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Patterns of regional hydrological variability in central-southern Altiplano (18°–26°S) lakes during the last 500 years

Blas L. Valero-Garcés[a,*], Antonio Delgado-Huertas[b], Ana Navas[c], Larry Edwards[d], Antje Schwalb[e], Norma Ratto[f]

[a] *Pyrenean Institute of Ecology – CSIC, Apdo 202, 50080 Zaragoza, Spain*
[b] *Estación Experimental de El Zaidín – CSIC, Prof. Albareda 1, Granada, Spain*
[c] *Estación Experimental de Aula Dei – CSIC, Apdo 202, 50080 Zaragoza, Spain*
[d] *Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455, USA*
[e] *Institut für Umwelt-Geochemie, Universität Heidelberg, INF 236, 69120 Heidelberg, Germany*
[f] *Universidad de Buenos Aires, 25 de Mayo 217, 1002 Buenos Aires, Argentina*

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Abstract

Paleohydrological reconstructions based on sedimentological, geochemical, and isotopic records from a lake transect in the central-southern Altiplano (18°–26°S) indicate abrupt moisture fluctuations during the last 500 years. A change to modern conditions occurred in the late 19th century in all the records, from northern Chile (Lago Chungará, 18°15′S) and the Atacama (Laguna Miscanti, 23°45′S) to the southern tip of the Altiplano (Laguna El Peinado, NW Argentina, 26°30′S). A previous drier period shows different patterns of timing, duration, and intensity. In Chungará, the arid period was shorter and occurred during the late 19th and early 20th centuries, while in Miscanti, it occurred earlier and ended at the beginning of the 20th century. In El Peinado, conditions were wetter during the 17–19th centuries and the arid period occurred prior to the 17th century. Other records from the region show abrupt paleohydrological and paleoclimatic changes synchronous with the termination of the Little Ice Age. Despite local differences and dating uncertainties, the Little Ice Age stands out as a significant though complex climatic event in the Andean Altiplano. The discrepancies between the northern and southern Altiplano records during the last few centuries may reflect contrasting responses to external forcing in two areas with different climatic regimes.

1. Introduction

Understanding the interannual to decadal climate variations in South America requires detailed analyses of the instrumental record and high-resolution archives for the last few centuries. However, neither set of archives is available for large regions in the Andean Altiplano. Historical archives (Prieto et al., 1998, 1999), dendrochronological reconstructions (Villalba, 1994; Villalba et al., 2001), and glacial advances in the Central Andes (Villalba, 1990; Villalba et al., 1998; Luckman and Villalba, 2001) have documented envi-

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[*] Corresponding author. Tel.: +34-976-716030; Fax: +34-976-716019.
E-mail address: blas@ipe.csic.es (B.L. Valero-Garcés).

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ronmental changes in southern South America during the last few centuries with potentially large implications for water availability. Although the timing and regional variability remains a matter of debate, the presence of strong isotopic, dust-content, and snow-accumulation signals during the Little Ice Age (LIA; about AD 1500–1900) in the ice cores from the tropical Andes (Huascarán, Quelccaya and Sajama) (Thompson et al., 1986, 1998) indicates that events of centennial scale have had a large impact on the Altiplano climate.

The Andean Altiplano lakes contain centennial- to millennial-scale records of effective moisture fluctuations during the late glacial and the Holocene (Valero-Garcés et al., 2000a). Some lake sequences may also provide higher-resolution records (decadal- to centennial-scale) for several time windows of environmental and climatic change. Here we present the paleohydrological evolution of three high-altitude (ca. 4000 m asl (above sea level)) Altiplano lakes located in a transect including northern Chile (Lago Chungará, 18°S), the Atacama Altiplano (Laguna Miscanti, 23°S) and the northwestern Argentinean Puna (Laguna El Peinado, 26°S). Sedimentological, geochemical, and isotopic analyses from sediment cores allow qualitative reconstructions of past lake-level changes. Due to the known large radiocarbon reservoir effects in the Altiplano lakes, the chronologies for the last few centuries are based on ^{210}Pb and U/Th techniques. Our results show large but extremely variable fluctuations in the water budget of the Altiplano lakes during the last few centuries. The discrepancies in paleohydrological behavior are discussed in the context of regional climatic variability of the Altiplano.

2. The lakes

2.1. Lago Chungará

Lago Chungará (18°15′S, 69°10′W, 4520 m asl) is located at the northeastern edge of the Lauca Basin (Fig. 1). It lies in a tectonic basin, with a maximum water depth of 40 m, a surface area of 21.5 km^2, and a volume of about 385×10^6 m^3 (Valero-Garcés et al., 2000a). The main inflow is the Chungará River (300–500 l s^{-1}). There is no surface outlet, and annual groundwater outflow has been estimated as about 6×10^6 m^3 yr^{-1}. The lake is polymictic, oligotrophic, contains 1.2 g l^{-1} total dissolved salts, and the water chemistry is of Na–Mg–HCO$_3$–SO$_4$ type and alkaline (pH = 9) (see references in Valero-Garcés et al., 2000a). Two seismic units overlie the massive volcanic bedrock in the smaller, shallower eastern sub-basin and also in the main, deeper, NW–SE trending basin. An older seismic unit, with less well-defined reflections, is found in the northwestern basin and it is interpreted as an earlier stage of basin infill with more alluvial influence. Sedimentary sequences identified in a 2.6 m long core from the eastern sub-basin show alternation of lake sub-environments (Characeae-lacustrine shelf, macrophyte-dominated littoral, and peat bog) that reflect century- to millennial-scale oscillations in lake level during the mid- and Late Holocene (Valero-Garcés et al., 2000a). Modern sediments in the deeper areas are composed of black, organic-rich, massive to faintly laminated mud.

2.2. Laguna Miscanti

Laguna Miscanti (23°45′S, 67°45′W, 4140 m asl) is one of the largest (13.5 km^2 surface) and deepest (up to 10 m) lakes in the Atacama Altiplano (Fig. 1). Laguna Miscanti is the least saline lake in the Atacama Altiplano (5 g l^{-1} total dissolved salts, 6400 µS cm^{-1} electric conductivity) with a Na–(K–Ca–Mg)–SO$_4$–Cl brine and alkaline conditions (pH = 8.0–8.8) (Valero-Garcés et al., 1996, 1999b; Grosjean et al., 2001). The lake sits in an endorheic basin and the water budget is mainly controlled by groundwater inflow from the large catchment area in the Cordón Puntas Negras (320 km^2) and by evaporation. The contribution of some springs is very small, and the seepage downstream to Laguna Miñiques is limited. Modern sediments are variegated, banded, charophyte-rich calcitic diatomaceous mud. A seismic survey and a 2.92 m long sediment core (Valero-Garcés et al., 1996) provided the first evidence for large paleohydrological

