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Spatial and temporal variation in cores from Lake Titicaca, Bolivia/Peru during the last 13,000 years

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Abstract
We compared the stratigraphy of sediment cores that span the last 13,000 yrs from three sites in the main basin of Lake Titicaca, Boliva/Peru as indicators of regional paleoclimate. The cores show similar patterns of change after ~6,400 calendar yrs before present (cal yr BP) but differ before that time. Site NE98-PC2, which is near the Rio Illave and its delta, shows differences in diatom species composition and in calcium carbonate concentrations relative to cores from the other two sites, particularly during times of inferred high precipitation. In contrast, the carbon isotopic stratigraphy of the three sites is relatively similar. The magnetic susceptibility data suggest that the proximity of site NE98-PC2 to the river and delta resulted in higher loads of detrital sediment prior to 6,400 yr BP, whereas pelagic sources contributed most of the sediment at the other sites. These differences highlight the potential for spatial heterogeneity of sediment records in large lake systems and the importance of evaluating multiple cores for robust interpretation of paleoenvironmental history.

1. Introduction

Most paleoenvironmental studies of lacustrine sediment records use one or a small number of cores, based on the assumption that sedimentation is sufficiently homogenous across the lake that a small number of cores are representative of the history of the basin. Studies of multiple cores from relatively small lakes suggest that for many biological and geochemical variables, stratigraphic trends are generally replicated from site to site. In contrast, accumulation rates are highly variable among cores from different depths and depositional settings (Engstrom and Swain, 1986; Anderson *et al.*, 1994). In large lakes, the potential for inter-site variability is greater, because larger basins commonly have greater morphometric complexity and the potential for significant variation in watershed geology and vegetation. In addition, physical processes, which mix and distribute sediments, chemical constituents and biota, are spatially variable in large lakes. All of these processes can produce variability in the water column and in sedimentary records (e.g. Rea *et al.*, 1994; Talbot and Laerdal, 2000). Nonetheless, many studies of multiple cores from large lake systems show similar behavior through time among multiple cores (Cross *et al.*, 2000; Takemura *et al.*, 2000; Johnson *et al.*, 2002; Prokopenko *et al.*, 2005).

Here, we compare temporal patterns of change in cores from three different locations in the large tropical Lake Titicaca, Bolivia/Peru to evaluate spatial variability among several sites within the main basin of the lake. The records span the late-Glacial and Holocene and represent deposition under a range of climate conditions, allowing us to evaluate whether the sites behave in a similar fashion under different mean climate states. We also use multiple proxies, including both biotic and geochemical variables, to determine whether some variables are more sensitive to location than others. This paper focuses on new high-resolution analyses from NE98-PC2 (15° 57.480′S 69°26.652′W), which we obtained in 142 m water depth in the main basin of the lake, off the Rio Ilave delta (Figure 1). Patterns of change in NE98-PC2 are compared with previously published analyses from NE98-PC1 (152 m) and NE97-PC7 (89 m), which were analyzed at coarser temporal resolution (Baker *et al.*, 2001; Tapia *et al.*, 2003).

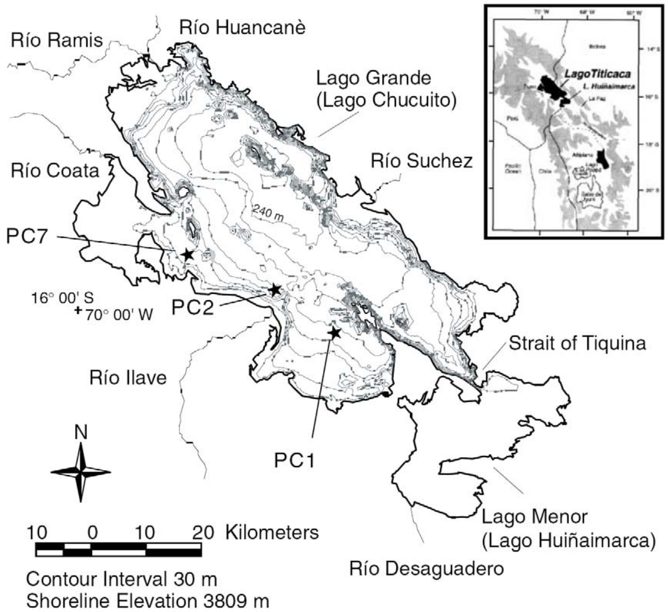

Figure 1. Map of Lake Titicaca showing the location of the NE98-PC1, NE98-PC2, and NE97-PC7 cores (indicated by stars).

