites after ca. 1200 B.C. Short-term sedimentation hiatuses and inferred low-level stands occur throughout the cores for the past 3500 yr and are described in detail in Abbott *et al.* (1997). Abbott *et al.* report four additional unconformities between the lower gray clay and the sediment–water interface. The most conspicuous occurs near the transition from laminated sediments to homogeneous gyttja in the three cores from shallower water. We focus here on the most prominent hiatus, which was coincident with the collapse of the Tiwanaku civilization as indicated by very different ages in close vertical proximity in the two shallower of the four cores that have been dated at close intervals (Fig. 3). This sedimentation hiatus and stratigraphic unconformity are found in cores B, C, and D. Core A was taken at a deep site covered by water at the lowest lake level, and therefore the hiatus is

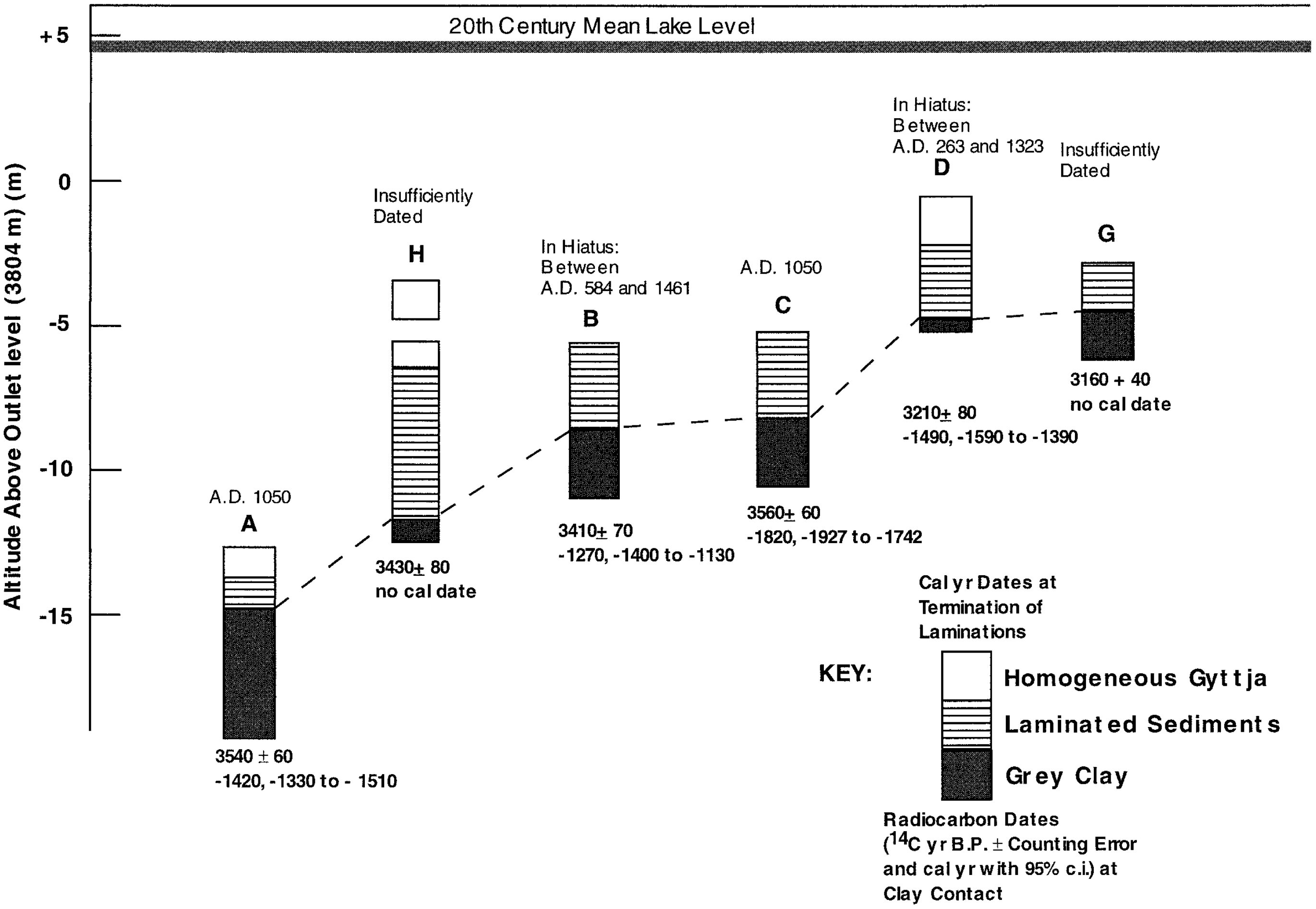

FIG. 2. Altitude, gross stratigraphies, and basal radiocarbon dates of six cores along a depth transect in Lake Wiñaymarka. The core stratigraphies are shown relative to altitude above or below the outlet level at 3804 m.

absent (Abbott *et al.*, 1997). Cores H and G were taken in 1988 and not examined in detail for erosion surfaces and unconformities because they were consumed by previous analyses.