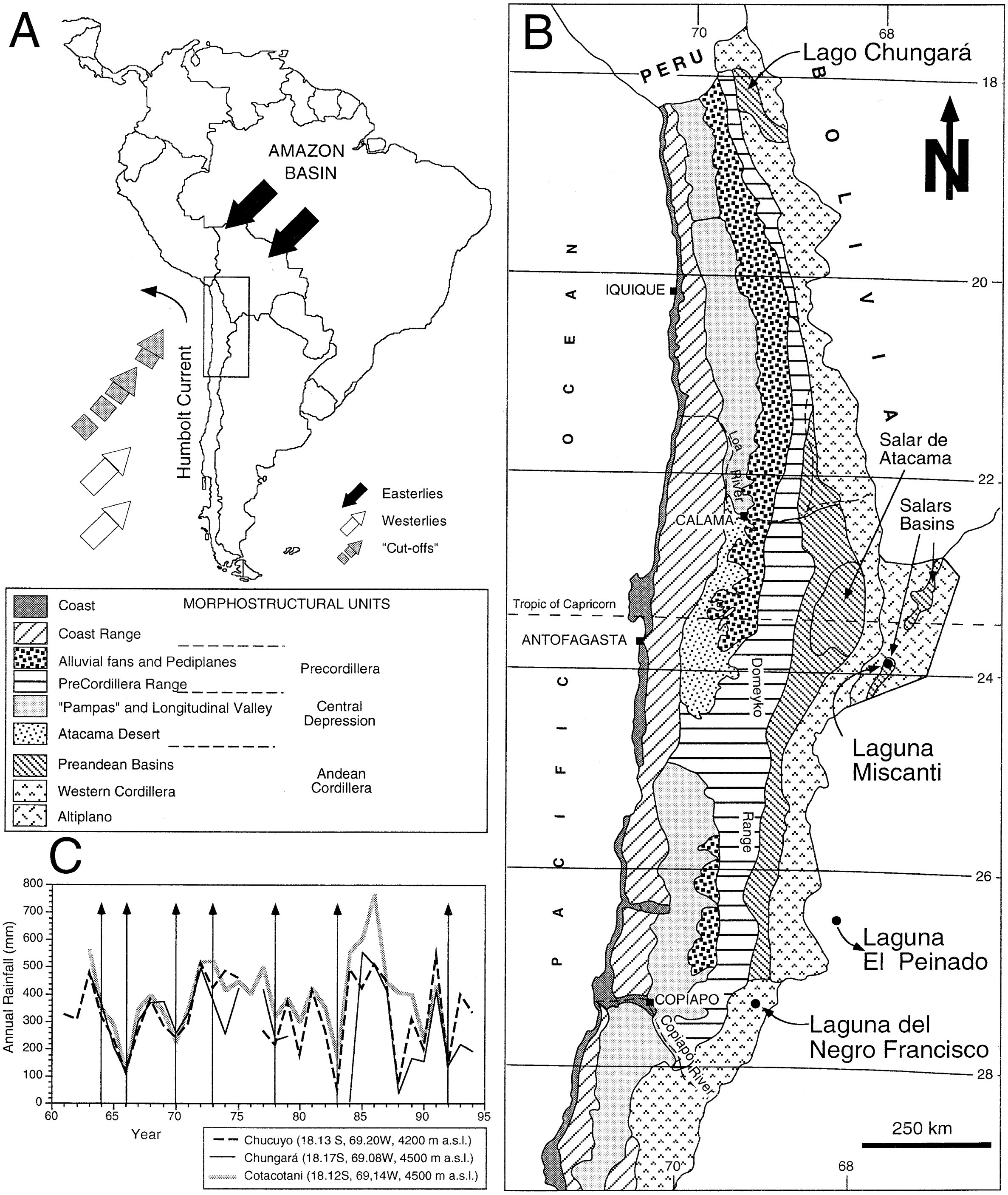

Fig. 1. (A) The location of the southern and central Altiplano region and the major air masses and oceanic currents affecting the area. (B) Location of the three lakes (Chungará, Miscanti and El Peinado) in the Andean Altiplano. (C) Annual rainfall in the Chungará region. The arrows indicate strong El Niño years.

changes during the Late Holocene. A 7.95 m long core provided a continuous lake record spanning the last 22 000 ^{14}C yr (Grosjean et al., 2001).

2.3. Laguna El Peinado

El Peinado Lake (26°30′S, 68°05′W, 3820 m asl) lies on a north–south elongated, topographically closed basin, north of El Peinado volcano and at the southern end of the Salar de Antofalla in Catamarca province (Argentina) (Fig. 1) (Valero-Garcés et al., 1999a, 2000a). The lake's main axes are about 2.5×1.5 km and the maximum depth is unknown. Waters are saline (electric conductivity 55 500 μS/cm) and alkaline (pH = 7.6), and of Ca–Na–SO_4–Cl–CO_3 type. The lake basin is endorheic and several thermal springs feed the lake. A 2 m long core retrieved in the littoral zone (water depth 2 m) is composed of laminated, carbonate tufa- and charophyte-rich calcitic diatomaceous muds, tufa facies (in situ and reworked), and calcitic crusts.

3. Climate setting

Our sites in the Altiplano are located on a transect from the north (Chungará) dominated by tropical summer moisture to the south (El Peinado) mostly affected by winter precipitation. Isotopic composition of rainfall (Aravena et al., 1999) and the synoptic situation of precipitation events in the Chilean Altiplano (Ruttlant and Fuenzalida, 1991) indicate that for both summer and winter precipitation, the moisture source is the Amazon Basin. During the summer months (DJFM), weak easterly flow prevails over the Altiplano, as a consequence of the southward migration of the subtropical jet stream and the establishment of the Bolivian high. This narrow time window defines the wet season in the Altiplano. Average annual rainfall in the Chungará region is about 350 mm yr^{-1}, but the actual range is variable (100–750 mm yr^{-1}) (Fig. 1). Potential evaporation has been estimated at over 4750 mm yr^{-1} (Valero-Garcés et al., 2000a).

Further south, the Atacama Altiplano is located in an extremely dry region. This is the transitional zone from tropical summer precipitation with Amazonian moisture sources (Chungará) to extratropical winter rainfall with Pacific and southern Atlantic moisture sources (Messerli et al., 1993). The driest portion of this desert lies in northern Chile and crosses the Andes diagonally south of the Tropic of Capricorn where the winter cyclonic precipitation connected with *Invierno Chileno* is blocked, and the tropical convective summer precipitation of the *Invierno Boliviano* is restricted to the eastern slope of the Andes and the high altitudes. In the Miscanti region, annual rainfall is about 200–250 mm, mainly during the austral summer (50–90%, '*Invierno Boliviano*') with tropical continental moisture sources from the east side of the Andes. Potential evaporation is about 2000 mm yr^{-1} (Grosjean, 1994).

The climate in the southern Altiplano (El Peinado region) is mostly influenced by the subtropical high-pressure systems of the southeastern Pacific and the southwestern Atlantic (Kull and Grosjean, 1998). Grosjean et al. (1997) estimated precipitation in Laguna del Negro Francisco (27°28′S, 4125 m asl, 250 km to the west) to be around 250 mm yr^{-1}, mostly during the winter months, and potential evaporation as higher than 1500 mm yr^{-1}. Winter snowfall is the dominant source of moisture (Vuille and Ammann, 1996). They distinguished two synoptic mechanisms for winter precipitation: cold fronts from the Pacific, often associated with blocking episodes in the South Pacific, and isolated cells of cold polar air that migrate far north and collide with tropical moist air masses. Convective activity over the Altiplano produces precipitation in the high elevation areas during the summer, but the contribution of this summer precipitation is unknown due to the absence of weather stations at high altitude.

At the present, three phenomena dominate climate variations on interannual to decadal timescales in the Altiplano region: The ENSO phenomenon on interannual (3–6 yr) and ENSO-like variations over the Pacific basin (Pacific Decadal Oscillation, PDO) and North Atlantic (North Atlantic Oscillation, NAO) on decadal timescales (10–50 yr) (Dettinger et al., 2001). In the Central Andes, there is a weak tendency for wet conditions during the cold ENSO phase and dry conditions during the warm phase (El Niño years). The weakness of the ENSO–Altiplano rainfall relationship could be partially explained by the high spatial precipitation variability (Vuille et al., 2000). El Niño years seem to be marked in the Sajama and Quelccaya ice-core records by significant decreases in snow accumulation (Thompson et al., 1986; Vuille et al., 1998; Vuille, 1999). This is consistent with data from the Chungará region, where precipitation is reduced during moderate to intense El Niño years (1965, 1972, 1983, 1992) (Fig. 1). However, there is no direct relationship between the relative El Niño strength and the amount of rainfall reduction. Long records from high-altitude weather stations are not available for Miscanti and El Peinado. At a global scale, equatorward shifts in westerly winds and storm tracks in both hemispheres produced by the PDO yield wetter subtropics (El Niño-like phases) and drier mid-latitudes and tropics. Warming south of the equator in the eastern Pacific extending poleward to the Chilean coast is associated with the positive phase of the PDO, showing a similar, but weaker pattern than the ENSO (Dettinger et al., 2001).