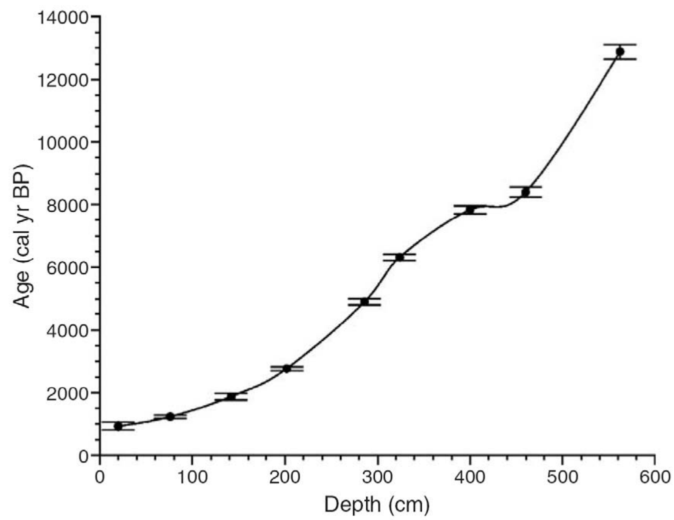

Figure 2. Relationship between core depth (cm) and calendar age (cal yr BP) based on accelerator mass spectrometry ^{14}C analysis of bulk organic carbon. A cubic spline was fit to the dates to generate an age model. Error bars represent 2σ.

1.1. Site description

Lake Titicaca (14°09′–17°08′ S, 68°03′–71°04′W) is a large tropical lake at 3,810 m on the Altiplano of Boliva and Peru (Figure 1), a high-elevation internally drained plateau between the eastern and western cordillera of the Andes. The lake consists of a large (7,131 km^2) deep (max depth 284 m, mean depth 125 m) main basin and a smaller (1,428 km^2) shallower basin (max depth 42 m, mean depth 9 m), which are connected at the Straits of Tiquina (25 m depth). Today, hydrologic inputs are balanced between direct rainfall (47%) and inflow (53%) from six major rivers. In the modern lake, water export is primarily via evaporation (91%), with <9% loss via the sole surface outlet, the Rio Desaguadero at 3,804 m elevation (Roche *et al.*, 1992). The lake is oligosaline (0.1 g l^{-1} salinity) and moderately productive (mesotrophic).

2. Methods

2.1. Field

Piston cores were obtained from multiple locations in Lake Titicaca in 1997 and 1998 (Figure 1). In this paper we use previously published data (diatoms, geochemistry, magnetic susceptibility) that span the last 13,000 yrs from sites NE97-PC7 and NE98-PC1 (uppermost 5.0 and 2.4 m, respectively). A detailed description of results and their interpretation for these sites are included in earlier publications (Baker *et al.*, 2001, Tapia *et al.*, 2003). Total core length of our new core, NE98-PC2, was 7.87 m; the last ~13,000 yrs is included in the uppermost 5.7 m of the record (Figure 2). Magnetic susceptibility of the cores was measured in the field. The cores were shipped to the US and stored at 4 °C prior to sampling. Samples from NE98-PC2 were analyzed for diatoms and sediment geochemistry at 2-cm intervals throughout the length of the core, yielding a total of 287 samples. Sample resolution ranges from ~10 yrs in the uppermost sediments to ~100 yrs in the basal meter.

2.2. Chronology

Core chronology is based on ten accelerator mass spectrometry ^{14}C dates on acid-leached bulk organic carbon (Table 1) that were calibrated using CALIB 4.4 (Stuiver and Reimer, 2004). No reservoir correction was applied, because surface sediments from box cores from the main basin of Lake Titicaca do not show a reservoir effect (Baker *et al.*, 2001). A cubic spline through the calibrated dates was used to generate an age model (Figure 2). Ages in the text are expressed as calendar years before present (cal yr BP).

