

CONTEMPORARY DISTRIBUTION AND LATE-QUATERNARY STRATIGRAPHY OF DIATOMS IN THE JUNIN PLAIN, CENTRAL ANDES, PERU

DISTRIBUCIÓN CONTEMPORÁNEA Y ESTRATIGRAFÍA DEL CUATERNARIO TARDÍO DE DIATOMEAS EN LA ALTIPLANICIE DE JUNÍN, ANDES CENTRALES, PERÚ

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ABSTRACT

A study of both modern and fossil diatoms was undertaken to reconstruct late-Quaternary environmental changes in the Junin Plains of Peru. Diatoms from contemporary lakes, streams, and springs were collected from a variety of substrates, and canonical correspondence analysis (CCA) was used to examine the relationships among modern diatom distribution and environmental data. CCA axis 1 ($\lambda_1 = 0.326$) contains high scores for $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and Ca and separates sites based on differences in the relative influence of groundwater versus surface water input on hydrologic budgets. CCA axis 2 ($\lambda_2 = 0.244$) has a high loading for Na, which is interpreted as a proxy for total dissolved solutes. The distribution of sites indicates a gradient from spring to stream to lake environments in multivariate space.

Some of the fossil diatom assemblages were inadequately represented in the modern samples, and many sections of a sediment core from Lake Junin were barren of diatoms. Three distinct local diatom zones were distinguished. The oldest zone (JU-1, ~46,000 to ~30,000 cal yr BP) is dominated by *Staurosira* sp. cf. *S. construens* var. *venter*, which is indicative of a shallow freshwater lake. Zone JU-2 (~17,500 to 16,000 cal yr BP) contains high abundances of *Cyclotella stelligera*, which suggests a freshwater lake with deeper waters than Zone JU-1. The youngest zone (JU-3, ~13,000 to 500 cal yr BP) is dominated by *Denticula elegans*, suggesting a shallow alkaline lake. A previously published paleoclimatic interpretation for Lake Junin, based on isotopes in authigenic calcite from the same core, indicates a gradual increase in effective moisture (precipitation minus evaporation) from the early to late-Holocene. However, the diatom flora appears to have been less sensitive to climatic changes in Lake Junin during the Holocene, and in this shallow environment, changes in lake chemistry and lake-level were insufficient to affect overall diatom composition.

Keywords: Late Quaternary, diatoms, CCA, paleoclimate, Lake Junin, tropical Andes, Peru.

RESUMEN

Un estudio de diatomeas actuales y fósiles fue llevado a cabo con el fin de reconstruir cambios ambientales durante el Cuaternario tardío en la altiplanicie de Junín, Perú. Diatomeas de lagos, riachuelos y manantiales fueron colectados de una serie de substratos, y una serie de análisis de correspondencia canónica (CCA) fueron usados para examinar las relaciones entre la distribución actual de diatomeas y los datos ambientales. El eje CCA 1 ($\lambda_1 = 0.326$) contiene altos valores para $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ y Ca, separando los sitios basados en diferencias en la influencia relativa de aguas freáticas frente al ingreso de aguas superficiales en el balance hidrológico. El eje CCA 2 ($\lambda_2 = 0.244$) tiene alto peso para el Na, el cual es interpretado como un proxy para solutos disueltos totales. La distribución de los sitios indica una gradiente de ambientes de manantiales a riachuelos a lagos en el espacio multidimensional.

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Algunas de las asociaciones fósiles de diatomeas estuvieron inadecuadamente representadas en las muestras actuales y muchas secciones de un testigo del Lago Junín fueron estériles para el análisis de diatomeas. Tres zonas locales de diatomeas fueron distinguidas. La zona más antigua (JU-1, ~46,000 to ~30,000 cal yr BP) es dominada por *Staurosira* sp. cf. *S. construens* var. *venter*, que es indicativo de un lago somero de agua dulce. La Zona JU-2 (~17,500 to 16,000 cal yr BP) contiene altas abundancias de *Cyclotella stelligera*, el cual sugiere un lago de agua dulce con aguas más profundas que en la Zona JU-1. La zona más joven (JU-3, ~13,000 to 500 cal yr BP) está dominada por *Denticula elegans*, sugiriendo un lago alcalino somero. Una interpretación paleoclimática previamente publicada para el Lago Junín, basada en isótopos de calcita autógena del mismo testigo, indica un incremento gradual en la humedad efectiva (precipitación menos evaporación) desde el Holoceno temprano al tardío. Sin embargo, la flora de diatomeas parece haber sido menos sensitivas al cambio climático en el Lago Junín durante el Holoceno, y en este ambiente somero, los cambios en la química del agua y nivel del lago fueron insuficientes para afectar la composición de diatomeas.

Palabras claves: Cuaternario tardío, diatomeas, CCA, paleoclimas, Lago Junín, Andes tropicales, Perú.

INTRODUCTION

The tropics receive the highest amount of solar energy on the globe, and this energy is redistributed via atmospheric and oceanographic processes to higher latitudes. Moreover, tropical areas in the world contain 50% of Earth's surface and currently about 75% of the total population (Thompson, 2000). Yet despite the importance of the tropics in the global climate system, scarce tropical paleoclimatic records limit our understanding of long-term climate evolution and variability, as well our understanding of climatic impacts on both ecosystem development and on tropical civilizations.

Our understanding of the late-Quaternary climatic history of the central Andes of tropical South America is based on geochemical records from ice cores (Thompson et al., 1995, 1998), paleolimnological reconstructions from lake cores (Rodbell et al., 1999; Seltzer et al., 2000, 2002; Baker et al., 2001a, 2001b; Cross et al., 2001; Rowe et al., 2002; Abbott et al., 1997, 2000; Wolfe et al., 2001), as well as pollen records (Hansen et al., 1984, 1994; Hansen & Rodbell, 1995; Graf, 1992), which together span latitudes from 2°S to 19°S and show the nature and timing of regional glacial-interglacial and higher frequency climate variability. The longest most continuous sedimentary records in the central Andes (Lake Titicaca, Salar de Uyuni) suggest that during the last glacial maximum (LGM), the tropical Andes were cold and had a positive moisture balance, which permitted the expansion of glaciers and produced large overflowing freshwater lakes. This scenario of a wet LGM is inconsistent the Refugia Hypothesis, which proposes tropical lowland forest fragmentation separated by savanna-like communities in a dry glacial environment (Haffer, 1969; Hooghiemstra & van der Hammen, 1998; Colinvaux et al., 2000). The Refugia Hypothesis is supported by interpretations of

pollen and algal remains from lacustrine sediments (Ybert, 1992; Mourgiart & Ledru, 2003), although not by any other pollen-based studies (Colinvaux et al., 2000). The central Andes climate during the early to mid-Holocene was characterized by severe arid conditions that prevailed for several millennia, followed by increased precipitation during the late-Holocene. Paleoclimatic records from central Peru (Lake Junin, 11°S) (Seltzer et al., 2000) and the Altiplano (Lake Titicaca, 17°S) (Baker et al., 2001a) show somewhat different patterns of change in effective moisture during the Holocene. The Lake Junin $\delta^{18}\text{O}$ authigenic calcite record suggests a gradual increase in precipitation from early to late-Holocene times, whereas the combined results of diatom, CaCO_3 , and $\delta^{13}\text{C}$ in Lake Titicaca suggest a moderately wet early-Holocene, followed by a dry mid-Holocene, and then a humid late-Holocene. Because multiple factors potentially can influence lacustrine oxygen-isotope records, we examined the stratigraphy of major siliceous microfossil groups throughout the entire 19-m Lake Junin sediment core (Seltzer et al., 2000) to see if the diatom record provided any additional insights on climate change in the Junin Plains.

The quasi-endorheic Lake Junin (11°S, 76°10'W; Fig. 1) is located about 300 km northeast of Lima in the center of the Junin Plains, a high altitude (4100 m) plateau between the Eastern and Western Cordilleras of the central Peruvian Andes. The lake has a large (300 km²) shallow (depth_{max} = 15 m) basin, which supports a marginal wetland of 1-3 km containing marsh vegetation (reeds, charas). The lake drains via a single outlet stream that joins the San Juan River to form the Mantaro River, one of the most important rivers in the Central Andes. The lake basin has been influenced by local glaciations, although the lake itself was never overrun by Late Pleistocene glaciers,

as indicated by terminal moraines and outwash fans near the present lake margin (Wright, 1983; Hansen et al., 1984).

Precipitation in this region is governed by the annual march of the Intertropical Convergence Zone (ITCZ), which affects the transport of moisture from the Amazon basin via easterly winds. Mean monthly precipitation (1988-1997) in Carhuamayo (Fig. 1) varies from about 10 mm in the austral winter (dry season, JJA) to 120 mm in the austral summer (wet season, DJF) (Fig. 2). The mean monthly atmospheric temperature varies little over the year, with maximum monthly temperatures of ~16°C. Minimum mean monthly temperatures follow the same general pattern of variation as precipitation, although the latter has a higher degree of variation (Fig. 2). Given the high seasonal and interannual variation in precipitation, proxy records from Lake Junin sedi-

ments are thought to reflect changes in precipitation. No evaporation measurements are available at this time. Water residence time in the Lake Junin main basin is ~2.5 yr; the annual lake-level fluctuation is about 1.5-m (Martin et al., 2001).

To evaluate the pattern of Holocene effective moisture at Lake Junin, this paper aims to 1) establish the relationship between modern diatom composition and environmental variables to apply to diatom-based paleoclimate interpretations, and 2) delineate past environments and infer paleolimnologic conditions in Lake Junin from the fossil diatom record.