The consistent sedimentation hiatus indicates a lake-level decline of >12 m, but <17 m. Sediments of lower organic matter and higher bulk density were formed during the period between calibrated ages A.D. 1030 and 1280 (Fig. 4), implying greater input of terrestrial material. These two dates, from cores A and D, respectively, represent the latest radiocarbon date before the sedimentation hiatus and decline in organic matter content and the earliest date after the hiatus or stratigraphic unconformity. Dates bracketing the hiatus (Fig. 3) were not in all cases measured in sediment exactly at the bottom and top of the unconformity. Therefore, we use the uppermost date before the hiatus and the lowermost date after the hiatus, to establish the chronology. Gross sediment stratigraphies are marked at this horizon by the transition from finely laminated to homogeneous sediments in several of the cores.

These data indicate a period of lower lake level and thus lower net precipitation, drying, and oxidation of exposed lake sediments, mineralization and proportional decrease of sediment organic matter at core sites from higher elevations, increased but periodic exposure to littoral input of organic material to sites at middle elevations, and decreased input of organic matter at sites of lower elevations. Although high-altitude glaciers in the lake's catchment receded at the same time, meltwater did not maintain lake level because the recession was caused by decreased precipitation, not increased melting (Seltzer, 1990, 1992).

Stable Oxygen Isotopes

In tropical regions where there is a distinct dry season and most water is lost to evaporation, the $\delta^{18}O$ of lake water is controlled mainly by the evaporation:precipitation ratio (E:P) (Fontes and Gonfiantini, 1967; Gasse *et al.*, 1990). Ostracods use dissolved carbonate in lake water to create their shells, so the carapaces of these organisms incorporate the $\delta^{18}O$ of lake water. Variations in $\delta^{18}O$ of sedimentary ostracod carapaces indicate changes in E:P.

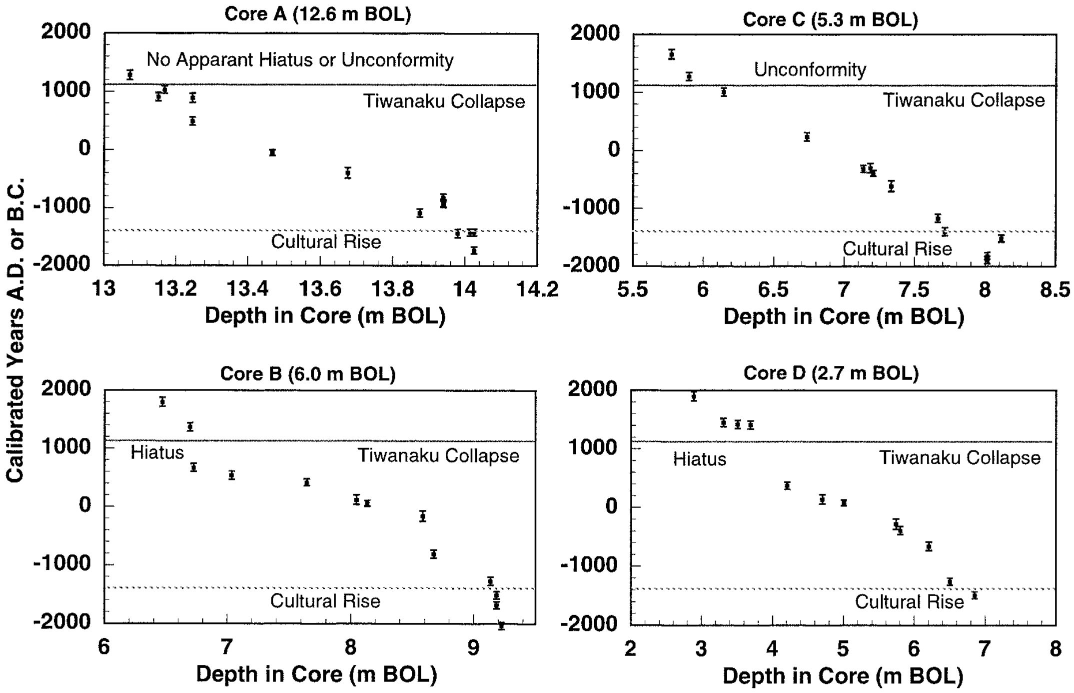

FIG. 3. Vertical distribution of calibrated radiocarbon dates in sediment cores. The lower dotted line indicates the approximate time of the first archaeological evidence of cultural activities in the area. The upper line indicates the approximate time of the collapse of the Tiwanaku civilization and reduced snow accumulation at the Quelccaya ice cap.