2.3. Diatoms

Samples for diatom analysis were treated with 10% hydrochloric acid and cold hydrogen peroxide to, respectively, remove carbonates and organic matter and then were rinsed to remove oxidation by-products. Prepared samples were dried onto coverslips, and the coverslips were mounted onto slides with Naphrax. Species were identified on a Zeiss Axioskop 2 microscope with a 1,000× (N.A. = 1.40) oil immersion objective. A minimum of 300 diatom valves was counted on each slide. Diatom abundance in each sample is expressed as a percent of the total diatom count. Diatom taxa are grouped into one of four main ecological groups (freshwater plankton, saline plankton, salinity indifferent plankton, and benthic) based on known ecological affinities (Servant-Vildary, 1992; Tapia *et al.*, 2003).

Table 1.
Radiocarbon and calibrated ages determined by accelerator mass spectrometry (AMS) on the total organic carbon of the mud. Age determinations were made at the University of Colorado (INSTAAR) and Woods Hole Oceanographic Institute (OS) radiocarbon laboratories. Upper and lower limits of the calibrated ages represent the 2 sigma ranges

Sample number	Sample depth (cm)	δ^{13}C PDB	Age ^{13}C yr BP	Age error	Calibrated age cal yr BP	Lower cal yr BP	Upper cal yr BP
INSTAAR	20	–22.1	1070	50	933	799	1056
OS-33544	76	–23.72	1340	30	1235	1174	1288
OS-33543	142	–22.84	1970	30	1875	1744	1950
OS-41669	202	–22.02	2690	40	2769	2730	2850
OS-33542	286	–17.39	4370	35	4897	4832	5026
OS-33541	324	–17.6	5560	35	6313	6205	6403
INSTAAR	400	–17.6	7060	65	7837	7691	7955
INSTAAR	460	–21.3	7650	50	8398	8218	8538
OS-41668	516	–15.78	6970	60	Excluded		
OS-33540	562	–23.07	10850	60	12878	12634	13108

2.4. Geochemistry

Samples for geochemical analysis were dried, powdered, weighed, and leached in buffered (pH = 5.5) ammonium acetate–acetic acid. Weight percent calcium carbonate was calculated from the atomic absorption spectrometric (Perkin Elmer 5000) determination of dissolved calcium, assuming that all calcium was originally present as calcium carbonate. The insoluble residue was rinsed several times in reagent-grade water. Portions of this material were dried and weighed prior to determination of organic carbon and its stable isotopic composition. Stable carbon isotopic compositions were measured on a Finnigan MAT Delta Plus XL isotope mass spectrometer in the Duke University Environmental Stable Isotope Laboratory and are reported relative to the PDB standard. Standard deviations for replicate carbon measurements were generally less than 0.5%. The precision for the carbon isotopic measurements was ±0.2‰.

3. Results

Throughout the PC2 core, the sediments consist of gray to brown silty mud that is faintly laminated or banded below 250 cm (~4,000 yr BP) and without visible structure above. Magnetic susceptibility values, which are indicative of detrital inputs to the lake from the watershed (Baker *et al.*, 2001), are high (>200 SI units) prior to 8,000 cal yr BP and then decline gradually, reaching values <20 SI units after ~6400 cal yr BP. This change in sedimentation character impacts the radiocarbon chronology for the core (Figure 2), which shows a major change in sediment accumulation rate over the interval between 8,000 and 6,400 cal yr BP.

Calcium carbonate is generally low (<3% by weight) throughout the sediments dated prior to ~5,300 cal yr BP (Figure 3), with intervals of slightly elevated concentrations (3–10%) from 10,600 to 10,300, 7,200–7,000, and 6,400–6,000. Peak values occur between 5,300 and 4,000 cal yr BP (3–30%), with low values (<5%) after 4,000 cal yr BP.

δ^{13}C is relatively depleted prior to 9,000 cal yr BP (<−24‰), excepting in the interval from 10,600 to 10,300, when values are higher (Figure 3). Values fluctuate (−18 to −25‰) from 9,000 to 7,600 cal yr BP, are heaviest between 7,600 and 4,000 cal yr BP, and become more depleted (<−20‰) after that time.