MATERIALS AND METHODS

Field Methods

The sediment core JU96-A was taken in 1996 with a modified Livingstone corer (Wright et al.,

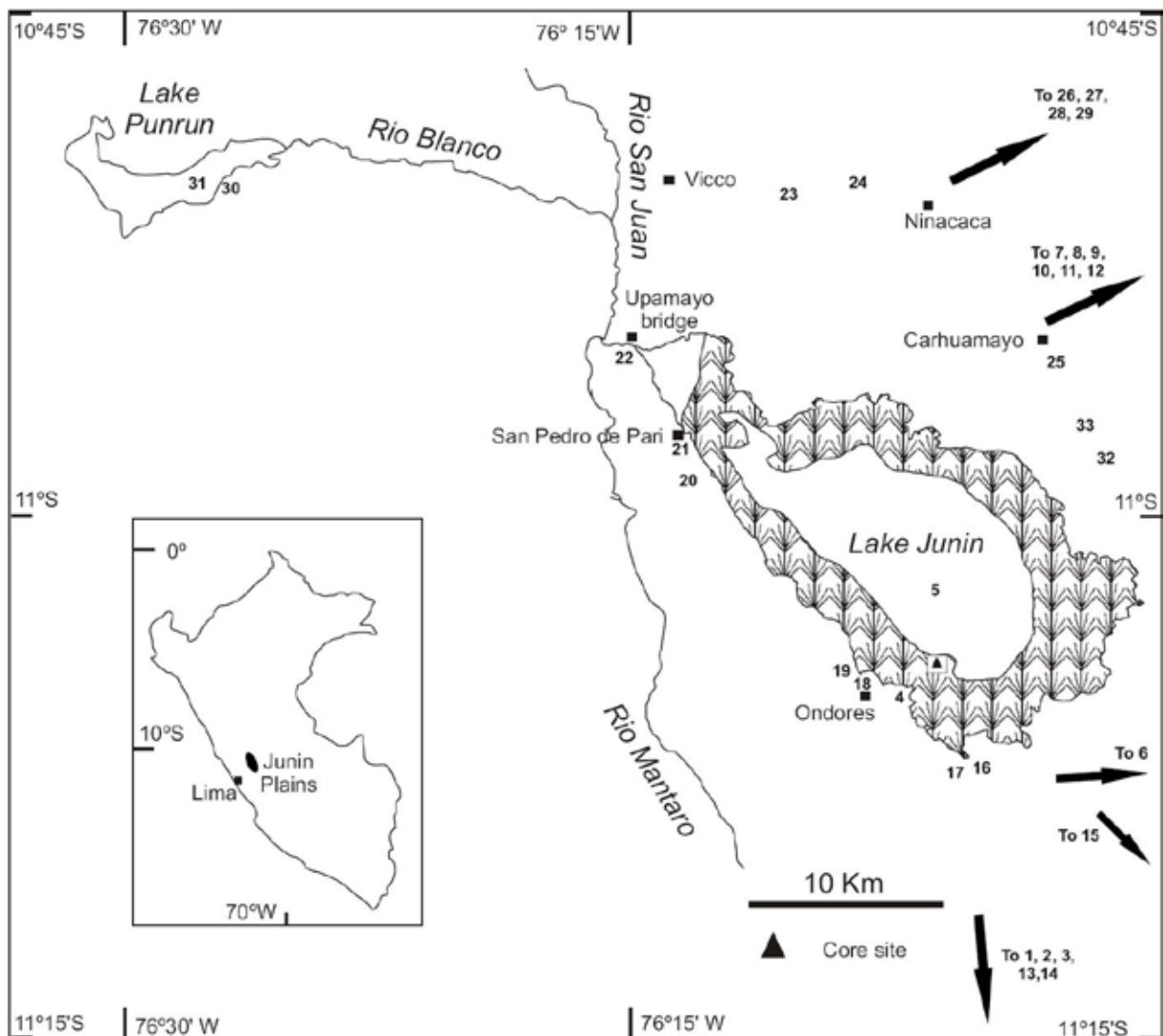


Figure 1.- Location map of Lake Junin with surrounding sample sites. Location numbers are the same as Tables 2 and 3. Arrows indicate the general direction of sample sites outside the map view.

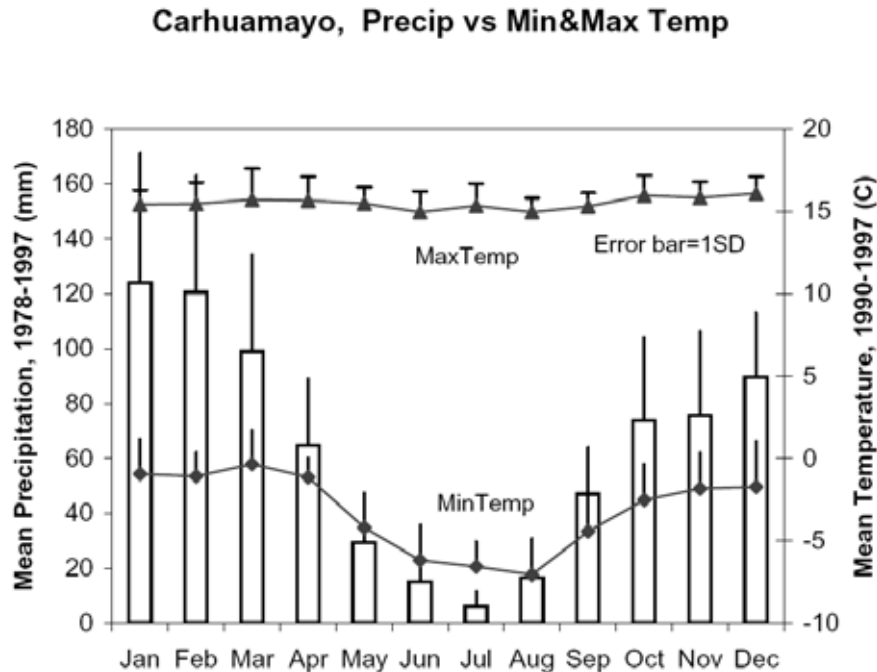


Figure 2.- Mean monthly precipitation (1978-1997), maximum and minimum temperatures (1990-1997) in the town of Carhuamayo, Junin, Peru. Data from Electroandes S. A. and furnished by A. J. Martin (Lorax Environmental Services, Canada).

1984) near the town of Ondores in 2-m water depth at the edge of a floating sedge mat adjacent to open waters (11°03.52'S, 76°07.27'W) (Fig. 1).

To assess modern diatom distribution, 34 localities were sampled for diatoms and water chemistry. We made *in situ* measurements of pH, conductivity, dissolved oxygen, water temperature, and water transparency. Ninety-three samples were collected for nutrient and modern diatom analyses (June - July 1999) from 5 distinct environments: lake offshore, lakeshore, stream, wetland, and springs (Table 1). Substrates sampled include epipellic (surface sediments, littoral muds), epilithic, epiphytic, and planktonic. We differentiate 14 different environment-substrate combinations, including a special epilithic type of algal bioherm (see Table 1 for details). All of these environment-substrate couplets are considered passive (biological) environmental variables in ordination analyses.

Laboratory Analyses

Water analyses from 32 localities (Table 2) included cations (Ca, Si, Fe, Sr, Mg, Al, K, Na), anions (Cl, SO₄, HCO₃/CO₃), nutrients (total phosphorous-TP and total nitrogen-TN) and stable isotopes (δ¹⁸O, δ¹³C, δD). Nutrient analyses followed standard procedures for total phosphorus (Lind, 1985) and total nitrogen (American Public Health Association, 1998) (Tables 2, 3). Details of other geochemical

methods are reported in Metivier (2000) and Flusche et al. (2005).

Fossil and recent diatom samples were acid-cleaned following standard techniques (Battarbee, 1986). Cleaned materials were permanently fixed in Naphrax® (R.I. 1.74), and identifications were made at 1000x magnification on a Leica DMRX transmitted-light microscope (N.A. 1.30) with differential interface contrast.

From modern material, fifty samples contained sufficient valves to warrant diatom analysis (Table 1). A complete set of water filters (34 samples) was barren of diatoms. In samples with adequate diatom preservation, a minimum of 400 diatom valves was identified to the lowest taxonomic level. Species with abundances greater than 3% in any of the distinct ecological groups were graphed and plotted. From the sediment core, sixty-nine sediment samples at 0.3-m intervals (temporal resolution of about 400 yr between samples) were analyzed for their siliceous microflora composition. From this set, twenty-four samples contained enough well-preserved diatom valves to warrant diatom analysis. A minimum of 300 diatom valves per slide were identified and counted in sediment-core samples. Diatom identification in modern and fossil samples is based on cosmopolitan floras (Krammer and Lange-Bertalot, 1991-2000; Lange-Bertalot et al., 1996; Hustedt, 1930; Hustedt,

Table 1.- Diatom, nutrient, and environment-habitat couplet samples list from the Junin Plains, Peru, central Andes. *M-lsh* = macrophyte lakeshore, *M-str* = macrophyte stream, *M-spr* = macrophyte spring, *M-wtl* = macrophyte wetland, *S-off* = surface sediment lake offshore, *S-lsh* = surface sediment lakeshore, *S-str* = surface sediment stream, *S-spr* = surface sediment spring, *P-off* = plankton tow lake offshore, *P-lsh* = plankton tow lakeshore, *P-str* = plankton tow stream, *R-str* = rock scrub stream, *R-spr* = rock scrub spring, *Al-bio* = algal bioherm.

Locality	Sample ID	Environment	Habitat	Environment - Habitat couplets	TN/TP
1	23.VI.99-1	Stream	Macrophyte	M-str	
1	23.VI.99-2	Stream	Rock scrub	R-str	
2	23.VI.99-5	Lake offshore	Water		Yes
2	23.VI.99-6	Lake offshore	Water		Yes
2	23.VI.99-9	Lake shore	Macrophyte	M-lsh	
3	23.VI.99-7	Lake offshore	Water		Yes
3	23.VI.99-8	Lake offshore	Water		Yes
3	23.VI.99-4	Lake offshore	Plankton tow	P-off	
4	25.VI.99-2	Lake shore	Water		Yes
4	25.VI.99-3	Lake shore	Water		Yes
4	25.VI.99-9	Lake shore	Macrophyte	M-lsh	
4	25.VI.99-11	Lake shore	Macrophyte	M-lsh	
5	25.VI.99-1	Lake shore	Macrophyte	M-lsh	
5	25.VI.99-4	Lake offshore	Water		Yes
5	25.VI.99-5	Lake offshore	Water		Yes
5	25.VI.99-12	Lake offshore	Surface sed	S-off	
6	26.VI.99-2	Lake shore	Water		Yes
6	26.VI.99-3	Lake shore	Water		Yes
6	26.VI.99-5	Lake shore	Macrophyte	M-lsh	
7	26.VI.99-7	Lake shore	Macrophyte	M-lsh	
7	26.VI.99-8	Lake shore	Water		Yes
7	26.VI.99-9	Lake shore	Water		Yes
7	26.VI.99-13	Lake shore	Algal bioherm	Al-bio	
9	27.VI.99-1	Wetland	Macrophyte	M-wtl	
10	27.VI.99-3	Stream	Macrophyte	M-str	
11	27.VI.99-5	Spring	Macrophyte	M-spr	
11	27.VI.99-6	Spring	Rock scrub	R-spr	
11	27.VI.99-8	Spring	Water		Yes
11	27.VI.99-9	Spring	Water		Yes
12	27.VI.99-12	Stream	Water/Sed. Interf.	S-str	
13	28.VI.99-1	Spring	Macrophyte	M-spr	
14	28.VI.99-3	Spring	Macrophyte	M-spr	
15	30.VI.99-1	Stream	Macrophyte	M-str	
15	30.VI.99-3	Stream	Water		Yes
15	30.VI.99-4	Stream	Water		Yes
16	30.VI.99-5	Spring	Macrophyte	M-spr	
16	30.VI.99-6	Spring	Macrophyte	M-spr	
16	30.VI.99-7	Spring	Water/Sed. Interf.	S-spr	
16	30.VI.99-10	Spring	Water		Yes
16	30.VI.99-11	Spring	Water		Yes
17	30.VI.99-12	Spring	Macrophyte	M-spr	
17	30.VI.99-15	Spring	Water		Yes
17	30.VI.99-16	Spring	Water		Yes
18	01.VII.99-1	Spring	Macrophyte	M-spr	