4. Methods

The sediment cores from Lago Chungará and Laguna Miscanti were collected in November 1993 at 19 m and 9 m water depth, respectively, and sampled in the field at 1 cm intervals. El Peinado sediment cores were retrieved from the littoral zone (depth = 2 m) in November 1996. Detailed sedimentological, geochemical and isotopic analyses for El Peinado have already been published elsewhere (Valero-Garcés et al., 1999a, 2000a). The sediment composition and mineralogy of the Miscanti cores were described by Valero-Garcés et al. (1996), and the results are summarized here. The stable isotope record for ostracods and bulk carbonates from Laguna Miscanti was published by Schwalb et al. (1999). In the Chungará core, organic matter and carbonate contents were measured by weight loss-on-ignition, and mineralogy was determined using X-ray diffraction and petrographic microscopy. Bulk sediment samples (0.5 g) from Chungará were digested with a heated mixture of HCl and HNO_3 acids (3:1 ratio), filtered, and analyzed for main element composition by spectrometry of atomic emission using an inductively coupled plasma (Perkin Elmer Optima 3200 DV). A sequential extraction procedure was used to differentiate five fractions: exchangeable metals, metals bound to carbonates, metals bound to Fe–Mn oxides, metals bound to sulfides and to organic matter, and the residual. Oxygen and carbon isotope analyses were performed on bulk sediment from Chungará and Miscanti. Calcite was the only carbonate in the two cores. The $\delta^{13}C$ values of organic matter were also measured in Chungará samples. Analytical precision was better than 0.1‰. Qualitative lake-level histories were reconstructed based on sedimentary facies analyses, combined with geochemical and isotopic data. Sedimentary facies indicative of subaerial exposure conditions were present in El Peinado. Sediments with calcite laminae and presence of gypsum suggested increased salinity and likely lower lake levels at some intervals in the Chungará core. The presence of gypsum marked lower lake levels in the Miscanti sediment sequence. Geochemical and isotopic trends are also interpreted with caution as a reflection of salinity and water-balance fluctuations. The chronology of the cores is constrained by ^{210}Pb analyses performed at the St. Croix Watershed Research Station (Minnesota, USA). Pure calcite samples from El Peinado core were selected for U/Th dating and analyzed at the Minnesota Isotope Lab (University of Minnesota, USA) (Valero-Garcés et al., 2000a).

5. Results

5.1. Chronology

Accurate ^{14}C dating of lacustrine sediments from the Altiplano has been complicated by the scarcity of terrestrial organic macrorests, and the large radiocarbon reservoir effects detected in the lake waters (Grosjean et al., 1995, 2001; Geyh et al., 1998, Valero-Garcés et al., 2000a,b). In Chun-

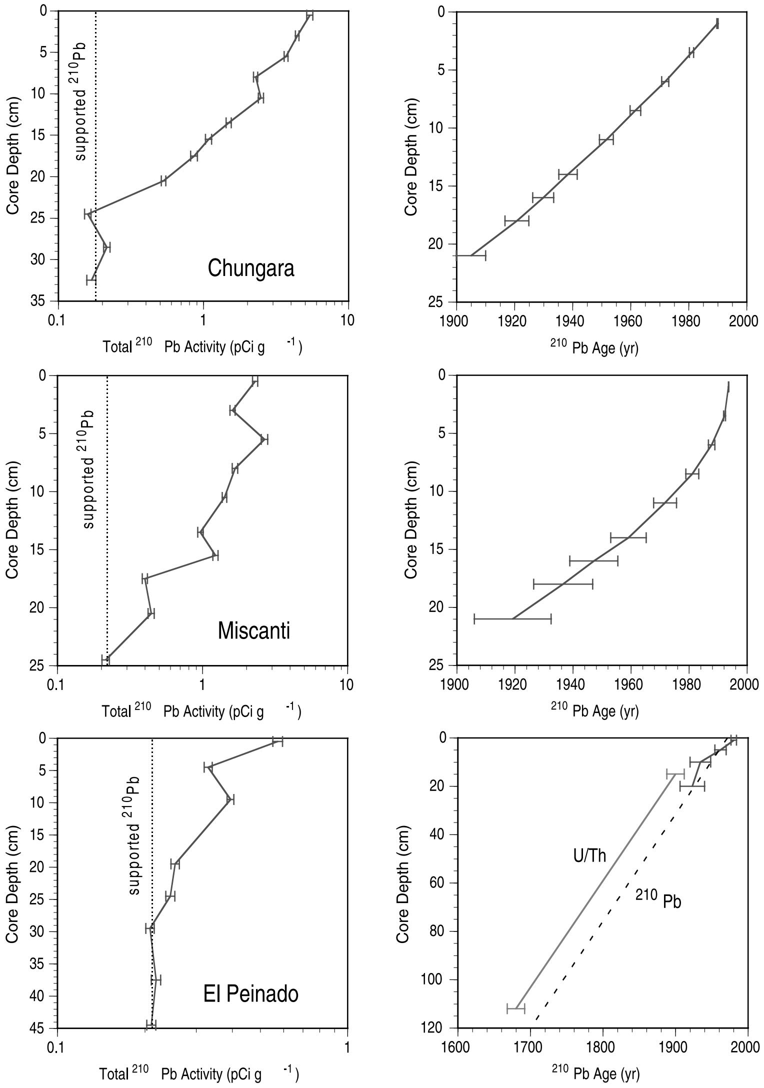

Fig. 2. Total ^{210}Pb activity profiles and depth–age relationships for the three lakes. Two U/Th dates are also available for El Peinado Lake.

gará and Miscanti, the reservoir effects are also strongly dependent on water depth and lake level changes (Geyh et al., 1998). The reservoir effect for modern sediments in Chungará is about 3000–4000 yr (Valero-Garcés et al., 2000a). In Miscanti reservoir corrections for the littoral fractions (*Ruppia* seeds) are between 2200 and 2500 yr, and for benthic fractions (Characeae) ca. 4000 yr (Grosjean et al., 2001). El Peinado shows even larger reservoir effects ($>12\,000$ yr) due to the influx of large quantities of ^{14}C-free CO$_2$ introduced from thermal and volcanic CO$_2$ (Valero-Garcés et al., 1999a). Therefore, it is not possible to construct a robust, accurate ^{14}C-based chronology in these Altiplano lakes. Thus, our chronology for the three cores is based on ^{210}Pb dating with some U/Th dates where suitable samples were found (El Peinado). The ^{210}Pb content in the cores declines to variable depths below which supported (background) values are reached (Fig. 2), but a significant problem in establishing a detailed chronology stems from the very low ^{210}Pb activities at the top of the cores. Total ^{210}Pb activity for top sediments decreases from north to south: 5.41 pCi g^{-1} in Chungará, 2.30 in Miscanti, and 0.57 in El Peinado. The values of supported ^{210}Pb activity are very low: 0.18 pCi^{-1} in Chungará, 0.21 in Miscanti and El Peinado. The calculated fluxes of unsupported ^{210}Pb to these core sites are extremely low (from 0.20 pCi cm^{-2} yr^{-1} in Chungará to 0.08 pCi cm^{-2} yr^{-1} in Miscanti and El Peinado) and this likely a reflects low atmospheric concentrations of ^{210}Pb in the southern hemisphere and low rainfall on the Altiplano resulting in a very low atmospheric ^{210}Pb flux. Taking all of this into consideration, we favor the cf:cs (constant flux:constant sedimentation) model because it provides more robust estimates of the sedimentation rates and the chronological framework. Given the uncertainties in the data, this conservative approach is more appropriate, because we are not interpreting each inflection in the ^{210}Pb profile; instead, we fit a regression line through the data to obtain an average sedimentation rate. On the other hand, the different sedimentary facies present in Miscanti and El Peinado have different accumulation rates, and the ^{210}Pb chronology lacks the adequate resolution to detect such changes.