The diatom stratigraphy of the lower part of the PC2 core (Figure 3 and Figure 4) fluctuates between the planktonic taxon *Cyclotella stelligera* and a suite of benthic diatoms. The benthic taxa include species that grow in both the lake and influent rivers (Tapia *et al.*, 2003): there are no taxa restricted to fluvial environments. Prior to 10,000 cal yr PB, benthic diatoms are >50% of the assemblage, followed by a decrease in relative abundance from 10,000 to 9000 cal yr BP. From 9,000 to 7,800 cal yr BP, benthic diatoms are typically >85% of the diatom assemblage, whereas between 7,800 and 6,800 cal yr BP, the planktonic *C. stelligera* is common. From 6800 to 3300 cal yr BP, two groups of diatoms alternate in dominance: (1) benthic diatoms; and (2) the salinity tolerant planktonic taxon, *Cyclotella meneghiniana*, together with *Chaetoceros muelleri*, which only grows in waters with a salinity >2 g l^{-1}. Benthic diatoms are most common between 5,700 and 4,800 cal yr BP; other periods in this interval are characterized by *C. meneghiniana* and *C. muelleri*. From 3,300 to 1,700 cal yr BP, *C. meneghiniana* dominates. The freshwater planktonic taxon, *Cyclostephanos andinus*, the dominant taxon in the modern lake (Tapia *et al.*, 2003), is the most abundant species after that time.

4. Discussion

The diatom and geochemical data from sites NE97-PC7 and NE98-PC1 in the main basin of Lake Titicaca (Baker *et al.*, 2001; Tapia *et al.*, 2003) show patterns that are characteristic of a fresh overflowing lake (freshwater planktonic diatoms, depleted δ^{13}C, low calcium carbonate) in the late-Glacial from ~13,000 cal yr BP, with a brief period of lowered

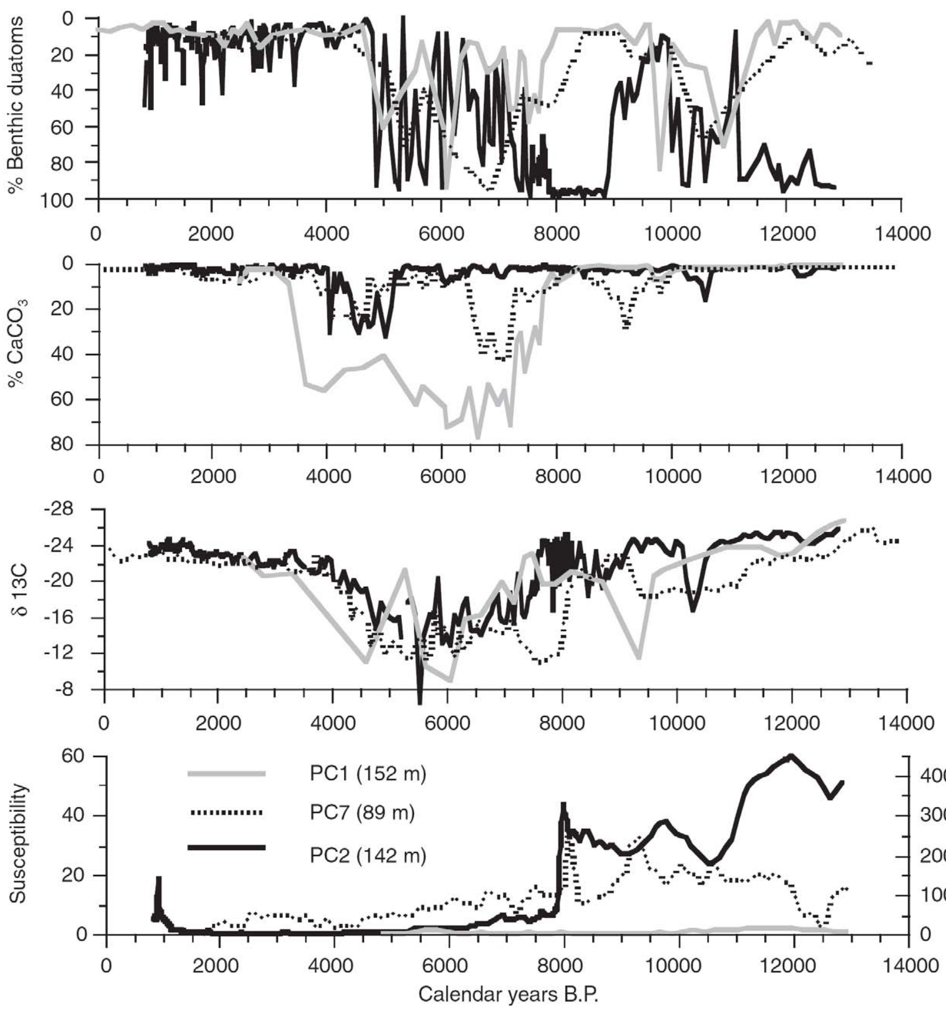

Figure 3. A comparison of the magnetic susceptibility (SI units), $\delta^{13}C$ (‰), %CaCO (by weight), and benthic diatom (%) stratigraphy in sites NE98-PC1, NE98-PC2, and NE97- PC7 over the last 13,000 yrs. On the magnetic susceptibility profiles, the right-hand *x*-axis is for NE98-PC2 and the left-hand *y*-axis provides the scale for the other two sites.