Locality	Sample ID	Environment	Habitat	Environment - Habitat couplets	TN/TP
18	01.VII.99-2	Spring	Rock scrub	R-spr	
18	01.VII.99-4	Spring	Water		Yes
18	01.VII.99-5	Spring	Water		Yes
19	01.VII.99-6	Spring	Macrophyte	M-spr	
19	01.VII.99-7	Spring	Water/Sed. Interf.	S-spr	
19	01.VII.99-9	Spring	Water		Yes
19	01.VII.99-10	Spring	Water		Yes
20	01.VII.99-11	Stream	Macrophyte	M-str	
20	01.VII.99-12	Stream	Water/Sed. Interf.	S-str	
20	01.VII.99-14	Stream	Water		Yes
20	01.VII.99-15	Stream	Water		Yes
21	01.VII.99-16	Stream	Macrophyte	M-str	
21	01.VII.99-18	Stream	Water		Yes
21	01.VII.99-19	Stream	Water		Yes
22	01.VII.99-20	Stream	Macrophyte	M-str	
22	01.VII.99-21	Stream	Plankton tow	P-str	
22	01.VII.99-23	Stream	Water		Yes
22	01.VII.99-24	Stream	Water		Yes
23	01.VII.99-25	Stream	Macrophyte	M-str	
23	01.VII.99-26	Stream	Water/Sed. Interf.	S-str	
23	01.VII.99-28	Stream	Water		Yes
23	01.VII.99-29	Stream	Water		Yes
24	01.VII.99-30	Stream	Macrophyte	M-str	
24	01.VII.99-31	Stream	Water/Sed. Interf.	S-str	
24	01.VII.99-33	Stream	Water		Yes
24	01.VII.99-34	Stream	Water		Yes
25	01.VII.99-35	Stream	Macrophyte	M-str	
25	01.VII.99-36	Stream	Water/Sed. Interf.	S-str	
25	01.VII.99-37	Stream	Rock scrub	R-str	
25	01.VII.99-39	Stream	Water		Yes
25	01.VII.99-40	Stream	Water		Yes
26	02.VII.99-1	Lake shore	Plankton tow	P-lsh	
26	02.VII.99-2	Lake shore	Water/Sed. Interf.	S-lsh	
27	02.VII.99-4	Lake shore	Macrophyte	M-lsh	
29	02.VII.99-7	Lake shore	Macrophyte	M-lsh	
29	02.VII.99-8	Lake shore	Plankton tow	P-lsh	
30	03.VII.99-1	Lake shore	Macrophyte	M-lsh	
30	03.VII.99-2	Lake shore	Plankton tow	P-lsh	
31	03.VII.99-5	Lake offshore	Surface sediment	S-off	
32	04.VII.99-1	Stream	Rock scrub	R-str	
32	04.VII.99-7	Stream	Water		Yes
32	04.VII.99-8	Stream	Water		Yes
33	04.VII.99-3	Stream	Macrophyte	M-str	
33	04.VII.99-9	Stream	Water		Yes
33	04.VII.99-10	Stream	Water		Yes
34	04.VII.99-5	Stream	Macrophyte	M-str	
34	04.VII.99-11	Stream	Water		Yes

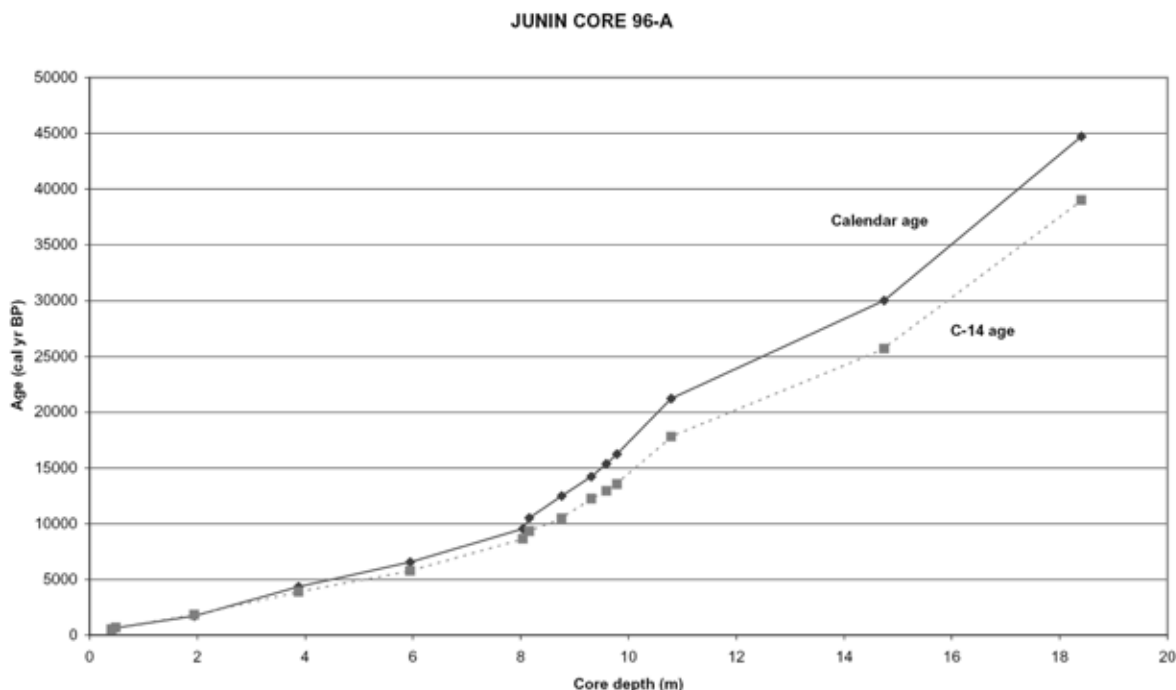


Figure 3.- Age-depth model for core JU-96A, Lake Junin, Peru. Based on Table 3 data.

1930-1966; Simonsen, 1987; Patrick and Reimer, 1966-1975; Germain, 1981) and regional studies (Frenguelli, 1939; Manguin, 1964; Metzeltin & Lange-Bertalot, 1998; Reichardt, 1995; Rumrich et al., 2000; Servant-Vildary, 1986). Counts of chrysophyte statocysts and sponge spicules are expressed as a percentage relative to the total number of diatom valves. Quantitative estimates of diatom concentration in core samples were made with polystyrene microspheres (Battarbee & Kneen, 1982). Local diatom zones are distinguished based on the dominant species in a given core interval. These distinctive zones were confirmed with stratigraphically constrained Cluster analysis CONISS (Grimm,

1987), using the dissimilarity method of Euclidian distances, and results are expressed as mean within-cluster sum of squares.

The age model for the Junin core is based on 14 AMS radiocarbon dates, with linear interpolation between fixed ages and linear extrapolation to the bottom of the core (Table 3, Fig. 3). ¹⁴C ages were transformed into calendar ages using CALIB (version 3.0) for ages less than 24 kyr (Stuiver & Reimer, 1993) and the calibration curve of Bard (1998) for older ages. The ages were not corrected for a reservoir effect, because it appears to be minimal (~60 ¹⁴C-yr) for modern times (Seltzer et al., 2000).

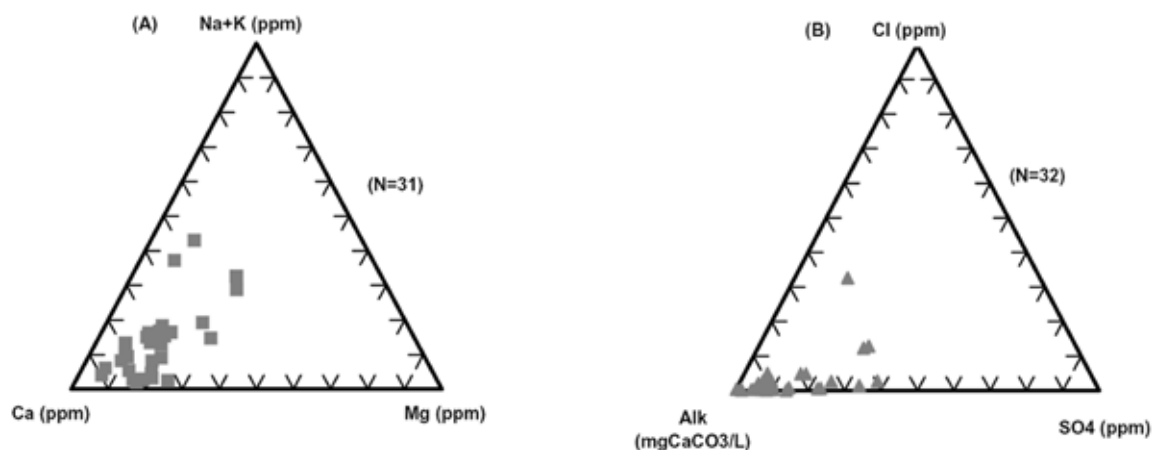


Figure 4.- Cation (A) and anion (B) composition of lake and stream waters in the Junin Plain, Peru.