If we assume a stable background activity of 0.21 pCi g^{-1} in Miscanti, the calculated mean sediment accumulation rate is 0.036 ± 0.006 g cm^{-2} yr^{-1} (2.8 mm yr^{-1}). This average sedimentation rate is valid for unit 1D. Sedimentation rates in previous units are likely to be different because of the change in sedimentary facies. If we assume a stable background activity of 0.21 pCi g^{-1} in El Peinado, the calculated mean sediment accumulation rate is 0.25 ± 0.06 g cm^{-2} yr^{-1} (4.2 mm yr^{-1}). The U/Th dates are coherent with the ^{210}Pb chronology and give a mean sedimentation rate of 4.3 mm yr^{-1} for the whole sequence. In Chungará, with a stable background activity of 0.18 pCi g^{-1}, the average sedimentation rate is 0.033 g cm^{-2} yr^{-1}(2.4 mm yr^{-1}). Although this average sedimentation rate is only valid for the upper three units defined in the Chungará core, we use this value to estimate, with caution, some older ages because of the presence of similar sedimentary facies in the older units.

5.2. Lago Chungará

5.2.1. Sedimentology, geochemistry and stable isotopes

A short core (55 cm long) retrieved at 19 m water depth in the western sub-basin is composed of black, organic-rich (up to 25 wt% organic matter) laminated mud with relatively low carbonate content (6–8 wt% $CaCO_3$). Quartz and plagioclase grains, clay minerals and volcanic rock fragments comprise most of the silicate fraction. Diatoms and ostracods are also present. Fragments of calcified charophytes are common and they likely provide most of the fine-grained calcite in the sediments. However, small (up to 100 μm) euhedral calcite crystals are also present. Most of the organic matter is composed of macrophyte fragments at several stages of decomposition. Seven sedimentary units have been distinguished based on sediment composition (Fig. 3A). Units 1, 3, 5 and 7 show low carbonate and relatively high (20%) organic matter content. Discrete mm-thick white laminae occur at two intervals (unit 2: 11–14 cm and unit 4: 20–26 cm), and are mainly composed of calcite (up to 50%), and contain euhedral calcite crystals up to 100 μm long. Reworked gypsum crystals also occur at these levels.

Sequential chemical analyses of samples taken at five intervals (0–10, 14–24, 24–34, 34–46 and 46–56.5 cm) show large compositional differences (Fig. 4A). The high Ca and Sr values between 14 and 24 cm correlate with the higher calcite content of units 2, 3 and 4. The main sources for aluminum, potassium, manganese, and iron are minerals from the silicate (clay) oxide fraction, thus their content may serve as a proxy for detrital input into the lake. All those elements show decreasing values from the base to the top; Al and Fe show the lowest values in the carbonate-rich interval (units 2–4). In addition, manganese and, to a lesser extent, iron appear to be closely associated with organic matter, probably as organic complexes. Both show higher values in the lower units. Phosphorus is also closely associated with organic matter, oxides and silicates, and peak values in the lower units. Sodium is clearly related to the carbonate–oxide fraction, although the mineral source has not been identified. In the

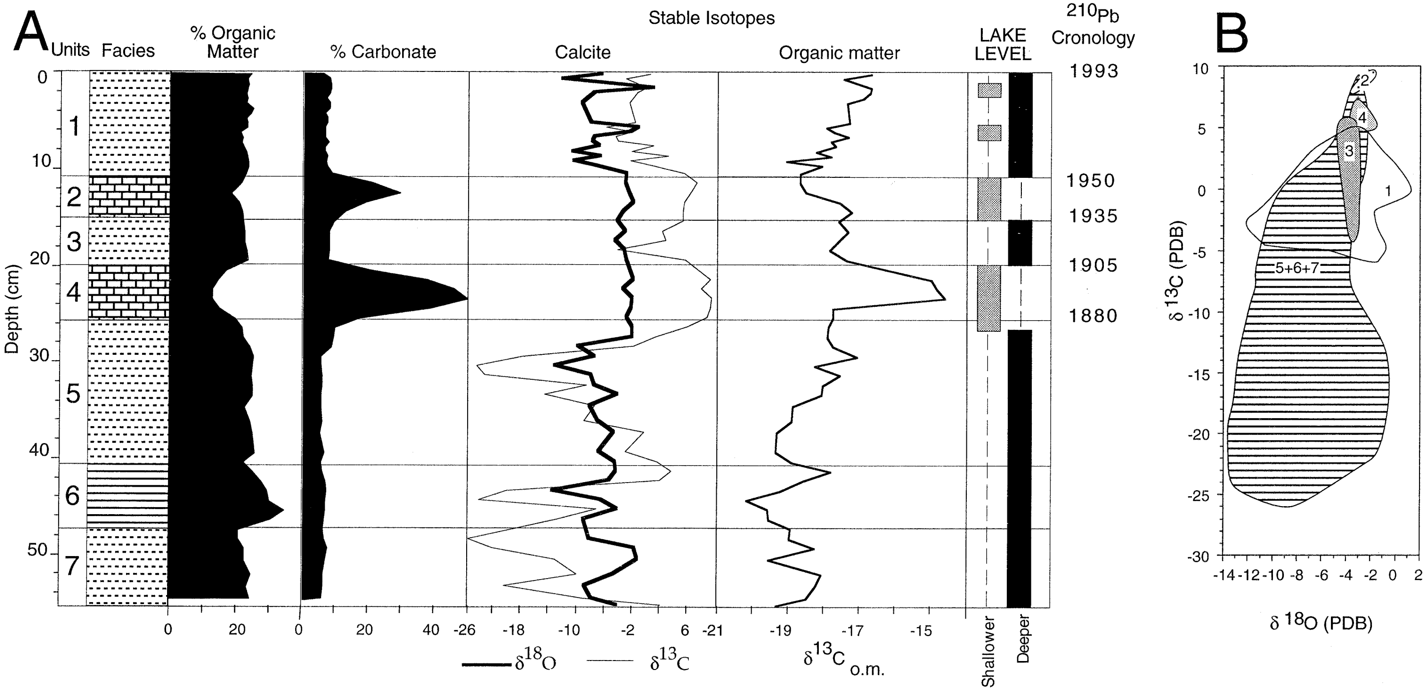

Fig. 3. The Lago Chungará record. (A) Facies, sediment composition, stable isotopes, qualitative reconstruction of lake-level changes and ^{210}Pb chronology of the main events. (B) Oxygen and carbon isotopes of authigenic calcite compositions plotted by sedimentary units.