The δ^{18}O in ostracod carapaces indicates highly evaporative lake environments prior to 1300 cal yr B.C. (Fig. 4). The trend in δ^{18}O from 1260 cal yr B.C. to A.D. 360 in core D indicates increasing moisture (i.e., lower E:P) and higher lake levels. The signal is variable but heavier than the whole-core average (dotted line on Fig. 4) to A.D. 200. The profile trends drier from A.D. 600 to the hiatus zone, but then indicates even drier conditions about A.D. 1400, with increasing moisture until A.D. 1600. No sediment was deposited during the apparent low stand, so no ostracods were recovered. The δ^{18}O variation from ca. A.D. 1400 to the present may represent a basin response to Little Ice Age climate (Bradley, 1995).

Water and Energy Budget Modeling

A 10–15% decrease of net precipitation from the modern average could cause the 12- to 17-m lake-level reduction (Fig. 5). This lowering reduces the surface area of the entire Lake Titicaca from the current 8490 to 6400 km^2 (for a 12-m decline) and to 5860 km^2 (for a 17-m decline) and the area of Lake Wiñaymarka from ~1400 to <60 km^2. In effect, most of Lake Wiñaymarka evaporated during this episode. This decline is within the range of interannual precipitation variability for the 20th century and consistent with the 15% decrease in snow accumulation measured at the Quelccaya ice cap (Thompson *et al.*, 1985; Ortloff and Kolata, 1993).

Raised Field Chronology

Archaeological excavations and survey established the principal periods of construction, use, and abandonment of raised-field systems. Most raised fields had similar profiles (Seddon, 1994; Fig. 6). Cultivation horizons were preserved in the profile as mottled, black organic sediments. After the fields were abandoned, they eroded slightly and were subsequently covered by 25–50 cm of homogeneous fine clay and silt.

Eleven of 14 dates from raised-field construction and use contexts range between 600 and 1100 cal yr A.D., indicating that this was the most intensive period of raised-field cultivation (Table 2). Two dates from construction/use contexts, at A.D. 1230 and 1300 cal yr A.D., indicate that small-scale use of raised fields occurred after 1150 cal yr A.D. However, seven dates, six of which are from postabandonment sediments, occur in the interval between 1150 and 1300 cal yr A.D. These dates indicate that effective abandonment of the regional scale raised-field system occurred before A.D. 1150.

Chronological Concordance

When raised-field chronology, lake-level variation (Abbott *et al.*, 1997), and snow accumulation at Quelccaya (Thompson *et al.*, 1985) are examined on a common time scale, a remarkable concordance emerges (Fig. 7). Snow accumulation declined beginning ca. A.D. 1000, and the

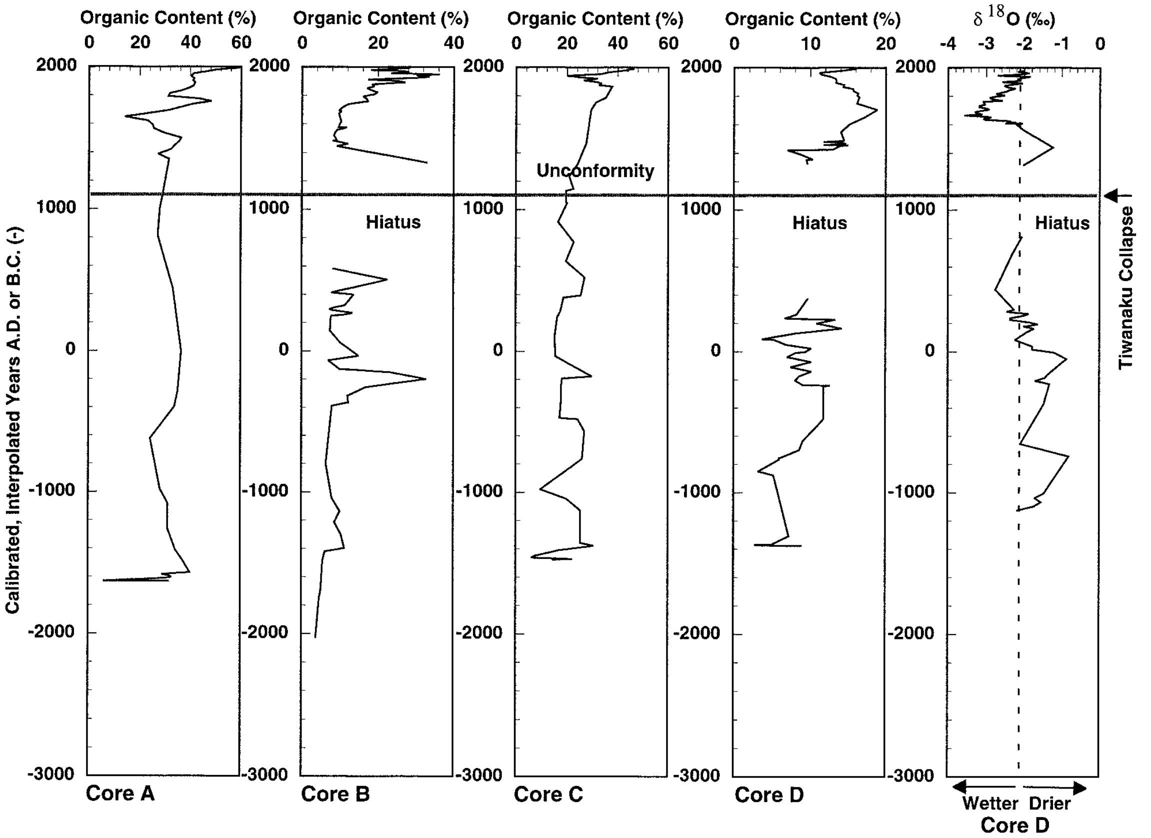

FIG. 4. The δ^{18}O for core D and sedimentary organic matter content for four major cores.