Locality	Sites name	Alkalinity (mg CaCO ₃ /L)	Ca (ppm)	Si (ppm)	Fe (ppm)	Sr (ppm)	Mg (ppm)	Al (ppm)	K (ppm)	Na (ppm)	Cl (ppm)	NO ₃ (ppm)	SO ₄ (ppm)	d18O (% VSMOW)	dD (% VSMOW)	d13C (% PDB)	Water Temp (C)	pH	Conductivity (uS/cm)	Diss. Oxygen (mg/L)	TN (ug/L)	TP (ug/L)	Secchi depth (m)	
1	L. Puen, inflow stream	150	41.5	4.1	0.2	0.1	9.7	0	2.4	9.1	1.9	1.8	10.6	-14.7	-98.4	-10.3	18	9.33	334	5.848	156.61	5.93	1.65	
2	L. Puen, surface	168.6	26	0.3	0	0.1	18.8	0	3.6	18.1	4.6	0	13.4	-5.2	-52.9	-2.4	15.1	9.13	329	5.848	541.49	8.54		
3	L. Puen, 12m deep	182.1	24.9	0.3	0	0.1	18.4	0	3.4	14.1	4.7	0.1	12.5	-3.4	-9.3	-6.1	11.9	7.89		553.76	5.93			
4	L. Junin, shore	111.1	35.6	2.4	0	0.2	9.2	0	0.8	5.8	4.1	0	38.4	-10.4	-86	-6.4	12	7.91	289	6.336	621.24	8.54	4.32	
5	L. Junin, center	82.2	37.4	2.4	0	0.2	6.7	0	0.9	6.9	3.9	0	51.8	-9.8	-86	-6.4	9.4	6.75	72.5		872.75	11.15		
6	L. Alcaoccha, shore	40	6.9	0.3	0	0	1.2	0	0.9	3.9	0.4	0	6.7	-13.3	-104	-7.5	12.4	7.85	336		633.51	13.75		
7	L. Yanaoccha, shore	162.3	44	2.9	0	0.2	12.2	0	0.6	5	5.6	0	13.4	-13.4	-103.6	-7.5	11.5	8.02	334	7.458			1.65	
8	L. Yanaoccha, center	200	42.6	3.5	0	0.2	12.4	0	0.6	10.2	6.2	0.1	13.4	-13.4	-103.6	-7.5	11.5	8.02	334	7.458				
9	Yanaoccha 1, wetland	105.5	19.4	1.6	0.1	0	10.7	0	0.7	4.5	0.5	0	0	-6.7	-70.1	-10.9	14.1	8.74	183.4					
10	Yanaoccha 2, inflow stream	161.1	41.7	0.9	0	0	14.3	0	0.2	1.2	0.3	0.7	25.9	-11.6	-114	-8.5	13.3	8.16	338	5.016				
11	Yanaoccha 3, spring	185.7	44.9	2.3	0	0.1	9.2	0.1	0.3	0.8	0.4	2.6	2.9	-16.6	-119.3	-11.8	11	7.75	312	3.96	805.27	18.96		
12	Yanaoccha 4, outlet channel	188.6	44.5	2.4	0	0.2	10.7	0	0.7	4.2	4.4	0.1	10.6	-13.6	-102.7	-7	9.8	9	325	4.224				
13	Huagapo Cave, inside	197.1	99.2	3.3	0.1	2.6	17.9	0.1	0.8	22	44.7	0.8	104.6				13.1	7.29	687	3.63				
14	Huagapo Cave, outside	211.4								44.6	0.5	104.6					13.7	7.34	680	3.432				
15	Junin 1, Chacachinpa R.	188.6	55.9	2.9	0	0.2	8.9	0.1	0.6	3.1	1.7	0	12.5	-14.9	-111	-10.2	12.5	7.91	337	5.016	271.57	16.36		
16	Junin 2, Warmipiquito spring	240	72.5	4.4	0	0.5	14.8	0.1	1.9	11.6	14.9	0	51.8	-15.2	-100	-10.4	12.5	7.62	519	2.838	375.86	8.54		
17	Junin 3, spring 2	216.7	74.1	4.9	0	0.6	15.9	0.1	2.1	12	13.3	0.7	42.2	-15.3	-114	-10.2	12.9	7.54	530	3.234	602.84	13.75		
18	Junin 4, Ondores spring	211.1	64.7	6.6	0.1	0.3	14.8	0.7	1.1	14.9	6.7	0.1	20.2	-15.5	-114	-11.5	16.2	7.56	445	2.772	1032.25	29.39		
19	Junin 5, Conoco spring	240.5	98.7	5.2	0	1.4	25.6	0.1	4.2	89.4	148.8	0	66.2	-15.8	-116	-11.5	16.8	7.35	1184	2.64	486.28	13.75		
20	Junin 6, Chuchuanacha R.	108.6	19.7	0.6	0	0	9.3	0	2.9	4	0.5	0	12.5	-13.6	-103	-10.4	15.2	7.98	426.4	4.884	118.21	16.36		
21	Junin 7, San Pedro de Pari	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	15.8	8.37	221	4.752	443.34	13.75		
22	Junin 8, Upanayayo Bridge	105.4	44.3	0.7	0	0.2	5.8	0	0.8	4.4	2.5	0.1	53.8			-8.8	10.7	8.45	306	4.092	443.34	8.54		
23	Junin 9, ditch before Shelby	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10.7	8.17	377	4.818	204.09	18.96		
24	Junin 10, Tambo del Sol	145.7	43.4	1.8	0	0	3.1	0	0.4	2.6	0.6	0.1	1.9	-14.7	-112	-10	10.7	8.21	256	4.224	283.84	16.36		
25	Junin 11, Gunoc Km 255	180	54.9	2.9	0	0.1	10.3	0.1	0.6	1.2	2.5	2.6	12.5	-16.2	-122	-12.7	10.7	8.04	354	4.092	1774.53	60.67		
26	L. Tauli, shore	200	46.8	3.5	0	0.1	12	0.1	0.7	2.1	0.5	0	18.2	-14	-107	-9.4	11.3	8.24	373	4.026				
27	L. Cochoahuaycho, shore	174.3	42.5	0.5	0	0.2	11.2	0.1	0.6	1.2	0.7	0	18.2	-13.8	-109	-10.7	10	8.64	372	4.29				
28	L. Cochoahuaycho, center	194.4	49.9	0.6	0	0.2	11.4	0.1	0.6	1.2	0.7	0.1	16.3	-13.9	-109	-10.7	10.1	8.29	355	5.742				
29	L. Lulicocha, shore	164.7	42.8	1.2	0	0.1	9.5	0	0.6	0.9	0.6	0	12.4	-12.8	-99	-8.8	10.4	8.78	292	4.224				
30	L. Purun, shore	106.9	31.7	1.7	0	0.4	3.8	0	0.6	3.4	0.9	0	30.7	-11.9	-95	-10.9	10.9	8.62	238	4.026				
31	L. Purun, center	101.5	34.9	1.8	0	0.5	4	0	0.6	2.9	0.9	0.1	30.7	-12.2	-94	-11	8.65	247	6.072					
32	Junin 12, Champus	106.9	25.4	1.2	0	0	2.6	0	1.3	3	0.4	0	4.8	-11.9	-95	-11.4	13.9	8.82	168	2.97	289.98	11.15		
33	Junin 13, Qdu. Anasemchi	88.6	47.1	2.3	0	0.1	3.3	0.1	0.6	1.5	0.5	0	4.8	-15.3	-111	-10.2	16.3	8.54	291	3.234	486.28	34.6		
34	Junin 14, Paicamayta R.	148.6	36.8	1.3	0	0.1	9.7	0	0.6	7.8	8.3	0	10.5	-13.2	-103	-7.6	12.8	9.04	304	3.564	320.65	18.96		
	Transformed data:																							
		log (x+28)	none	log (x+0.25)	Not used	Not used	sqrt	Not used	log (x+0.25)	log (x)	log (x)	log (x)	log (x+15)	log (x+18)	log (x+25)	log (x+15)	sqrt	sqrt	sqrt	none	log (x)	log (x)	Not used	

Table 2.- Lake and stream environmental data from the Junin Plains, Peru, central Andes.

Lab Access #	Depth (m)	Material	14C Date	Cal age (yr BP)
AA-24001 (1)	0.41	Molluscs	520 ± 40	529
OS-16053 (1)	0.49	Molluscs	680 ± 30	652
OS-16054 (1)	1.945	Molluscs	1820 ± 40	1720
OS-16055 (1)	3.88	Molluscs	3880 ± 45	4342*4335*4287
OS-16056 (1)	5.95	Molluscs	5760 ± 60	6540
OS-16057 (1)	8.04	Molluscs	8640 ± 40	9532
NSRL-11587	8.16	Molluscs	9320 ± 95	10498
NSRL-11585	8.76	Molluscs	10490 ± 95	12484
NSRL-11588	9.31	Molluscs	12240 ± 100	14226
OS-16052 (1)	9.59	Molluscs	12950 ± 150	15360
AA-24002 (1)	9.785	Organic macrofossils	13560 ± 95	16240
AA-24003 (1)	10.79	Organic macrofossils	17795 ± 145	21220
OS-18137 (1)	14.74	Organic macrofossils	25700 ± 330	30018
AA-24004 (1)	18.4	Molluscs	39020 ± 1045	44728

*Range of calibrated ages

Table 3.- Radiocarbon dates from core Ju96-A, ⁽¹⁾ reported in Setzler et al. (2000).

Numerical analysis

Species and environmental data were screened to standardize the data matrix. Species with more than 1% (113 taxa) of the total count were considered for multivariate analysis. All environmental data were transformed to follow a Gaussian distribution. Variables were $\log(x)$, $\log(x+n)$, or square-root transformed using Calibrate (v. 0.82) (Juggins, 1998) to approximate a normal distribution (Table 2). From the 35 measured environmental variables (21 active and 14 passive), we considered 17 active (temp., pH, conductivity, dissolved oxygen, TN, TP, alkalinity, Ca, Si, Mg, K, Na, Cl, SO_4 , $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and δD) and 6 passive (M-Str, M-lsh, M-spr, R-Str, S-Str, and P-lsh) variables (Tables 2, 3). The exclusion of 5 active variables was because of scarce data (Secchi depth), skewed data with extreme values (Sr, Al, Fe), or because ICP-MS measurement of nitrate (NO_3) is not sufficiently precise for biological processes. The diatom environment-habitat couplets (passive variables) were entered as binary elements (0, 1) in the data matrix. To decrease environmental variability, we only considered passive variables that included 3 or more samples ($n=6$).

All ordination analyses were made using CANOCO (v. 4.5, 2002) (ter Braak & Šmilauer, 1998). Missing values were replaced with mean values within each set of parameters; species percentages were square-root transformed to avoid the effect of higher abundances, and abundances of rare species

were downweighted.

A Principal Component Analysis (PCA) was performed in order to visualize the general pattern of variation among environmental parameters and sample localities. The scaling was focused on inter-sample distances, and the environmental scores were divided by the standard deviation. Only the environmental variables were centered and standardized. An initial Canonical Correspondence Analysis (CCA) was performed to detect samples that had environmental variables with extreme influence ($>10x$) and active environmental variables with high variance inflation factor ($\text{VIF}>15$), which were eliminated (Birks et al., 1990; ter Braak, 1988). This analysis included scaling focused on inter-species distances, biplot scaling, and Monte Carlo tests for significance of all axes with 499 unrestricted permutations in a reduced model. The pattern of interspecies variation among sampling sites was determined by Detrended Correspondence Analysis (DCA), with detrending by linear segments to determine if the compositional gradient lengths ($\text{DCA1}>3.84$, $\text{DCA2}>2.87$ SD-units; ter Braak & Prentice, 1988) justified further ordination analyses. A second CCA with the forward selection option was used to identify the most important environmental variables that explain the variance in the diatom data. Each variable was tested with Monte Carlo permutation tests (999 unrestricted permutations), with the addition of new variables into the model until a p -value >0.05 was exceeded.

Non-significant environmental parameters were excluded from further analyses. With the selected set of significant parameters, we ran a series of constrained CCAs on each individual environmental variable. The significance of the first axis was tested using Monte Carlo permutation tests ($p \leq 0.05$) with 199 unrestricted permutations. Any non-significant environmental variable was excluded from further analyses. An additional CCA was performed with the statistically significant environmental parameters, and then we identified highly correlated environmental variable pairs ($-0.6 > r > 0.6$) from the Pearson correlation matrix. Partial CCAs were performed for each correlated pair; one variable as the sole variable and the other as covariable, and the significance of each pair of variables was determined with a Monte Carlo permutation test on the 1st axis ($P \leq 0.05$, 999 unrestricted permutations). Non-significant results indicate that the variate-covariate variables explained the same part of data variance; in this case we choose the variable explaining the highest amount of variance in the original CCA1.