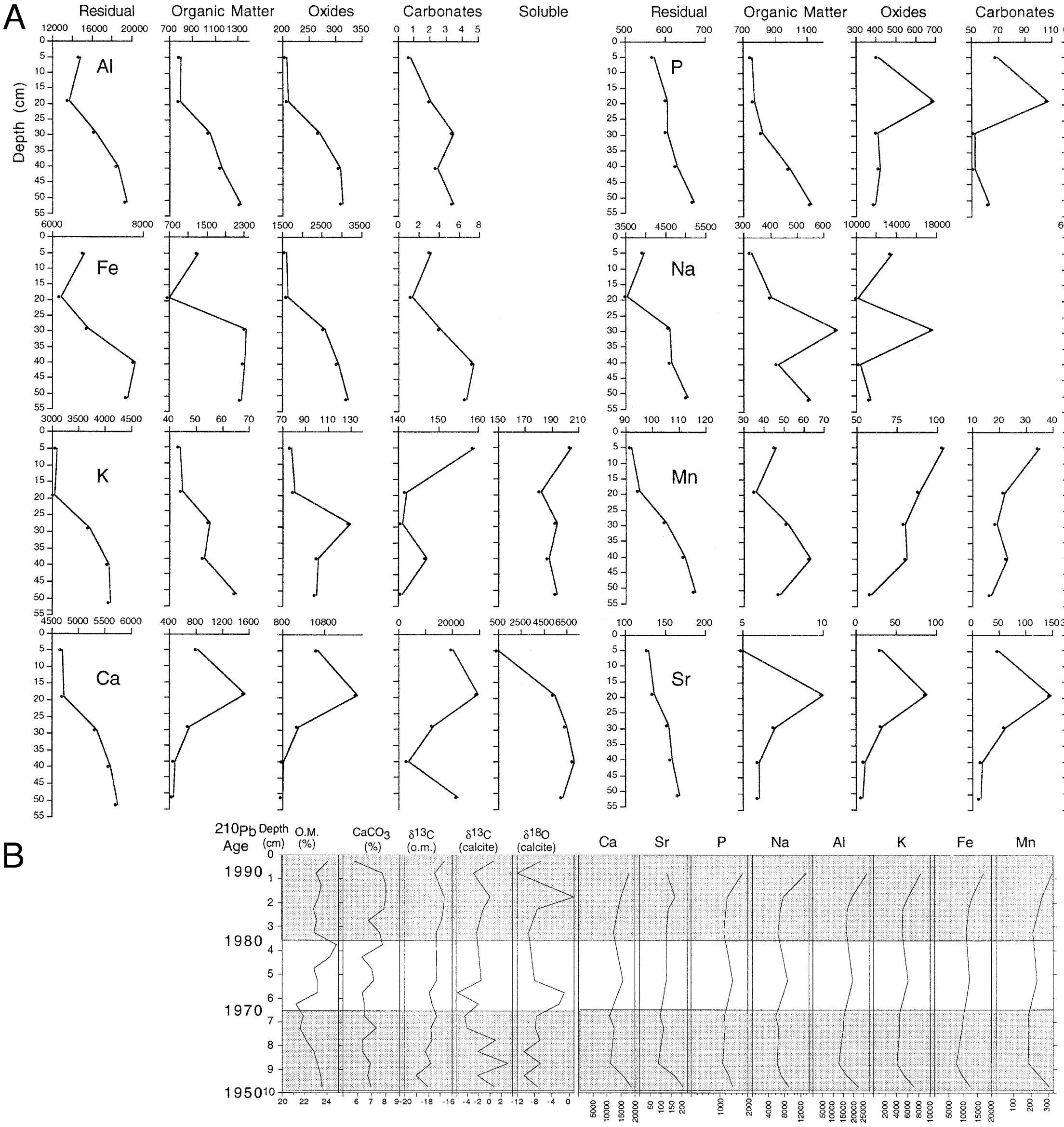

Fig. 4. The Lago Chungará record. (A) Sequential geochemistry of selected elements. (B) Chemical and isotope composition of the upper 10 cm.

soluble fraction there is an increase in Na content in the upper units, particularly in the carbonate-rich units, suggesting more chemically concentrated waters. The homogeneous mud from the upper 10 cm contains 7–8% carbonate and 21–25% organic matter contents and was sampled at less than 1 cm intervals (Fig. 4B). Most elements show higher values at the base (10–9 cm), relatively lower and increasing values upwards, and higher values within the top 3 cm.

The $\delta^{18}O_{calcite}$ curve shows a large range (+0.97 to −13.06‰) and it can be correlated with sedimentary units (Fig. 3A). Particularly, units 2, 3 and 4 show the highest $\delta^{18}O_{calcite}$ values in the core and lowest variability (−4.18 to −1.83‰). The onset of unit 1 is characterized by a large negative shift of 8‰; this upper unit is characterized by low values with large positive excursions up to +0.97‰. The $\delta^{13}C_{calcite}$ curve shows very low and fluctuating values in the lower units 7 and 6, a very large range and an upcore-decreasing trend in unit 5, and the highest values in units 2, 3 and 4, with a sharp negative excursion within unit 3. Decreasing values in the lower part and more constant values in the upper part characterize unit 1. The highest $\delta^{13}C_{organic\ matter}$ values occur in unit 4 – correlating with the highest $\delta^{13}C_{calcite}$ and $\delta^{18}O_{calcite}$ – followed by intermediate values in unit 3 and decreasing values in unit 2. The upper calcite-rich unit 2 shows a different pattern than the lower calcite-rich unit 4: decreasing $\delta^{13}C_{organic\ matter}$ and high $\delta^{13}C_{calcite}$. Finally, increasing $\delta^{13}C_{organic\ matter}$ values in unit 1 correspond with decreasing $\delta^{13}C_{calcite}$.

5.2.2. Paleohydrological interpretation

The sedimentological, chemical and stable isotope composition of the sediments indicates large changes in the water balance of the lake, particularly during the deposition of units 2, 3 and 4. Increased precipitation of authigenic calcite suggests either a period of higher salinity or higher biological productivity conducive to carbonate formation, or both. Higher sodium content in the soluble fraction of the sediments indicates higher salinities during these periods. On the other hand, the abundance of Chara remains points to more developed charophyte meadows and more extensive littoral sub-environments in the lake. The upcore increase in Mn associated with oxides and carbonates could be a reflection of more efficient precipitation of oxides as a consequence of less frequent seasonal anoxic periods in the lake (Dean, 1993). Several mechanisms may contribute to ^{18}O enrichment during deposition of units 2, 3 and 4, mainly changes affecting the water balance in the lake (inputs and outputs) and in the moisture (sources, seasonality). The oxygen isotopic compositions of the waters in high-altitude saline lakes in the Altiplano are mainly controlled by the composition of the input waters (rainfall and groundwater) and by large evaporation effects. Complex interactions between numerous processes control the isotopic composition of precipitation in the Altiplano (Rozanski and Araguas-Araguas, 1995; Aravena et al., 1999). The $\delta^{18}O$ values from Sajama ice cores become more depleted as annual precipitation increases (Hardy et al., 1998). On the Altiplano, the maximum of precipitation during the austral summer (November–March) is characterized by depleted $\delta^{18}O$ values that can reach −20‰ (Fritz et al., 1981; Aravena et al., 1999). The contribution of groundwaters and thermal springs may also be significant, but has not been quantified.

Although evaporation is the main mechanism responsible for ^{18}O enrichment of the lake waters in most saline lakes in the Altiplano, the $\delta^{18}O_{carbonate}$ record cannot be interpreted exclusively as an evaporation or salinity indicator (Kelts and Talbot, 1990; Talbot, 1990; Valero-Garcés et al., 2000a). In the absence of major changes in water sources, increasing $\delta^{18}O$ values are interpreted as decreases in the precipitation–evaporation balance, a warmer mean air temperature, colder lake-water temperatures, or a combination of all the above (Talbot, 1990). Large negative $\delta^{18}O$ shifts in unit 6 (ca. 44 cm), at the top of unit 5 (ca. 30 cm depth), and at the base of unit 1 (Fig. 3) most likely represent an increased input of isotopically depleted waters. Both mineralogical (increased precipitation of calcite and presence of gypsum) and chemical (increased Na content) evidence support the interpretation of the isotope enrichment of units 2, 3 and 4 as a result of less positive water balance in the lake during lower lake levels. The sharp positive $\delta^{18}O_{calcite}$ excursions in unit 1 (Fig. 4B) could correspond to drier periods during the last decades, although the range is unexpectedly large.