lake level between ~11,500 and 10,000 cal yr BP, as indicated by a large amplitude increase in benthic diatoms, a slight increase in calcium carbonate concentration, and enriched carbon isotopic values. Between 10,000 and 8,500 cal yr BP the lake was also fresh and overflowing, followed by a major lake-level decline at 8,500 cal yr BP, when benthic diatoms increased in abundance, inputs of isotopically enriched organic carbon increased, and calcium carbonate began to increase as the lake dropped below the outlet and salinity built up. Lake level remained low until about 4,500 cal yr BP, although fluctuations in benthic diatom abundance suggest some high-frequency variation superimposed upon the generally low lake levels. After 4,500 cal yr BP, lake level increased, flooding the shallow Lago Huiñaimarca subbasin at ~3,500 cal yr BP. The lake reached modern high-stand levels after 2,000 cal yr BP, as indicated by the dominance of *C. andinus*, depleted carbon isotopic values, and absence of calcium carbonate in the sediments.

A comparison of data from site NE98-PC2 with these previously published results demonstrates that the three sampling locations in Lake Titicaca show both major and minor differences in pattern of change that are produced by several causes. The chronology of the cores is based on radiocarbon analysis of bulk organic matter, with associated errors of 50–250 yrs, and some of the differences between cores are undoubtedly a product of the precision of chronological control. Sampling resolution also influences the shape of stratigraphic profiles, and the three sites have very different sample spacing: core PC7 has the lowest resolution (mean spacing 400 yrs; range 140–710 yrs), PC1 has intermediate resolution (mean spacing 175 yrs; range 20–511 yrs), and PC2 has the highest sampling resolution (mean spacing 40 yrs; range 8–100 yrs). The impact of sample resolution is evident in the diatom records (Figure 3): the PC2 stratigraphy suggests that the period between 6,800 and 4,800 cal yr BP was highly variable, whereas the coarsely resolved PC7 shows largely directional changes