RESULTS

Water characterization of high-altitude lentic and lotic environments

Water bodies in the Junin Plain and surrounding areas contain calcium-rich alkaline waters. Cation composition indicates elevated concentration of Ca^{+2} (range from 6.9 to 99.2 mg/L, $n=31$) with respect to Mg^{+2} and $\text{Na}^{+1}+\text{K}^{+1}$ (Fig. 4a), and alkalinity is high (40.0–240.5 mg CaCO_3 /L, $n=32$) with respect to SO_4^{-2} and Cl^{-1} concentration (Fig. 4b). Waters have circum-neutral to alkaline pH (6.8–9.3, $n=33$); moderate to high conductivity (168–1184 $\mu\text{S}/\text{cm}$, $n=32$), and low to moderate dissolved oxygen (2.6–7.5 mg/L, $n=29$). Total phosphorous concentrations range from 5.9 to 60.7 $\mu\text{g}/\text{L}$ ($n=21$), total nitrogen from 118.2 to 1774.5 $\mu\text{g}/\text{L}$ ($n=21$) (Table 2), and silica concentrations range between 0.3 and 6.6 mg/L ($n=31$).

Modern diatom communities

The diatom composition in macrophyte samples is represented by 58 species (relative abundance $>3\%$) distributed over the 4 environments (Fig. 5). The most common species in lakeshore regions are *Gomphonema minutum*, *Nitzschia denticula*, *Synedra ulna*, *Denticula elegans*, *Diatoma vulgare*, and *Cymbella cistula*. Some planktonic species are also encountered in this association, such as *Synedra acus* var. *angustissima*, *Synedra delicatissima*, and *Fragilaria crotonensis*. Dominant taxa in stream

macrophyte samples are *Achnantheidium minutissimum*, *Synedra ulna*, *Cocconeis placentula*, *Navicula cryptocephala*, and *Staurosira* spp. Wetland macrophyte samples are dominated by *Synedra delicatissima*, *N. cryptocephala*, and *Navicula radiosia*. Species composition in spring samples is more diverse and includes *A. minutissimum*, *Diatoma mesodon*, *N. denticula*, *G. parvulum*, *Naviculadicta seminulum*, *Planothidium lanceolata*, and *Staurosira* spp.

Common lakeshore and lake offshore planktonic species from plankton tows (Fig. 6) are *Synedra delicatissima*, *Gomphonema minutum*, *Fragilaria crotonensis*, *A. minutissimum*, and *Fragilaria vaucheriae*. Stream planktonic diatom samples were dominated by *A. minutissimum*, with low percentages of *S. delicatissima*, *S. ulna*, *F. capucina*, *N. palea*, and *P. zeilleri*. Surface-sediment samples from lakes have a diatom flora primarily composed of *Staurosira* cf. *S. construens* var. *venter*, *Staurosira construens* var. *construens*, and *A. minutissimum*, whereas stream sediment samples contained *Staurosira* cf. *S. construens* var. *venter*, *A. minutissimum*, *Staurosira construens* var. *subsalina*, *Staurosira* spp., *Amphora pediculus*, and *Navicula capitatoradiata* (Fig. 6).

Samples from rock-scrub and algal bioherm environments have a lower diatom diversity of 15 species (Fig. 7). Dominant species for stream and spring habitats are *A. minutissimum*, *C. placentula*, and *Reimera sinuata*, whereas algal bioherm taxa are *A. minutissimum*, *D. elegans*, and *Encyonopsis microcephala*.

The fossil record

Lake Junin sediments (core JU96-A) are composed of four distinct lithological units (Fig. 8): 1) 18.79 to 14.5-m: gray to tan silt with disseminated plant remains and mollusk shells; 2) 14.5 to 11.2m: inorganic massive gray silt; 3) 11.2 to 9.7m: dark organic-rich silt and gyttja; and 4) 9.7 to 0.37m: yellowish-brown laminated marl with abundant gastropod shells.

Diatom species composition of this 19-m core suggests three distinct zones. Diatoms from the lower lithologic unit (18.79 to 14.5 m, Fig. 8) consist of benthic taxa, with the dominance of *Staurosira* sp. cf. *S. construens* var. *venter* (up to 85%) and other benthic littoral and tytoplanktonic species, such as *Pseudostaurosira brevisstrata*, *Staurosira construens* var. *construens*, *Staurosira construens* var. *subsalina*, and *Staurosirella pinnata*. In some levels the epiphytic diatoms *Cocconeis placentula*

Junin Plains, central Peru
plankton & epipellic diatoms

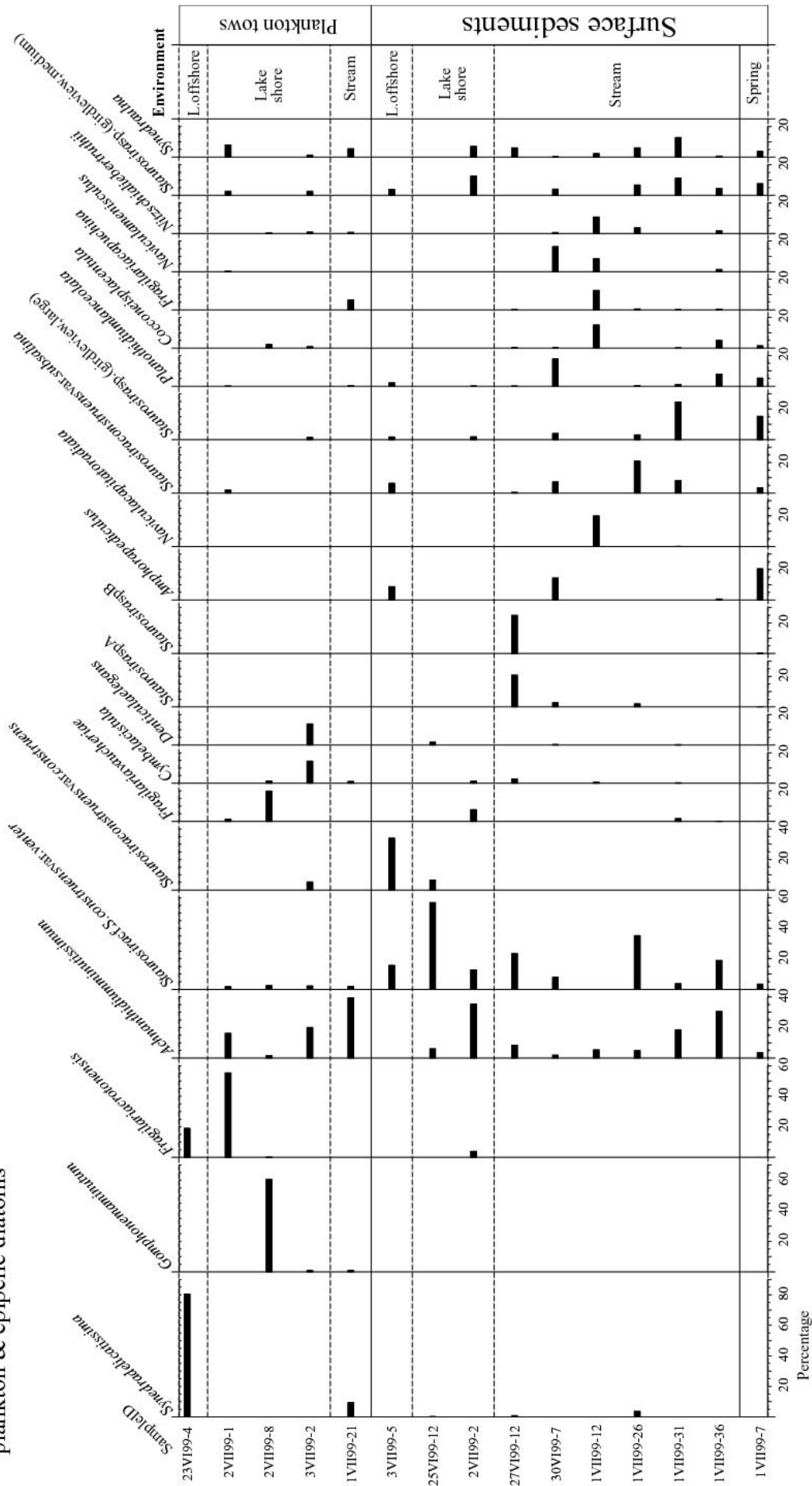


Figure 6.- Plankton and epipellic diatom distribution from lakes and spring localities in the Junin Plain, Peru. For sample locations see Tables 1 and 2.

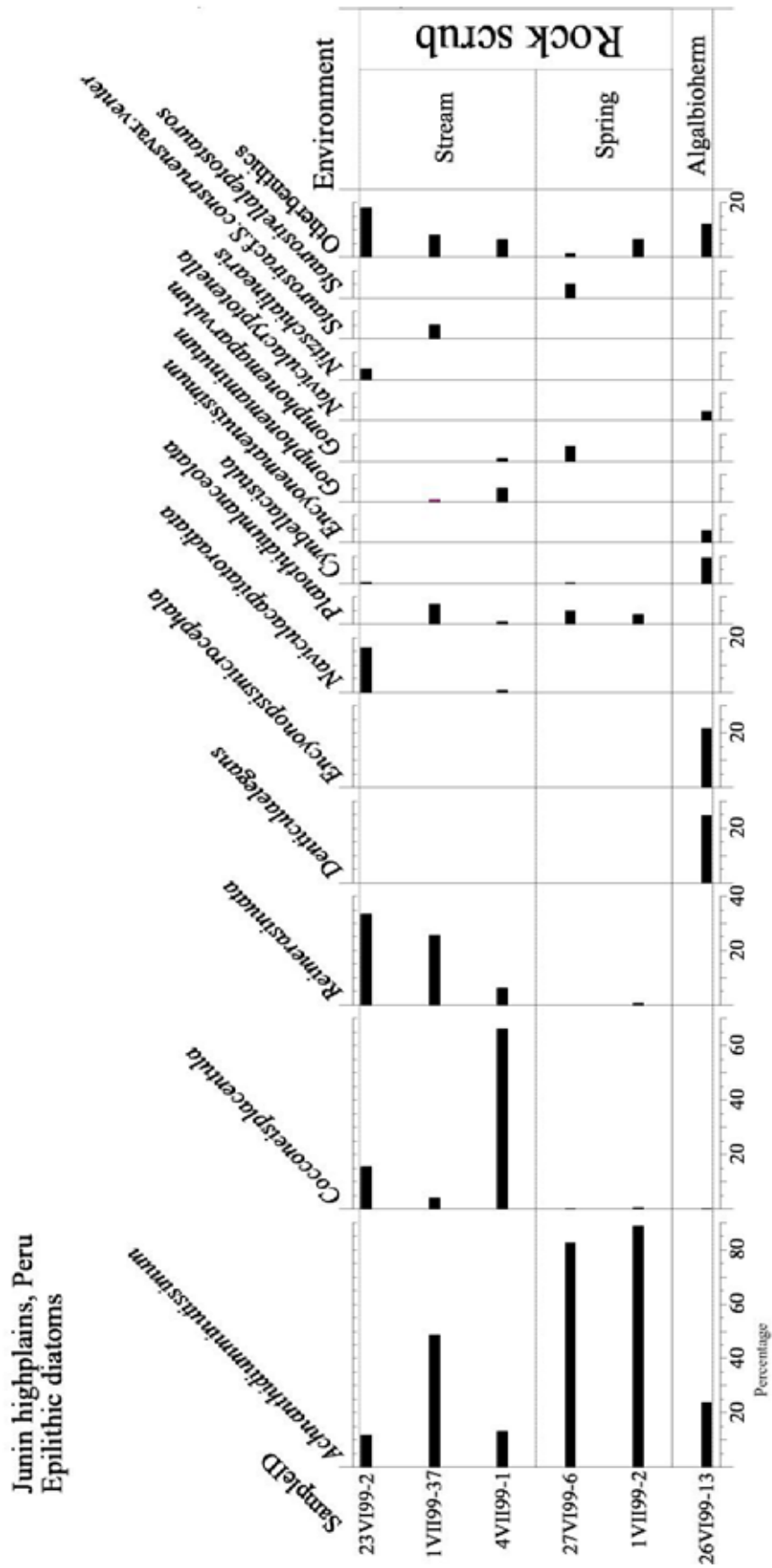


Figure 7.- Epilithic diatom distribution in the Junin Plain, Peru. For sample locations see Tables 1 and 2.