Peaks in calcite production (units 4 and 2, Fig. 3) are associated with periods of increased biological productivity and ^{18}O-enriched waters. Changes in the $\delta^{13}C$ of authigenic carbonate and organic matter reflect variations in the dissolved inorganic carbon (DIC) pool, controlled by input and biological processes, mainly respiration and photosynthesis (Talbot and Kelts, 1990). Fluctuations in groundwater input and composition, changes in the limnological and biological parameters of the lake, and in early diagenetic processes are important to the isotopic-carbon budget of lakes (Kelts, 1988). The dissolved-carbon species in lakes come from: (i) groundwater and runoff that incorporates dissolved carbon through the dissolution of carbonates from soils and rocks, the decomposition and respiration of plants; (ii) equilibration of atmospheric CO_2 with the lake waters; (iii) oxidation of lacustrine and terrestrial organic matter in the sediments; and (iv) methane oxidation and CO_2 reduction in the sediments. Higher $\delta^{13}C_{calcite}$ values in carbonate-rich units 2 and 4 could reflect the interplay of increased lake productivity and evaporation. Increased photosynthesis results in DIC enrichments and consequently relatively ^{13}C-enriched carbonates (Aravena et al., 1992; Meyers, 1994). Longer residence time and greater evaporation also result in ^{13}C enrichment (Talbot, 1990; Talbot and Kelts, 1990). The large positive excursion in $\delta^{13}C_{organic\ matter}$ in unit 4 could represent a change in the main organic producers in the lake associated with a phase of increased productivity. General agreement between the $\delta^{13}C_{organic\ matter}$ and $\delta^{13}C_{calcite}$ trends in units 2, 3 and 4 suggests that the Lago Chungará carbon budget in these upper units could reflect fluctuations in lacustrine productivity. The negative covariance between $\delta^{13}C_{organic\ matter}$ and $\delta^{13}C_{calcite}$ values in the other units – particularly the lower part of unit 1 and unit 5 – indicates that other processes, such as changes in biota, early diagenetic conditions and fluctuations in anoxia and meromixis, could exert a major role in the carbon budget. The very negative $\delta^{13}C_{calcite}$ values of the lower units (5–7) indicate that ^{12}C-enrichment processes took place. Among them, increased plant respiration, changes in the redox conditions at the bottom of the lake with recycling of organic matter, and sulfate-reduction processes could lead to the precipitation of calcite with low $\delta^{13}C$ values (Kelts, 1988).

The absence of significant correlation between oxygen and carbon isotope values in carbonate samples suggests dominant hydrologically open conditions (Talbot, 1990; Li and Ku, 1996) (Fig. 5). However, sharp transitions of similar sign occur at the base and top of the carbonate-rich interval (units 2, 3 and 4), suggesting a more hydrologically closed behavior when both carbon and oxygen are affected by increased residence time and evaporation.

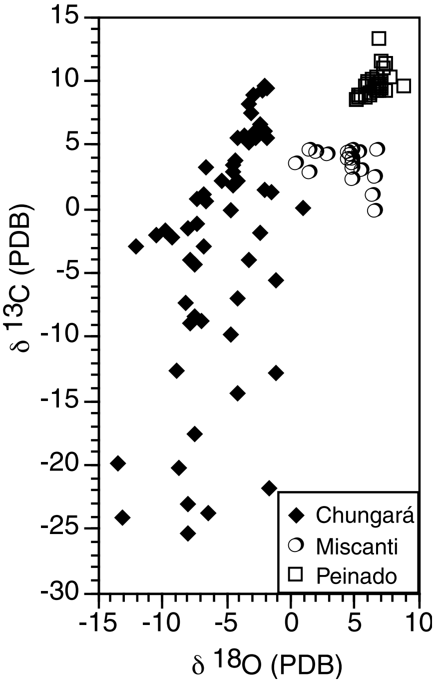

Fig. 5. Oxygen–carbon isotope cross-plot of authigenic carbonate compositions for the three lakes.

5.3. Laguna Miscanti

5.3.1. Sedimentology and stable isotopes

Sediments of unit 1 (Valero-Garcés et al. 1996; Grosjean et al., 2001) in the Miscanti lacustrine sequence are composed of banded (> 1 cm thick), variegated, charophyte and organic matter – rich calcitic (high magnesium calcite, HMC) diatomaceous mud (Fig. 6A). Five units are defined in the core according to sedimentary facies and stable isotope compositions (Fig. 6A,B). Unit E encompasses gray, banded, organic-rich calcitic diatomaceous mud with a cm-thick black, laminated, organic-rich interval at the top. Subunit D is characterized by the lowest organic matter content (< 10%) and the presence of gypsum. Subunit C is composed of gray calcitic diatomaceous mud with increasing organic matter content (10–20%), relatively high carbonate content (around 30%), and some intervals with calcite laminae.

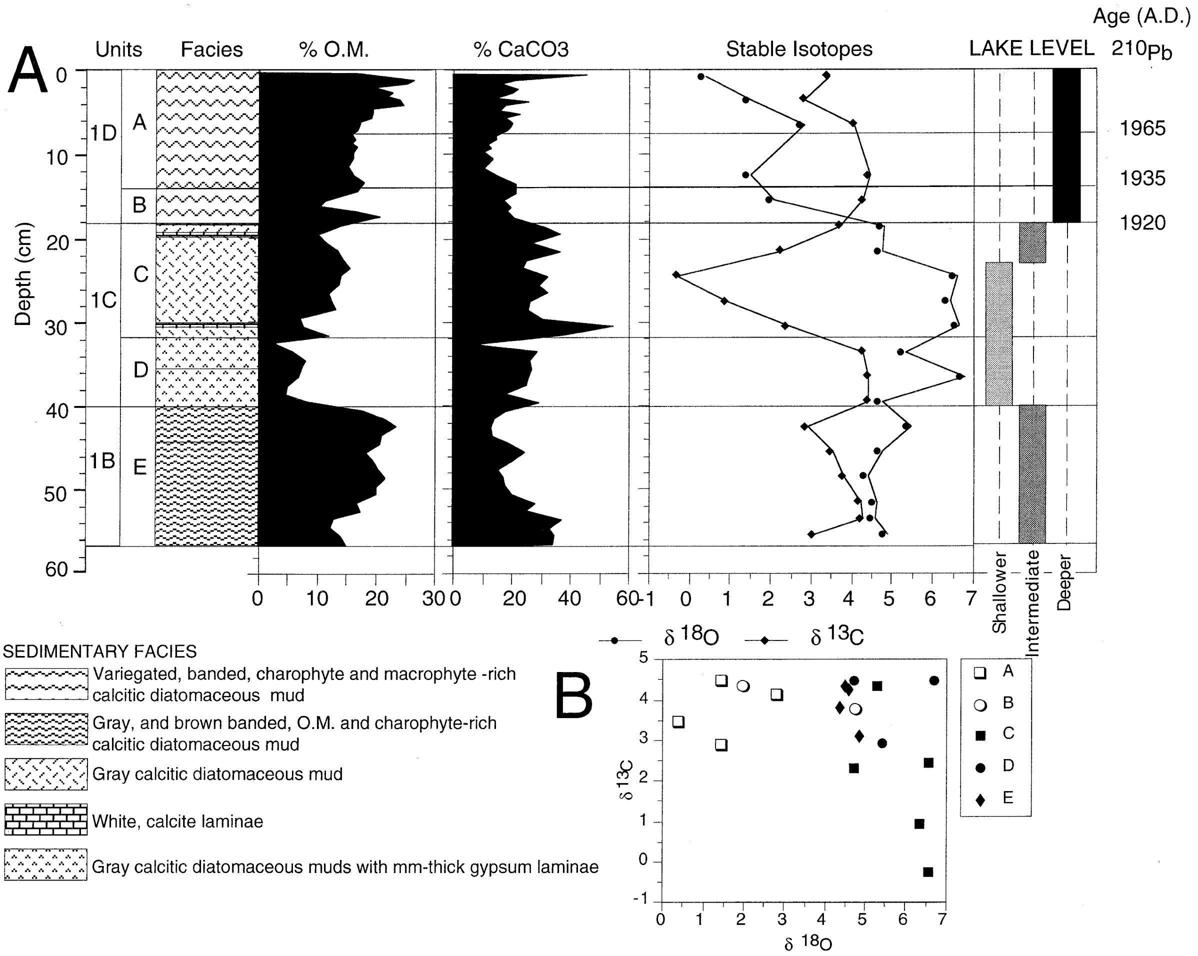

Fig. 6. The Laguna Miscanti record. (A) Facies, sediment composition, and stable isotopes. Reconstructed lake level and ^{210}Pb chronology of the main events. (B) Oxygen and carbon isotopes of authigenic calcite plotted by sedimentary units.

Subunits A and B are composed of finely laminated, variegated, charophyte-rich calcitic diatomaceous mud and characterized by the presence of abundant plant remains, particularly in the top of unit A. Fig. 6A,B shows the stable isotope composition of calcite in the core and the correlation with sedimentary units.