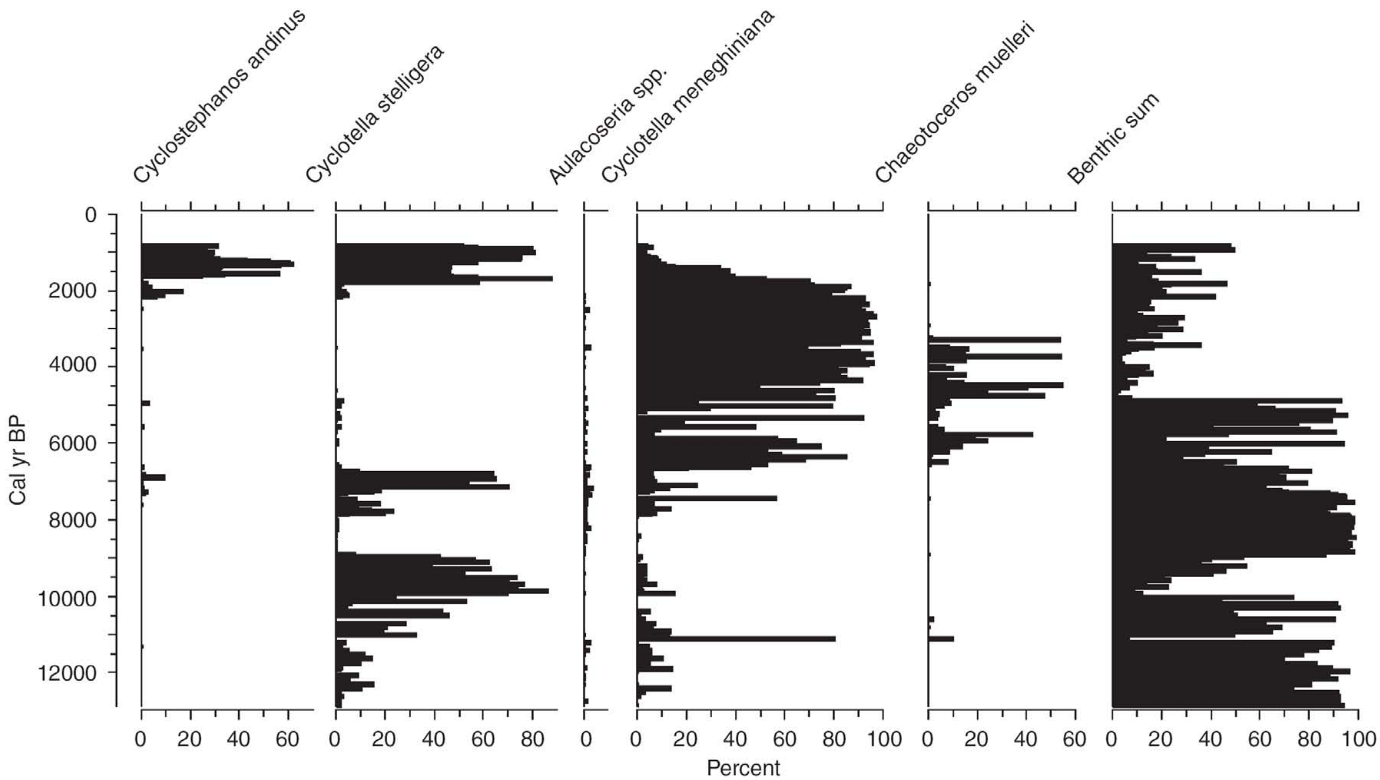

Figure 4. The relative abundance (%) of the dominant diatom species in the PC2 core during the last 13,000 yrs. *Cyclotella stelligera, Cyclostephanos andinus,* and *Aulacosiera* spp. are planktonic freshwater species; *Cyclotella meneghiniana* is a planktonic salinity indifferent taxon, *Chaetoceros muelleri* is a saline planktonic species. Benthic sum is a group of shallow-water diatoms, including some benthic species characteristic of elevated salinity.

from low benthic abundance at 6,800 cal yr BP to high abundance by 4,800 cal yr BP. In this case, it is likely that the record from PC7 was sampled too coarsely to capture much of the high-frequency variation observed in PC2.

In general, the higher sampling resolution of the PC2 core relative to the other cores allows climate variation at millennial to centennial scales to be more clearly defined. However, some stratigraphic features of PC2 differ from the other two sites, particularly in the period prior to 7,800 cal yr BP. We argue that the pattern observed in the PC2 core is not characteristic of the basin-wide depositional pattern. This hypothesis is bolstered by recent data from drill cores in Lake Titicaca (Fritz and Baker, unpublished data), which replicate the patterns evident in PC1 and PC7. The most striking difference among the cores is that planktonic diatoms dominate at sites PC1 (152 m water depth) and PC7 (89 m) prior to 11,800 yr PB and in the interval from 9,000 to 7,800 cal yr BP, whereas benthic diatoms dominate the PC2 core (142 m), despite water depths equivalent to those at PC1. In addition, prior to 7,800 cal yr BP, periods of freshwater diatom dominance in the other sites include both *C. stelligera* and *C. andinus,* whereas in PC2 (Figure 4), *C. andinus* is present only in very small percentages (<5%). The calcium carbonate stratigraphy of the PC2 core also differs from the other cores in the early part of the records. Prior to 6400 cal yr BP, PC2 shows only muted increases at times when carbonate concentrations increased in PC7 and PC1. In general, despite similar water depths in PC1 and PC2, the $CaCO_3$ stratigraphy of PC2 most closely resembles that of the shallow water site PC7, near Puno Bay (Figure 1).