and *Gomphonema pumilum* contribute between 30 and 40% of the diatom total. This association, which defines the diatom zone JU-1, clearly indicates shallow and freshwater conditions, with development of littoral submerged macrophytes, for the time interval from ~46,000 to ~30,000 cal yr BP. An extensive zone in the core between 14.5 and 10.2-m is barren of diatoms, or the valves are so scarce as to be considered statistically significant. This zone of barren or poorly preserved diatoms (from 14.5 to 10.2m) includes the complete gray silt unit and the lower two-thirds of the organic-rich silt unit. A second diatom association (local diatom zone JU-2), dominated by the planktonic species *Cyclotella stelligera* (up to 85%), occurs in the interval from 10.2 to 9.7 m, together with a minor contribution of the species *Cyclotella meneghiniana* and *Denticula elegans*. We interpret this diatom assemblage as fresh and high-stand waters between 17,500 and 16,000 cal yr BP. Sediments changed markedly from organic-rich silt to mollusc-bearing marl at 9.7 m, and this lithology continues to the top of the core. This change is also reflected in the quality and composition of the diatom assemblage. An interval barren of diatom valves is present between 9.7 and 8.9 m. Marl deposition continues from 8.9 to 0.5 m (local diatom zone JU-3), and many samples bearing diatoms are dominated by *Denticula elegans* (up to 95%), a species that prefers high-conductivity waters. Additional epiphytic and epipelagic diatoms in this interval include *Encyonema gracilis*, *Epithemia argus*, *Navicula cryptotenella*, *Nitzschia denticula*, and *Gomphonema pumilum*. This diatom association, which spans *circa* the past 13,000 cal yr BP, suggests a shallow lake with alkaline waters surrounded by submerged littoral macrophytes. Some samples, however, are barren of diatoms, which suggest fluctuating limnological conditions that affected diatom preservation. A surface sample from Lake Junin is dominated by *Staurosira* sp. cf. *S. construens* var. *venter*, but this assemblage is not present in the uppermost part of the sediment core, which suggests that the core does not extend to contemporary times.

Multivariate analyses

Principal Components Analysis of the environmental data was carried out with 50 samples and 17 active environmental variables. Fe, Sr, Al, and NO_3 were excluded, because of large variance effects in the data matrix. PCA axes 1 and 2 have eigenvalues of $\lambda_1=0.359$ and $\lambda_2=0.256$ respectively, and both axes comprise 61.5% of the environmental variance. Environmental parameters with strong loadings for PCA1

are Ca, conductivity, pH, and, dissolved oxygen whereas $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, δD , TP, and TN had high loading on PCA2 (Fig. 9a). Sample sites are distributed along PCA1 from spring to stream and finally to lakeshore environments (Fig. 9b). This environmental gradient reflects the transition of diatom assemblages from flowing waters to lake waters.

DCA analysis (not shown) was carried out with 49 samples (see initial CCA analysis below for exclusion of 1 sample), 17 active environmental parameters, and 113 diatom species. DCA axes 1 and 2 have gradient lengths of 3.960 and 3.697 SD-units for the first and second axes respectively, which indicate that unimodal response models are appropriate. Additionally, this analysis identified that the macrophyte sample I.VII.99-6 at Conoc spring has a high sample-environmental variable interaction (influence of 13.3x) with conductivity (1184 $\mu\text{S}/\text{cm}$). This sample was excluded in further ordination analysis.

The initial CCA identified sample I.VII.99-7 at Conoc spring as having a high influence (11.4x) with conductivity (1184 $\mu\text{S}/\text{cm}$) in the sample-environmental variable interaction; this sample was excluded before the DCA analysis. No environmental variables had VIF greater than 15. The first two CCA axes have eigenvalues of $\lambda_1=0.388$ and $\lambda_2=0.275$, high species-environmental correlations (>0.89), and together explained 14.8% of the variance for species data and 30.9% of the species-environment relation. Monte Carlo permutation tests for significance of the first and combined axes were significant ($p=0.002$). A second CCA utilizing the forward selection option reduced the pool of significant environmental variables to 10 ($\delta^{18}\text{O}$, K, DO, pH, Ca, Na, δD , $\delta^{13}\text{C}$, TN, and Si). The excluded variables were TP, Temp., SO_4 , Alk., Cl, Cond., and Mg.

The series of constrained CCA-s of each environmental variable and axis 1 revealed that TN is a marginally significant (P-value = 0.055) environmental parameter. High Pearson correlation coefficients ($r > 0.6$) were identified for 5 pairs of environmental variables: Si-Ca, Na-K, $\delta^{18}\text{O}$ - δD , $\delta^{18}\text{O}$ - $\delta^{13}\text{C}$ and δD - $\delta^{13}\text{C}$. Partial CCA analyses of these selected variables indicate that all are statistically significant, except for the δD - $\delta^{13}\text{C}$ pair. In this case, $\delta^{13}\text{C}$ was chosen because it explains a higher amount of variability ($\delta^{13}\text{C}$ - $\lambda_1=0.1441$; Deu - $\lambda_1=0.1134$). At the end of this screening process, we identified 6 active environmental parameters (Si, Ca, Na, K, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$) that are independent and explained statistically

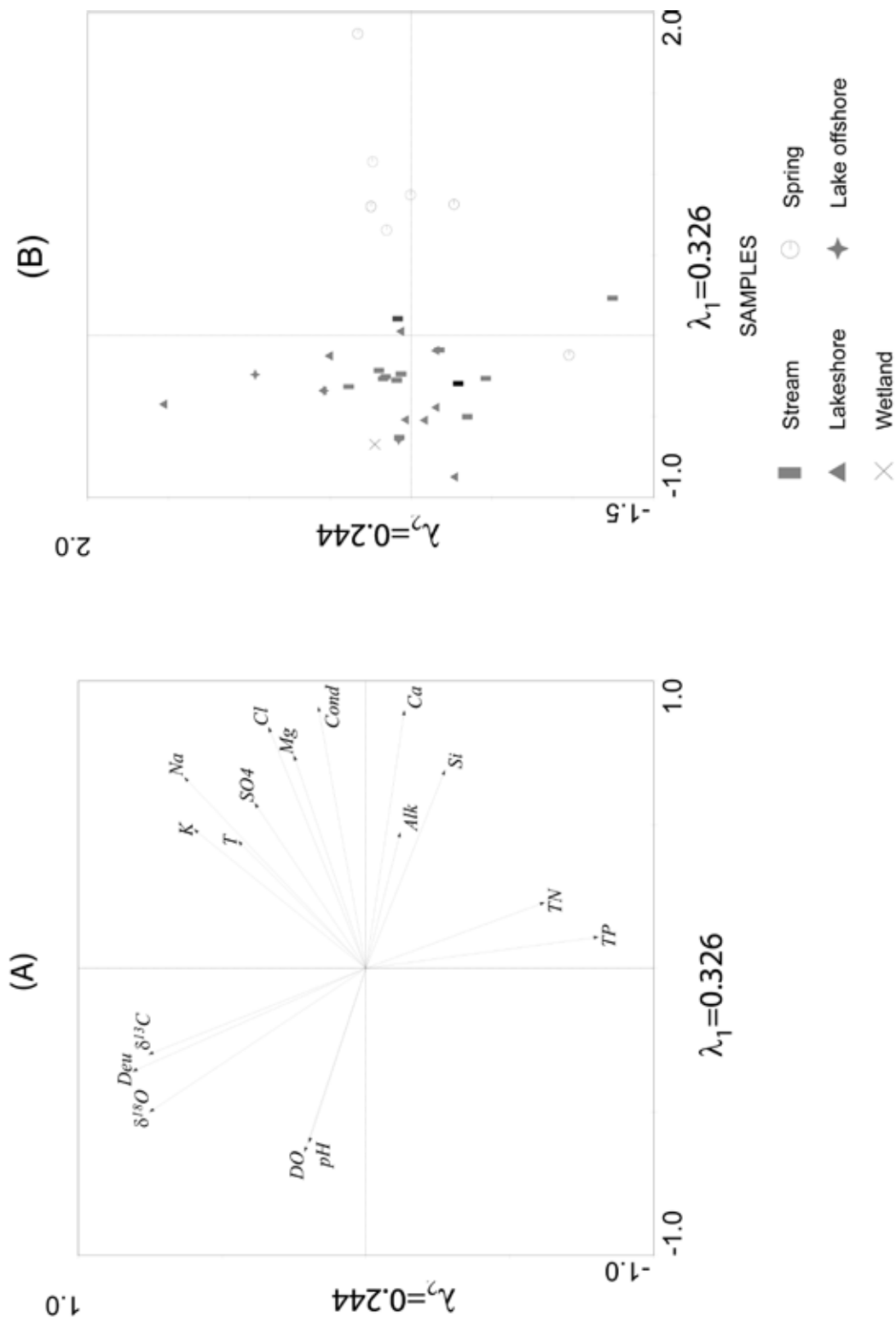


Figure 9.- PCA plot of the active environmental variables (A) and sample sites (B) scores in the Junin Plains area, Peru. Sample sites are grouped by their main environmental setting.

significant variability of our diatom dataset.

The final CCA consisted of 48 samples and twelve (6 active, 6 passive) environmental variables. Eigenvalues for the first two axes are $\lambda_1=0.326$ and $\lambda_2=0.244$, and the axes have high species-environmental variables correlations ($r>0.85$). The combined axes explained 12.8% of the variance in species data and 53.3% of the species-environment relationship. Monte Carlo permutation tests for significance of the first and all canonical axes were significant ($p=0.001$). High positive scores of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, together with negative scores of Ca and Si, influence the distribution of active environmental variables along CCA axis 1 (Fig. 10a). Negative scores of Na and K characterized CCA axis 2. Passive variables also follow this distribution: the lakeshore macrophytic variable (M-lsh) has high loadings on CCA1, with negative scores from M-spr and R-str. High positive scores along CCA2 are attained only by plankton-lakeshore samples. Sampling sites are gradually segregated along CCA1 (Fig. 10b) from lake offshore (+) to stream to spring (-) habitats, as in the initial PCA analysis (Fig. 9b), although with a moderate degree of overlapping. Diatom species distribution follows the sequence of habitats from inland to lake environments (Fig. 10c). CCA1 effectively segregates epiphytic diatoms from lakeshore macrophytes (e.g. *Rhoicosphenia abbreviata*, *Epithemia argus*) and spring macrophytes (e.g. *Diatoma mesodon*, *Nitzschia fonticola*). CCA2 segregates lakeshore species (*Cocconeis titicaensis*, *Gomphonema minutum*) from stream species (*Nitzschia linearis*, *Navicula cryptocephala*).