drier period lasted until A.D. 1300 but did not reach the long-term average until A.D. 1500. The lake reached its low stand by A.D. 1200 and recovered its higher water level coincident with the rise in precipitation at Quelccaya. Raised fields were used only on a small scale after the precipitation and lake-level declines. The raised fields dating between A.D. 1100 and 1200 were located in the lowest-lying areas or near stream mouths, suggesting that they may have been the last to dry. Their calibrated dating uncertainties all range to before A.D. 1100, and all but one of the raised-field dates from postabandonment contexts were during the driest of the periods.

The Quelccaya data indicate a briefer drier period from A.D. 500 to 750 (with a 50-yr wet period interposed) that does not correspond with an observed lake-level lowering or any raised-field dates. The archaeological record does not yield much about the culture during the period (Binford and Kolata, 1996). We have no explanation for this observation. Likewise, no raised-field dates correspond with earlier lake-level or precipitation highs.

DISCUSSION

This analysis suggests that subtle climate changes in the altiplano of Bolivia and Peru caused significant changes in water availability and, consequently, lake elevation and surface area. Major lake-level changes occurred rapidly (within 50-yr intervals) and several times during several periods of human occupation. These changes in lake water balance and available moisture had profound effects on local human activities.

Climate Change and Cultural Response

Periods of cultural change (initiation, intensification, and abandonment of agriculture) coincided with shifts in the water balance of the Lake Titicaca drainage basin. Insufficient water prior to ca. 1500 B.C. inhibited intensive agriculture and the development of large, sedentary human populations. People may have lived around the shores of a much diminished or even nonexistent lake, but there is no archaeological evidence of intensive agriculture prior to 1500 B.C. (Binford and Kolata, 1996). Widespread cultivation became feasible only when the climate became wetter. Human settlements and cultivation then existed for 1900 years before the development of raised fields. Raised fields, which converted wetlands to cultivable areas, increased crop production relative to dry-land farming, protected against frost, retained nutrients, and mitigated soil salinization, may have assured reliable harvests year after year.

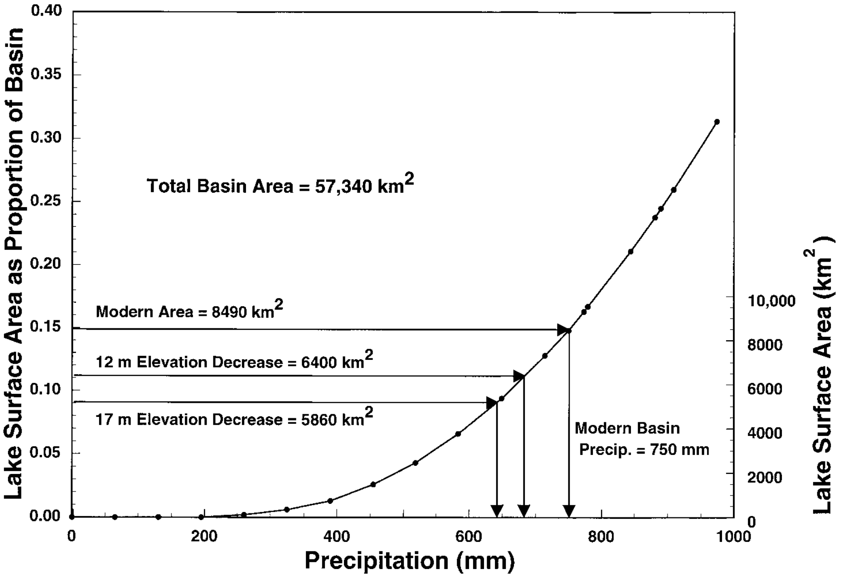

FIG. 5. Relationship between lake surface area and precipitation according to water- and energy-budget (climatonomy) modeling (Hastenrath and Kutzbach, 1985).

Intensive and highly productive agricultural production on raised fields stimulated human population growth and sustained dense populations, beginning ca. A.D. 600. By A.D. 1150 population in the Tiwanaku core area was at least an order of magnitude greater than it is today. Although the drier period after A.D. 1150 was not as extreme as the dry conditions before 1500 B.C., large urban and rural populations had become dependent upon raised-field systems that relied on abundant water. Increased aridity induced declining agricultural production, progressive raised-field abandonment, population dispersal, and ultimately Tiwanaku cultural collapse.