5.3.2. Paleohydrological interpretation

Valero-Garcés et al. (1996) inferred higher than modern salinities during deposition of unit 1A from higher Mg content in the HMC and higher Sr/Ca ratios. Unit E (1B) is characterized by the highest organic content in the core, suggesting high organic productivity, higher lake level and lower salinity. Low organic content and presence of evaporites indicate an abrupt transition in unit D from brackish to saline conditions with greatly reduced macrophyte production. Higher carbonate and organic content in unit C are indicative of progressively less saline waters. Modern, fresher conditions began with the deposition of unit B. The dominance of macrophytes and charophytes above the base of unit B points to an abrupt transition to more dilute waters and higher lake levels during the deposition of unit A.

The presence of evaporites in units D and C supports the interpretation of these units as having been deposited in highly evaporative waters during low lake-level and more saline conditions.

Higher $\delta^{13}C$ and $\delta^{18}O$ values also suggest evaporative enrichment. The organic matter content and the $\delta^{13}C_{calcite}$ curves do not show coherent patterns. In the lower units E and D, they have a negative correlation, while in the upper units there is no clear pattern. However, the correspondence between high $\delta^{13}C_{calcite}$ values in unit C and the intervals with calcite laminae suggests higher organic productivity during the deposition of unit C.

5.4. Laguna de El Peinado

5.4.1. Sedimentology, geochemistry, and stable isotopes

The El Peinado core sediments consist of indurated calcite crusts (unit III), overlain by banded to laminated mud (unit II), and topped by tufa facies (unit I) (Fig. 7A) (Valero-Garcés et al., 1999a, 2000a). The sediments are carbonate-rich (up to 85 wt% calcite), and low magnesium calcite is the only carbonate phase present. Unit III is composed of indurated calcite crusts (facies 3a and 3b) with some intercalated banded mud (facies 2). Iron content is higher in this basal unit. Unit II groups laminated, muddy facies in six sequences (average thickness 10 cm). These laminated facies have a higher organic matter content than the crust facies, generally lower carbonate content, and peak values of salinity indicators such as boron. Unit I is composed of reworked and in situ tufa deposits.

Similar to the Miscanti samples, calcites from El Peinado are strongly enriched in ^{18}O (range 5–9‰; Figs. 5 and 7A). The correlation between oxygen and carbon isotopes and sedimentary facies is complex (Fig. 7B; see Valero-Garcés et al., 2000a for details). The $\delta^{13}C$ $_{calcite}$ record shows extremely ^{13}C-enriched values (up to 13‰). High $\delta^{13}C$ values for carbonates in the Andean Altiplano have been found in other saline lakes (Grosjean, 1994; Grosjean et al., 1995; Schwalb et al., 1999) and fluvial travertine deposits (Aravena and Suzuki, 1990), although only in one site (Laguna Seca; Schwalb et al., 1999) were the values comparable to El Peinado. Schwalb et al. (1999) and Valero-Garcés et al. (1999a) discuss the mechanisms that can generate ^{13}C enrichment in lake waters over values in equilibrium with atmospheric CO_2. They conclude that the influence of geothermal and volcanic CO_2 and degassing during groundwater discharge can explain the enriched $\delta^{13}C$ values for primary calcite. The $\delta^{13}C_{calcite}$ values are lower and with a smaller range in units III and I, and generally higher and with a larger range in unit II. The highest $\delta^{13}C_{calcite}$ values correspond to facies 2c, characterized by higher organic matter content and abundant macrophyte remains, suggesting periods of increased organic productivity in the lake (Kelts and Talbot, 1990).

The $\delta^{13}C_{organic\ matter}$ curve shows a clearer relation with sedimentary facies: lower values in the calcitic crust facies from unit III (<-14‰ PDB (PeeDee Belemnite)) and higher $\delta^{13}C_{organic\ matter}$ values in the littoral and travertine facies of subunits IIIc and IIIa, II and I. This correlation with sedimentary facies indicates that changes in the biological assemblages are likely the main factor controlling the isotopic composition of the organic matter. The modern emerged aquatic vegetation around El Peinado Lake has lower $\delta^{13}C_{organic\ matter}$ values (-26.6‰ PDB) than the submerged vegetation (-8.4 to -11‰, PDB).

5.4.2. Paleohydrological interpretation

The crusts of unit III represent shoreline deposits cemented with low magnesium calcite during periods of low lake levels and sub-aerial exposure. Muddy facies were deposited during higher lake levels (units IIIc and IIIa). Sedimentological and geochemical evidence suggests deposition in the littoral–sub-littoral realm of a shallow saline lake for unit II. The fining–upward, energy-decreasing sequences identified in unit II can be related to fluctuations in lake level of a few meters from littoral to sub-littoral conditions, and changes in, for example, wave intensity. Unit I represents deposition in littoral sub-environments, slightly shallower than those of unit II.

The El Peinado sedimentary sequence records the evolution from a low lake-level stage with sub-aerial exposure (unit III) to higher lake-level environment (unit II), and a subsequent smaller lake-level decrease during deposition of unit I. Minor lake-level fluctuations are reflected by fa-

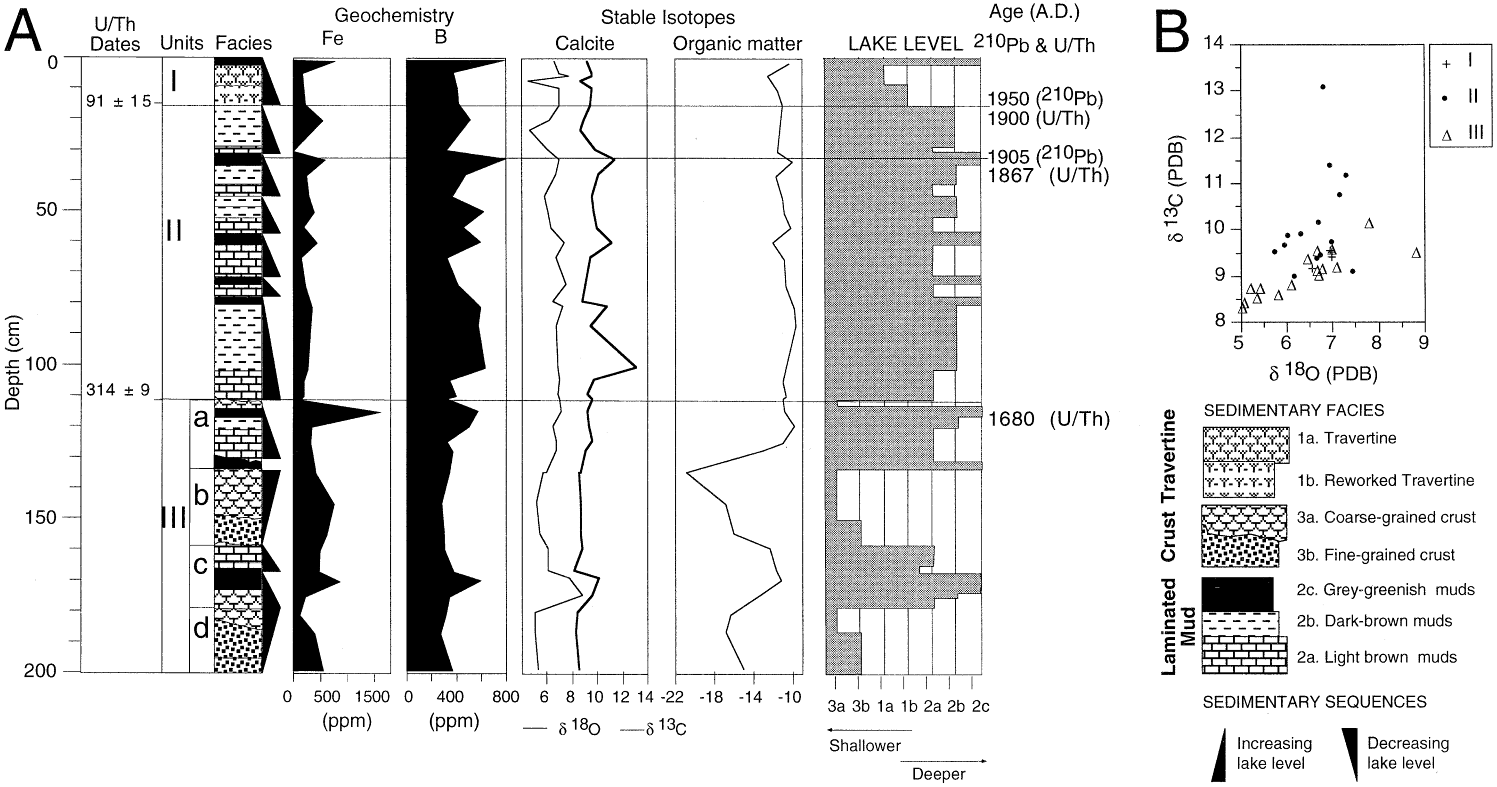

Fig. 7. The Laguna El Peinado record. (A) Facies, sediment composition, geochemistry and stable isotopes. Reconstructed lake level and ^{210}Pb and U/Th chronology of the main events. (B) Oxygen and carbon isotopes of authigenic calcite compositions plotted by sedimentary units.