DISCUSSION

Modern environments

Alkaline waters with an elevated Ca^{+2} concentration characterize the lake and stream waters in the Junin Plain, as also indicated in previous studies (Hegewald et al., 1976; Hegewald & Runkel, 1981). A general view of environmental variable and sample site distribution was attained with PCA (Fig. 9). Conductivity and Ca are distributed with vectors towards the positive portion of PCA axis 1. The distribution of sites along this axis indicates that this gradient represents differences in water chemistry from spring to flowing waters (streams) to still waters (lakes). Interpretation of PCA axis 2 is more difficult; the similar vectors for δD , $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$ in contrast to negative values for TN and TP do not reveal a simple explanation. It seems that isotopic depletion is characteristic of lake samples, whereas

heavier values occur in some stream samples, suggesting that water source and residence time play important roles in explaining axis 2. Axis 2 is also partially explained by the availability of nutrients (TN, TP).

CCA ordination analyses identified 6 environmental variables (Si, Ca, Na, K, $\delta^{18}\text{O}$, and $\delta^{13}\text{C}$) that explain the majority of variability in the diatom species composition of regional aquatic habitats and separate sampling sites into main environmental groups (Fig. 10a). $\delta^{18}\text{O}$ has the longest vector along CCA axis 1, which suggests that the gradient from enriched to depleted $\delta^{18}\text{O}$ values is the strongest correlate with the modern diatom distribution. Because this gradient represents changes from groundwater-dominated springs to flowing waters to lake-waters (Fig. 10b), a positive excursion along CCA1 can be interpreted as a proxy for the relative influence of groundwater versus surface inputs (precipitation and runoff) on the hydrologic budget. This hypothesis needs further evaluation, because all samples were collected in austral winter (dry season), and contrasts with wet-season samples (austral summer) would be useful. Sodium is most strongly correlated with CCA axis 2 (Fig. 10a). Because Na has a high correlation with conductivity ($r=0.89$, $p<0.001$, $n=49$), CCA2 can also be used to infer the concentration of total dissolved solutes.

Paleoenvironments and paleoclimates

Comparing diatom assemblages from modern environments to the fossil record provides some clues to aid interpretation of the diatom stratigraphy. *Staurosira* sp. cf. *S. construens* var. *venter* dominates (85% relative abundance) the diatom record in zone JU-1. In the modern Lake Junin surface sediment sample (25VI99-12), this species comprises 55% of the total assemblage, and it is also found in stream and spring areas, although in lower abundance (Fig. 5, 7). Therefore, we can infer that the environment of zone JU-1 was shallow with freshwater, as it is in present day. The short zone JU-2 is dominated by *Cyclotella stelligera* (85%) and has no modern analog among the modern samples from the Junin Plain. *C. stelligera* occurs in surface sediments of modern Lake Titicaca in variable abundances (up to 40%) in water depths from 20 to 200-m (Tapia et al., 2003), as well as in other smaller glacially-formed freshwater lakes (up to 35%) in the central Andes (Abbott et al., 2000; Fritz, unpublished data). Thus, we can infer a freshwater environment most likely with deeper waters than present day. *Denticula elegans* dominates zone JU-3, reaching abundances of up to 95%. This species is

present in modern lakeshore environments at lakes Yanacocha and Purun with moderate abundances (~15 to 35%) (Figs. 6-8). Currently, these lakes are deep with moderate alkalinity values, but because *D. elegans* occurs in littoral settings of these lakes, we infer that zone JU-3 flora was deposited in shallow alkaline waters.

The three distinctive diatom assemblages found in Lake Junin core sediments suggest the development of 3 different paleoenvironments throughout basin evolution (Fig. 8). Diatom zone JU-1 contains diatoms indicative of shallow freshwaters during part of Marine Isotope Stage 3 (MIS-3; ~46,000 to ~30,000 cal yr BP), and based on its diatom composition, this environment seems to resemble present day conditions. Geomorphological evidence suggests that the Junin Plains was surrounded by glacier ice during the Rio Blanco glaciation phase (Wright, 1983) favoring the development of Lake Junin in the middle of the high-plateau before 40,000 ¹⁴C yr BP. Palynological evidence from Lake Junin suggests the development of cold puna vegetation from ~42,000 to 39,000 ¹⁴C yr BP (pollen zone 2, Hansen et al., 1984). Coeval plant remains and gastropod shells found in core sediments at diatom zone JU-1 suggest the presence of aquatic vegetation in shallow waters. This evidence coupled with the diatom data and large-amplitude fluctuations in organic and inorganic carbon (Seltzer et al., 2000) suggest a productive shallow lake environment punctuated by short-term droughts. An extensive zone barren of diatom frustules began post 30,000 cal yr BP, when outwash sediments loaded the basin with glacial clastics, as evidenced by high magnetic susceptibility (Seltzer et al., 2000). At about 21,000 cal yr BP, the basin started to accumulate organic-rich silt sediments (Seltzer et al., 2000), but diatoms were not preserved in abundance until about 17,500 cal yr BP, possibly because of the dilution effect of high sediment input.

Diatom zone JU-2 (~17,500 to 16,000 cal yr BP) assemblage is characteristic of fresh and deeper waters than zone JU-1, as indicated by the dominance of the planktonic *Cyclotella stelligera*. Junin pollen zone 3 (24,000 to 12,000 ¹⁴C yr BP) contains high amounts of subpuna grass and shrubland indicating upslope migration, probably in response to increased precipitation. Similarly, abundant *Isoetes* spores suggest the presence of an oligotrophic lake (Hansen et al., 1984). Thus, both diatom and pollen and spore data suggest evidence of positive moisture balance in the basin. After about 17,000 cal yr BP, marl deposition began in the lake. The change in the nature

of sedimentation marked an important event in the lake as the diatom assemblage and organic and inorganic carbon shifted in character. Diatoms are not preserved in the initial stages of this zone, perhaps because of very high alkalinity (Fig. 8).

Diatoms are preserved again in the sediments beginning ~13,000 cal yr BP, and the diatom assemblage from zone JU-3 (13,000 to 500 cal yr BP) suggests alkaline shallow waters with aquatic macrophytes. This period contains a non-continuous diatom record, with some intervals of poor silica preservation. These intervals of intense dissolution likely are indicative of highly alkaline waters during times of reduced moisture. A level of shallow waters is suggested by the high sponge spicules to diatom ratio at about 10,000 cal yr BP, contemporaneous with enriched stable isotope values (Seltzer et al., 2000). A relationship between increased diatom accumulation rate (DAR) and depleted $\delta^{18}\text{O}$ values during the Holocene (figure not showed) indicates that the same millennial-scale variability has affected both stable isotope and DAR records. The enhanced diatom preservation is perhaps a direct result of decreased alkalinity in the waters due to increased effective moisture. Junin pollen zone 4 (12,000 to 3,000 ¹⁴C yr BP) contains grasses and Andean forest types, which have two alternative explanations. One is that the climate was wetter than today with effective upland migration of Andean forest. An alternative hypothesis is that effective moisture decreased and Andean forest types were windblown upland and intermixed with grass pollen. The limited diatom data suggest that for the late glacial and most of the Holocene (13,000 to 500 cal yr BP), Lake Junin has been a shallow alkaline lake, probably with high rates of evaporation. Today the shallow-water Lake Junin supports a diatom flora that reflects freshwater conditions, in contrast with the diatom record throughout most of the Holocene (until 500 cal yr BP) with its flora indicative of shallow alkaline waters.

Although with local differences, the climatic record of lakes Titicaca and Junin show some common patterns of variation during the past 16,000 cal yr BP. A correlation between diatoms (benthic + planktonic saline) from Lake Titicaca and $\delta^{18}\text{O}$ (from Lake Junin) records (Fig. 11) suggests similar overall patterns in the late-glacial and late-Holocene, as evidenced by low benthic plus saline diatom abundances and moderately depleted isotope values, each indicative of positive effective moisture. Thus, these data indicate a regionally synchronous climate spanning the latitudes from Lake Junin to Lake Titicaca from

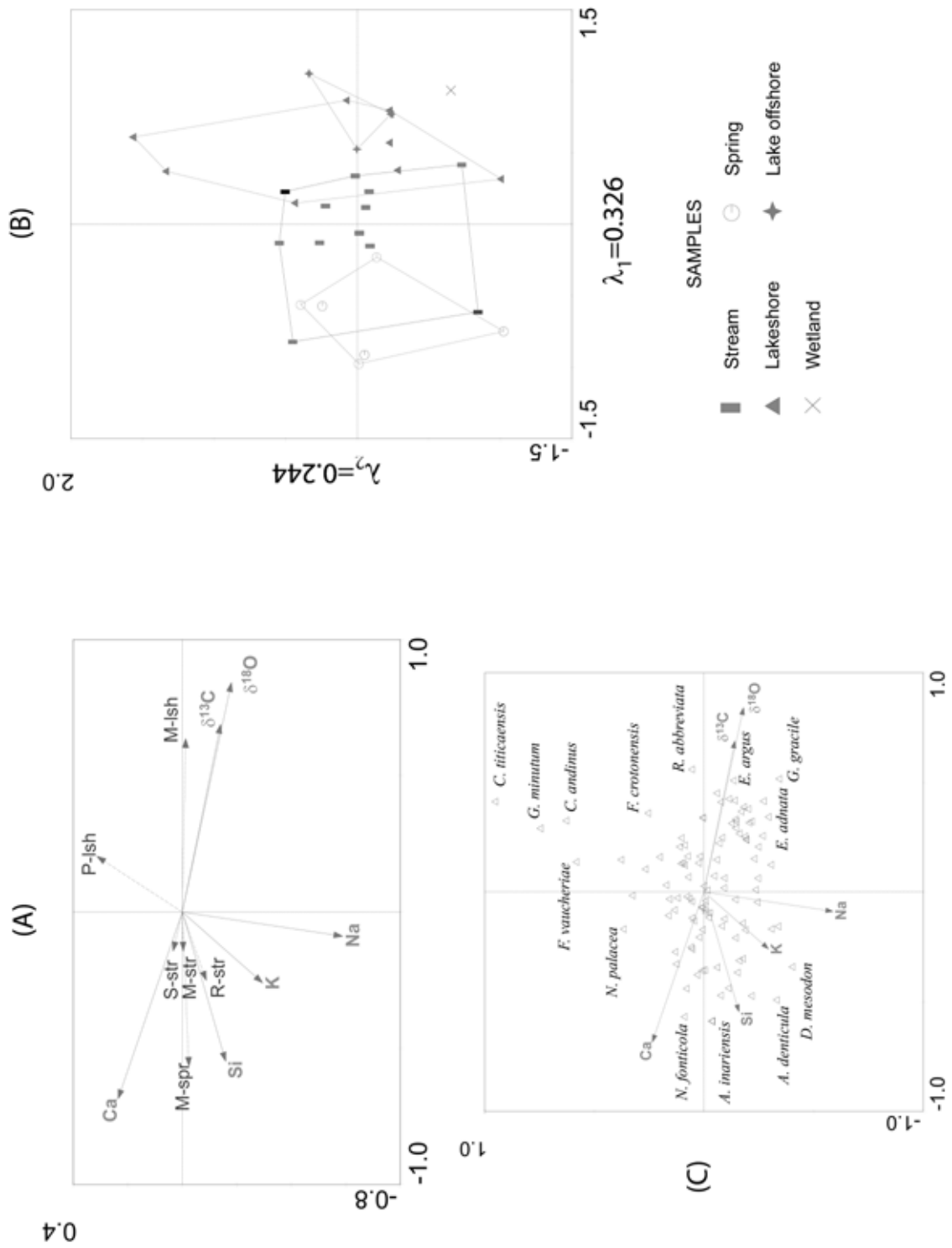


Figure 10.- (A) = CCA biplot of active and passive environmental variables in the Junin Plain area, Peru. (B) = CCA sample site score plot, sites are grouped by their main environmental setting. (C) = CCA species-environmental variable biplot showing only selected (end members) diatoms.