The resolution of our data require this interpretation of times when cultivation was untenable, then became possible, and at yet a later time was again made difficult. The smallest time unit that we can see is about 50 yr, and while agricultural failure may have been gradual, with different crops failing at different times, there is nothing in our data that describes the pattern by which crops failed, so we do not cite water and temperature requirements for specific crops. Lower precipitation would have caused drying of most or all of the canals and soils, leading to failure of all previously described functions of the raised fields. Over the 50+ yr, all crops would have been affected.

Human settlement patterns also indicate that the major period of construction and use of raised fields occurred in the late Tiwanaku IV and Tiwanaku V periods (A.D. 600–1100). During these periods, most settlement in the Catari basin occurred in nucleated centers surrounded by raised fields and linked by roads and elevated causeways. After the collapse of the Tiwanaku state, settlement consisted of small (<1 ha) dispersed occupations having no direct associations with the raised fields (Kolata, 1993). This pattern is repeated in the Tiwanaku valley to the south and in areas of Tiwanaku-related raised fields in the Juli-Pomata region of Peru (Kolata, 1993; Albarracin-Jordan and Mathews, 1990; Stanish, 1994). Alternate hypotheses about the timing of the end of raised fields, such as Graffam's (1992) argument that Little Ice Age (~A.D. 1480 to the 19th century) temperature decline ended raised-field use, are not supported by our data because no radiocarbon dates for raised-field surfaces from construction or use contexts occur after A.D. 1300 (Table 1).

Alternative interpretations of the linkage between climate change and human responses are possible. Once the fields had been constructed with enormous labor investment, they may not have been abandoned unless the system became physically impossible to maintain. As lake level declined, Tiwanaku could have created new fields following the retreating shoreline. The regional system may not have been abandoned until some configuration of the lake bottom created an impediment to cultivation, the labor required to sustain the system was reduced, or the population of the basin dropped to a point where raised fields were unnecessary. Thus, some or all fields in the deeper part of the basin would have been sustained, even with a diminished population.

We do not believe that this alternative occurred for four reasons. First, decreased precipitation would have decreased recharge of the aquifers which are the sources of the springs and streams which provide the water that maintains the raised fields (Ortloff, 1996). Without continuous input to