The sedimentology of the PC2 core suggests that the differences in the PC2 stratigraphy relative to the other cores in the lower sections likely are related to inputs from the nearby Rio Illave and its delta. Magnetic susceptibility (Figure 3), which is an indicator of detrital inputs to the coring site, reveals a strong fluvial influence at site PC2. Magnetic susceptibility values in PC2 are more than an order of magnitude higher than at sites PC1 and PC7 in the period prior to 6400 yr BP, suggesting substantially greater clastic inputs during this time. Geomorphic data from the Rio Illave and Ramis valleys indicate that the intervals prior to 11,600 and from ~9,000 to 8,000 yr BP were periods of high discharge from rivers in the Lake Titicaca drainage basin (Rigsby *et al.*, 2003; Farabaugh and Rigsby, 2005). We suggest that inputs of diatoms and sediment from the Rio Illave and its delta during periods of high discharge dominate the record at site PC2 from the late-Glacial through the mid-Holocene. The PC2 core represents a predominantly pelagic signal only after ~8,000 cal yr BP, and substantial fluvial inputs continue until ~6,400 yr BP.

Local influences associated with the proximity of site PC2 to the Rio Illave also may have contributed to differences in the diatom species composition during the intervals dominated by planktonic diatoms. In modern Lake Titicaca, *C. stelligera* is most common in the open waters of nearshore regions of the lake, whereas *C. andinus* is common in offshore areas (Tapia *et al.*, 2003). Therefore, the high abundance of *C. stelligera* and the low abundance of *C. andinus* in the planktonic dominated parts of the PC2 record prior to 6400 yr BP may result because of the proximity of the coring site to the Rio Illave delta. Variability among the cores in species composition only occurs during planktonic dominated parts of the record, because the flora of the delta and the coring site are likely similar during arid intervals when lake level drops and both areas are dominated by benthic diatoms.

The proxy with the greatest fidelity among the three sites is the δ^{13}C of bulk organic matter. In Lake Titicaca, δ^{13}C is a proxy for lake-level change, such that as lake level lowers, the increased contribution of carbon from submersed littoral macrophytes relative to planktonic algal sources produces heavier isotopic values (Cross *et al.*, 2000; Rowe *et al.*, 2002). Our hypothesis of a strong fluvial influence on the PC2 site during wet periods in the late-Glacial and early Holocene suggests that these intervals should contain riverine carbon. Riverine carbon is likely to have a terrestrial source, which in the Lake Titicaca catchment would be composed primarily of C3 plants that are depleted in δ^{13}C values relative to littoral sources (Cross *et al.*, 2000). Thus, the δ^{13}C characteristics of the fluvial (C3 terrestrial) sources of carbon likely were similar to the carbon isotopic signature produced from C3 planktonic algae during intervals of high lake level. As a result, the δ^{13}C stratigraphy is generally coherent among the three sites throughout the last 13,000 yrs.

Spatial variations in sedimentary diatom assemblages and geochemical variables have been demonstrated in a number of paleolimnological studies, although the majority of these studies examine distributional patterns in surface sample transects rather than long-term stratigraphic variation in cores (e.g. Bradbury and Winter, 1976; Downing and Rath, 1988; Kienel and Kumke, 2002). It is also well known that some diatom taxa are restricted to rivers (rheophilic) and that these species have potential as indicators of changing river inflow with time (Ludlam *et al.*, 1996). Yet, relatively few examples of long-term spatial variability of stratigraphic pattern for diatoms or other proxies have been documented in large lake systems. In Lake Titicaca, the influence of the river system on sedimentation patterns extends to a deepwater site at considerable distance (>10 km) from the river's mouth. It is unclear whether the river itself is the direct source of sediment or whether the river is transporting material from its delta to the PC2 core site during times of high flow. Alternatively, the position of the delta may have migrated and produced a change in the distribution of deltaic sediments. In any case, the influence of the fluvial system and its delta was temporally variable. During the late-Glacial and early Holocene, fluvial influence produced spatial heterogeneity primarily during wet periods, because the riverine and deltaic material transported during periods of high flow differed from the material characteristic of the open lake. In contrast, any riverine influence during dry intervals would have simply reinforced the sedimentary characteristic of low lake stands. Beginning about 8,000 cal yr BP, over a period of approximately 1,500 yrs, the fluvial impact on site PC2 gradually diminished, which is evident in the magnetic susceptibility data. As a result, the three core sites converged and show a similar pattern of change after 5000 cal yr BP. Given that precipitation increased after 4,000 yr BP (Baker *et al.*, 2001), the reduced fluvial signature after this time is likely related to changes in patterns of sediment deposition associated with evolution in the morphometry of the river valley, the river delta, and the lake, rather than a change in flow. Overall these data highlight the complex depositional environments in large lake systems in space and time and the need for multiple cores to adequately infer environmental history.

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