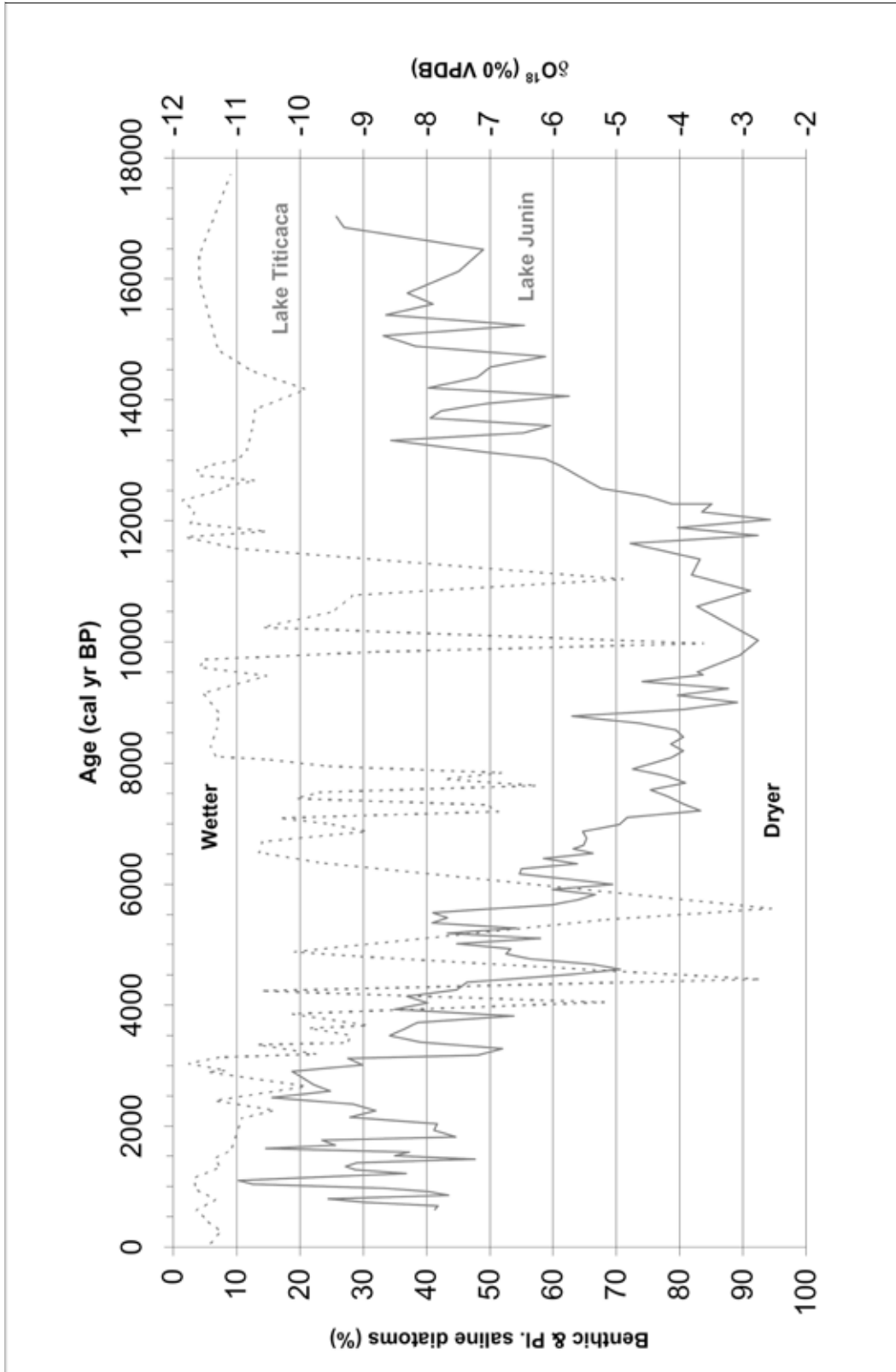


Figure 11.- Climatic records from lakes Titicaca and Junin, tropical Andes. Diatoms are expressed as the percentage of both benthics and saline planktonics from cores NE98-IPC and NE98-Bx4B (Baker et al., 2001a; Tapia et al., 2003). $\delta^{18}O$ curve from Seltzer et al. (2000).

16,000-13,000 and during the past 3,000 yr. In the transitional periods, the curves are dissimilar, which points towards a complex response of the lakes to climate, perhaps influenced by lake morphology and local hydrology, or alternatively spatial gradients in regional climate.

The stable diatom assemblage through most of the Holocene in Lake Junin (Fig. 8) is not entirely consistent with stable isotope studies ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) from marl and ostracode caparaces from the same core, which indicate a gradual depletion of $\delta^{18}\text{O}$ values from the early to late Holocene suggesting a directional and gradual increase in precipitation over time (Seltzer et al., 2000; Metivier, 2000). During the late-Holocene, most other sites from the tropical Andes register increased precipitation, yet we do not observe major changes in the Lake Junin diatom composition until the last century. So, why do diatoms show no changes in assemblage composition during the Holocene? Assuming a continuous supply of groundwater to the basin, it may be that the benthic diatoms reflect the geochemistry of groundwater inputs, whereas authigenic-calcite stable-isotope ratios are more strongly influenced by precipitation balance. This isotopic behavior is evident in modern CCA of environmental variables and site distributions, which shows isotopic depletion in lake and stream sites (rain and runoff influenced), whereas heavier isotopic values are found in spring waters (groundwater influenced) (Fig. 10a,b). Contrary, recent studies show that Lake Junin waters are 6‰ enriched via evaporation with respect to input waters (Flusche et al., 2005). Thus, with a long-term steady groundwater supply, perhaps lake salinity and alkalinity may not change sufficiently to affect diatom composition, despite precipitation and evaporation variations over time. It may also be that the shallow lake morphology or the relatively marginal coring location did not experience sufficient changes in depth during the Holocene to affect diatom species composition. Therefore, it is evident that diatoms are not responding sensitively to climate changes in Lake Junin, in contrast to other central Andes records that show significant climate change during the Holocene. Additional insight may be provided by testing both diatoms and stable isotopes in another nearby lake basin to evaluate the differences between two proxies in the pattern of change throughout the Holocene.

In any case, the $\delta^{18}\text{O}_{\text{calcite}}$ record in Lake Junin suggests that the mid-Holocene was less humid than the late-Holocene and that the Holocene increase in regional effective moisture began earlier in Lake

Junin than in the Titicaca basin (Fig. 11, see also Abbott et al., 2003).

This time-transgressive southerly increase in effective moisture can be explained by long-term variation of the ITCZ summer position across South America. Today the warming of the continent during the austral summer displaces the ITCZ to the south (Martin et al., 1997), which brings precipitation to the Peruvian central Andes and Altiplano. As summer solar insolation increased from the mid- to late-Holocene, the ITCZ may have been gradually displaced to a more southerly location, gradually spanning the spatial gradient from lower (Lake Junin 11°S) to higher (Lake Titicaca 16°S) latitude locations. This north-south time transgressive change in effective moisture conditions is also been reported in several Bolivian lakes (Abbott et al., 2003).

Appendix: Local Diatom Zones

Zone JU-1 (~46,000 to ~30,000 cal yr BP). This zone is defined as the stratigraphic interval of the maximum abundance of *Staurosira* cf. *S. construens* var. *venter*. The lower boundary is at 18.79-m and the upper boundary at 14.5-m in core JU96-A; this lower lithologic unit is composed of silt with plant remains and gastropod shells. Sub-dominant diatoms are *Cocconeis placentula* and *Gomphonema pumilum*. Accompanying taxa are *Navicula radiosa*, *Pseudostaurosira brevisstrata*, *Staurosira construens* var. *construens*, *Staurosira construens* var. *subsalina*, and *Staurosirella pinnata*.

Zone JU-2 (~17,500 to ~16,000 cal yr BP). Defined as the stratigraphic interval of the maximum abundance of *Cyclotella stelligera*. The lower boundary is located at core Ju96-A level 10.2-m and the upper boundary at 9.7-m, in the upper zone of the organic-rich silt unit. The upper limit coincides with the sharp division between the organic-rich silt and marl lithologic units. Accompanying diatoms are *Cyclotella meneghiniana*, *Denticula elegans*, and *Cocconeis placentula*, which are present in low abundances.

Zone JU-3 (13,000 to ~500 cal yr BP). Defined as the stratigraphic interval of the maximum abundance of *Denticula elegans*. The lower boundary of the JU-3 zone is located at 8.9 m and the upper boundary is the top of the core Ju96-A at the marl unit (0.37-m). Accompanying diatoms in this zone are *Encyonema gracilis*, *Epithemia argus*, *Navicula cryptonella*, *Nitzschia denticula*, and *Gomphonema pumilum*.

ACKNOWLEDGEMENTS

We would like to acknowledge the INRENA (Instituto Nacional de Recursos Naturales) for allowing us to work in the Reserva Nacional de Junin. Carlos Yuri Veliz assisted with fieldwork. Alan J. Martin (Lorax Environmental Services) provided meteorological data from the Lake Junin

area. Nutrient analyses were performed in the Water Sciences Laboratory at the University of Nebraska-Lincoln. The National Science Foundation provided research funds to SCF, GOS, and DTR. This contribution is in partial fulfillment of requirements of PMT for a doctoral degree at the University of Nebraska-Lincoln. Comments and suggestion by María del Carmen Morales is greatly appreciated.

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