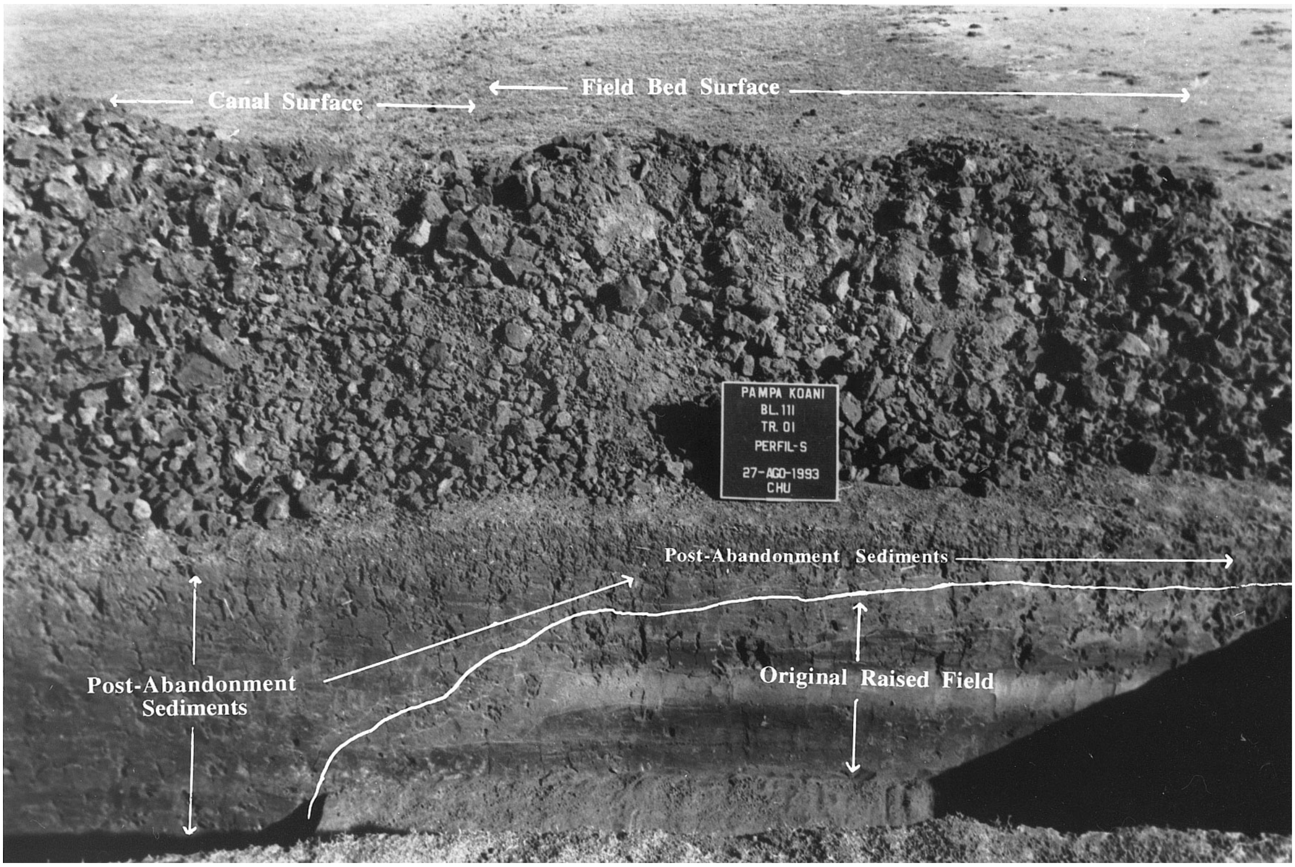

FIG. 6. Raised-field excavation profile. The trench extends from the middle of the raised field to the middle of the adjacent canals. Postabandonment, homogeneous clay sediments are highlighted in the illustration. The internal structure of the original raised-field bed incorporates black organic cultivation horizons and, immediately below the postabandonment sediments, a light, mottled loam that reflects field maintenance events.

headwaters and upland aquifers, streams and downhill springs would have had reduced or zero output. Two of the most important consequences of lower or no freshwater input, along with periodic inundation by slightly saline Lake Titicaca waters, are a decrease in soil moisture and an increase in soil salinity (Kramer and Boyer, 1995; Sanchez de Lozada, 1996; Ortloff, 1996).

A modern, although more severe, analog to drier conditions may be found in the Lake Poopo drainage basin to the south of Lake Titicaca. Average annual precipitation is about 330 mm yr^{-1}, or 56% lower than that in the Titicaca basin now (Carmouze *et al.*, 1978) and 43% lower than the modeled mean precipitation (Fig. 5). Thus, the modeled decrease of precipitation in the Lake Titicaca basin at A.D. 1100 is not as low as the modern precipitation in the Lake Poopo basin. Like Lake Titicaca, Lake Poopo has undergone wide fluctuations in water level and salinity and was part of a much larger (~63,000 km^2) and deeper (as much as 100 m) lake coextensive with the more southerly *salares* during the middle to late Pleistocene (Clapperton, 1993; Blodgett *et al.*, in press). Lake Poopo catchment soils are saline, as Lake Titicaca's would have been, and there is minimal, low-yield cultivation of irrigated crops because the lake water itself is saline (Carmouze *et al.*, 1978).

Second, primary production and production of reproductive tissues is controlled partly by water availability and the rate of actual evapotranspiration (Kramer and Boyer, 1995, chaps. 10 and 12). A soil–moisture budget (Thornthwaite and Mather, 1955; Dunne and Leopold, 1978), calculated by assuming a wide range of available soil–water capacities, indicates that a deficit occurs in all months but January and February when precipitation (P) is slightly greater than potential evapotranspiration (PEt). Therefore, annual actual evapotranspiration (AEt) equals annual precipitation, and any decrease in P results in an equivalent decrease in AEt and a proportional reduction in crop production. Furthermore, AEt can remove moisture beyond the permanent wilting point, killing crop plants.

Third, newly exposed land would have had to be converted to raised fields as the lake retreated and the fields located increasingly far from the shore became drier, colder, and less productive. This activity would have required another investment of labor equal to the creation of earlier raised

TABLE 2
Radiocarbon Dates from Raised-Field Excavations Grouped According to Archaelogical Contexts

NOSAMS No.	Mateial	Location (provenience)	Context	^{14}C Age	Calibrated years (All A.D.)	Calibrated 1 sigma age range (All A.D.)
OS-2541	Mollusc	6 (86-4-2)	Construction/use	1040 ± 35	1010	990–1020
2540	Mollusc	7 (86-2-1)	Construction/use	820 ± 30	1230	1220–1280
2538	Mollusc	8 (109-2-3)	Construction/use	1070 ± 30	990	970–1010
2539	Mollusc	10 (88-3-3)	Construction/use	1070 ± 30	990	970–1010
2654	Mollusc	11 (111-2-3)	Construction/use	1030 ± 35	1010	990–1020
2564	Carbon	11 (111-2-3)	Construction/use	1360 ± 40	670	650–680
2651	Mollusc	11 (111-2-4)	Construction/use	930 ± 30	1050, 1090, 1120, 1140, 1160	1040–1170
2649	Mollusc	12 (112-3-2)	Construction/use	1290 ± 50	710, 750, 760	670–780
2557	Carbon	13 (113-3-2)	Construction/use	950 ± 30	1040, 1150	1030–1160
2565	Carbon	13 (113-3-3)	Construction/use	690 ± 30	1300	1290–1300
2544	Mollusc	14 (134-4-2)	Consruction/use	980 ± 30	1030	1020–1150
2652	Mollusc	16 (114-5-3)	Construction/use	990 ± 30	1030	1020–1040
2559	Carbon	17 (35-1-7)	Construction/use	1220 ± 40	790	780–880
2653	Mollusc	18 (89-3-4)	Construction/use	1440 ± 45	640	600–660
2542	Mallusc	1 (83-2-1)	Postabandonment	775 ± 60	1280	1220–1290
2563	Carbon	2 (62-1-3)	Postabandonment	840 ± 45	1220	1170–1260
2558	Carbon	3 (CC33-1)	Postabandonment	875 ± 35	1190	1160–1220
2650	Mollusc	9 (110-3-1)	Postabandonment	955 ± 30	1040	1030–1160
2561	Carbon	9 (110-3-2)	Postabandonment	910 ± 30	1160	1050–1180
2566	Carbon	15 (147-2-5)	Postabandonment	840 ± 35	1220	1180–1250
2758	Carbon	16 (114-5-1)	Postabandonment	860 ± 40	1210	1170–1230
2537	Mollusc	4 (63-3-1)	Problematic	1410 ± 30	650	630–660
2560	Carbon	4 (63-3-1)	Problematic	615 ± 30	1320, 1340, 1390	1310–1400
2543	Mollusc	5 (85-3-5)	Problematic	1140 ± 30	890	890–970
2562	Carbon	5 (85-3-5)	Problematic	425 ± 45	1450	1440–1480

Note. Refer to Figure 1 for site locations. The four problematic assays reflect two pairs of dates from identical stratigraphic contexts that returned highly divergent dates.

fields (the land area available for raised-field cultivation increases as the lake level decreases to 9 m BOL, then decreases as the lake drops further; M. W. Binford, unpublished data). The transition would not have been simple or easily accomplished. Furthermore, we have found no evidence of abandoned raised fields at altitudes lower than 3808 m. Inundation may have obliterated the surface morphology or the fields may never have existed.

Fourth, the much smaller lake and associated peripheral wetlands would have had lower total heat capacity to ameliorate the freezing temperatures that often occur during the night. The current lake–wetland complex creates a microclimatic effect that stabilizes near-ground temperatures a few degrees centigrade higher than would occur in a dry system (Ortloff, 1996). Crop plants might have been damaged more often, and the harvests would have been less certain in an era of a smaller lake.

Cultural factors for the creation and management of the raised fields, such as differential levels of surplus production, the control of domestic labor by elite groups, and opportunistic economic strategies by the elite, described as ‘‘key variables’’ by Stanish (1994), are not excluded by this interpretation. The lack of water simply made the physical and biological functions of the fields impossible. Even Stanish (1994, p. 329) states that ecological conditions underlie the viability of the fields: ‘‘Significant ecological changes occurred in the Titicaca region between the eleventh and the fifteenth century that may have rendered raised-field agriculture unfeasible.’’

Cultural Response

Specific mechanisms of cultural adaptation to climate variability are not addressed by our data. A controversy about the organizational structure of agriculture and the society (Erickson, 1992, 1993; Graffam, 1992; Kolata, 1986) is not considered here.

Social upheaval may have accompanied the drying-caused decline in agricultural output (Janusek, 1994). Not only did the people of Tiwanaku stop cultivating raised fields, they also abandoned their urban centers. There is no evidence of monumental construction projects or other indices of urban life in the region for nearly 300 years after the A.D. 1150 collapse (Kolata, 1993).

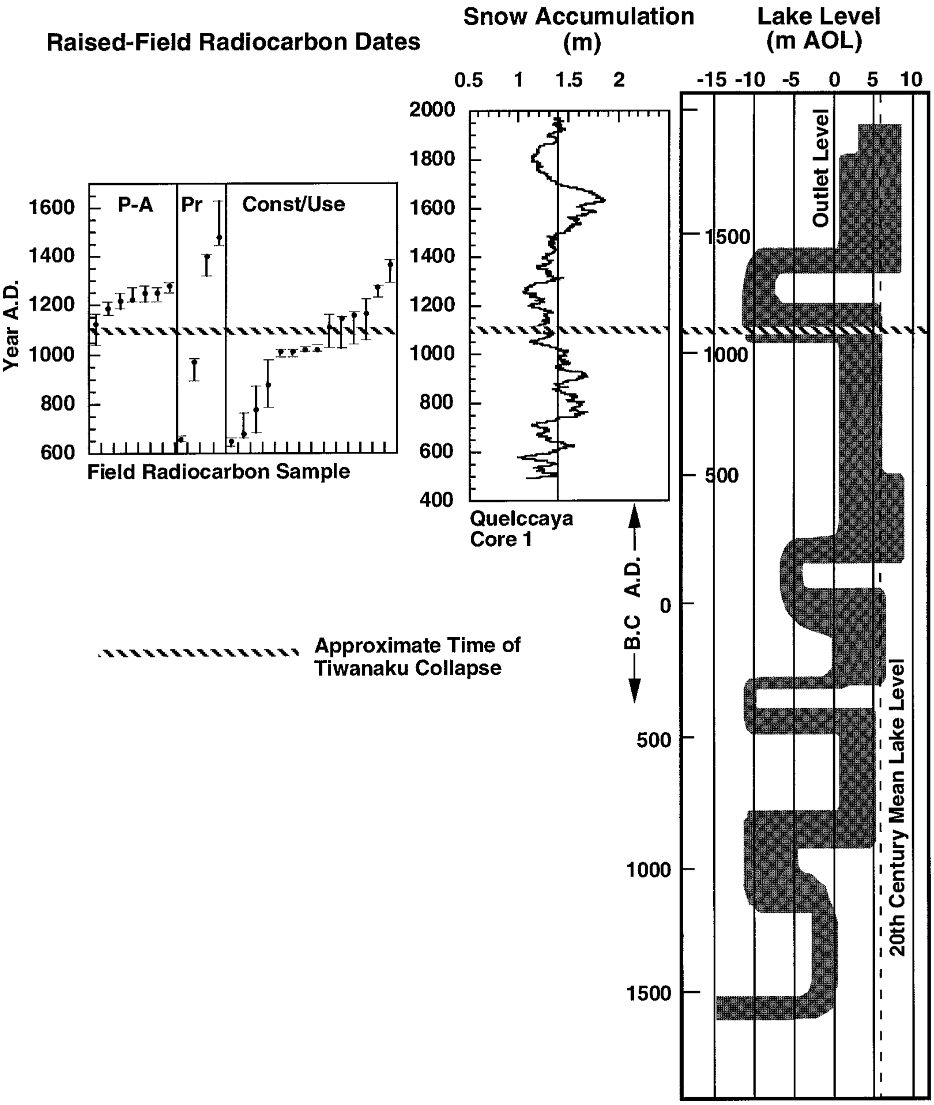

FIG. 7. Calibrated radiocarbon dates, snow accumulation on the Quelccaya ice cap (redrawn from Thompson *et al.*, 1985 and smoothed with a 10-yr moving mean), and proposed lake-level curve redrawn from Abbott *et al.* (1997). P-A, Pr, and Const/Use denote material taken from postabandonment, problematic, and construction/use contexts, respectively (Seddon, 1994). The cross-hatched line at A.D. 1100 denotes the approximate beginning of reduced precipitation at the Quelccaya ice cap and the beginning of the collapse of the Tiwanaku civilization. The lake-level line is drawn thickly to illustrate century-scale variability, e.g., the 20th-century variation has been about 6 m, so the line is 6 m thick (Abbott *et al.*, 1997).

Populations may have dispersed through the rural landscape and colonized new environmental niches unoccupied during the Tiwanaku florescence (Albarracin-Jordan, 1992). The drier climate and much smaller lake of this period would have created a harsher environment similar to that of the altiplano south of the Tiwanaku heartland, where mineral extraction and pastoralism rather than agriculture are the principal economic activities. In addition to dispersal, some measure of population decline on the altiplano may have been an element of the adaptation to changed environmental conditions, but demographic data for this time period are insufficiently resolved to provide quantitative measures.

Human cultures adapt to changing environmental conditions within a range of normal variation. ''Normal'' is usually defined by recent and short time scales, rather than by long-term variability during which thresholds at environmental extremes can significantly affect cultural adaptability. In commonly defined normal periods, thresholds can be exceeded for short periods without seriously affecting a civilization. However, in the long term, lower frequency variations with larger amplitudes may exceed the limits of human adaptability.

These data demonstrate that climate changes within the range of measured long-term variability occurred rapidly and had significant hydrological and ecological implications for inhabitants of the altiplano. The accumulation of recent evidence of similar climate–culture interactions in other regions suggests a significant environmental component in human behavior (Hodell *et al.,* 1995; Weiss, 1993; Stine, 1994). Furthermore, the suggestion by Overpeck (1996) that the 20th century has had an unusually stable climatic regime and that ''. . . warm climate surprises of the type apparent in the Holocene interglacial paleoclimatic record may be our biggest worry in the years to come'' is given added urgency.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation Grants DEB-9207878 to M.W.B., DEB-9212641, and BNS-8805490; National Oceanic and Atmospheric Administration Grants NA56GP0370 and GC-95-174; and by National Endowment for the Humanities Grant RO-21806-88 to A. L. K. Additional support for AMS dating was provided to the National Ocean Science AMS Facility at Woods Hole Oceanographic Institution under NSF Cooperative Agreement No. OCE-801015. The Light Stable Isotopes Laboratory, Department of Geology, University of Florida, provided oxygen isotope analyses. Debra Edelstein, Richard T. T. Forman, David Foster, Joanne Harrison, Kathleen McCormick, and three anonymous referees commented on drafts of the manuscript.

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