cies alternation. The change in dominant biota from emerged macrophytic plants during periods of sub-aerial exposure to submerged macrophytes would explain the sharp $\delta^{13}C_{\text{organic matter}}$ positive shifts in units IIIc and IIIa, and the higher values of the upper two units.

6. Discussion

The geochemical, sedimentological and isotopic analyses of three lacustrine sequences in a north–south Altiplano transect provide continuous records of limnological changes that can be related to lake-level fluctuations during the last few centuries. The reconstructed hydrological variability cannot be directly translated into climate variability due to the lack of calibration with modern climatic data and the need for replication with other lakes from the same hydroclimatic areas. However, they show coherence with other regional climatic paleorecords.

The Lago Chungará record shows a main period of lower lake levels and increased water salinities between AD 1880 and 1950 with a higher lake-level fluctuation in the early 20th century (AD 1905–1935). In Miscanti, the arid period ended at the beginning of the 20th century, and its duration is unknown. Farther south, in El Peinado, the main arid period occurred significantly earlier (prior to AD 1680) and the 18th and 19th centuries were more humid than at the northern sites. The transition to more arid conditions at the end of the 19th century in Chungará and Miscanti coincides with a small decrease in water levels in the El Peinado sequence. Our 500-yr time-series from the three sites lack the resolution to decipher decadal variability, but the time intervals represented by the different sedimentary units can be correlated with other high-resolution regional records (Fig. 8). At the Quelccaya ice cap, a distinct wet period occurred from AD 1500 to 1720 and a marked dry period is interpreted at AD 1720–1860 (Thompson et al., 1986). The transition from the LIA to the 20th century occurred over a 2–3-year period centered on AD 1880 and it is one of the most abrupt changes detected in the Quelccaya ice cores. The 19th-century arid period detected in Chungará correlates with the arid period interpreted from the second half of the LIA in the Quelccaya record. The 20th-century arid period is roughly coeval with the greatest drought in southern Peru (1933–1945) that also produced a large drop (almost 5 m) in Lake Titicaca water level (Roche et al., 1992). The short arid periods inferred from the sharp positive oxygen isotope excursions could be related to droughts of decadal recurrence and intense El Niño years during the second half of this century.

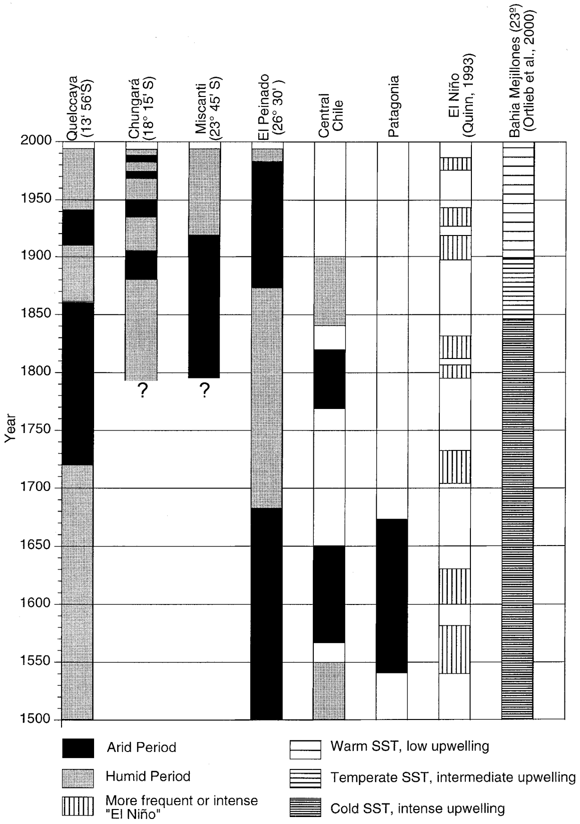

Fig. 8. Comparison of the main arid periods in the three lakes with selected records in the region (see text for details and references).

In the Miscanti core, the arid period (units D and C) ended at about AD 1920, although the $\delta^{18}O$ shift to more negative values shows that the change to more humid conditions occurred earlier and could be coeval with the termination of the LIA. The sharp changes in sediment composition and isotope values between units C and

B indicate an abrupt and rapid change to higher effective moisture. Variations in organic matter and carbonate content and isotope values during the 20th century suggest minor lake-level fluctuations within a general trend to moister conditions.

The lake-level evolution recorded in El Peinado core reflects a large paleohydrological change at the end of the 17th century (transition between units II and III). Prior to the late 17th century, lake level oscillated at the coring site, and subaerial exposure was reached frequently. After AD 1680, mean lake level was higher. This period of higher lake levels in El Peinado corresponds with the LIA as defined in the Quelccaya ice core (Thompson et al., 1986). However, the intense arid periods identified in Quelccaya (AD 1750–1860), Chungará (AD 1880–1950), and Miscanti (prior to AD 1920) do not occur in El Peinado. Six sedimentary sequences reflect changes in lake water volume at a decadal scale during the period AD 1680–1900 (Unit II), but none of them stands out as a candidate for an intense arid period. In El Peinado, the termination of the LIA may correspond to the beginning of the last sedimentary sequence in unit II (ca. 30 cm depth) that indicates the onset of a decreasing lake level trend. According to the U/Th date, lake level started to decrease after 1860 and continued until the mid-20th century. The transition to more arid conditions at the end of the 19th century in Chungará and Miscanti coincides with a small decrease in water levels in the El Peinado sequence. A small increase in lake level seemed to have occurred during the late 20th century.

Comparison with other paleorecords in the southern latitudes of South America suggests that the increase in effective moisture indicated by the abrupt transition between units III and II (ca. AD 1650) in El Peinado is of regional significance. Historical sources (Prieto, 1994; Prieto et al., 1998) document a dry period in northwestern Argentina since the arrival of the Spaniards (1580) until 1641, and a marked humid period between AD 1663 and 1710. Dendrochronological and glaciological records in Central Chile (30°–45°S) show precipitation above the long-term mean from AD 1450 to 1550 and from 1840 to 1900, and extended droughts from AD 1570 to 1650 and from 1770 to 1820 (Villalba, 1994). A review of glacier fluctuations (Luckman and Villalba, 2001) during the last 500 years in the Southern Andes suggests initial glacial advances in ca. the 13th–14th century, little evidence for extended glaciers during the 14th–16th century and advance during the 17th–20th century. Although there are no obvious glacier fluctuation–precipitation relationships, glacier advances in the early 17th and mid-20th century seem to be related to a combination of higher precipitation and lower temperatures. The northernmost tree-ring chronology on the western slopes of the Andes (32°S) covers the interval AD 956–1996, and it shows that the 1820–1910 interval was the longest wet period in this region of the Central Andes during the past 8 centuries. The inferred decreasing moisture availability during the mid-20th century is coherent with the interpreted lower lake levels at the top of unit II and unit I in El Peinado. Interestingly, deposition of relatively deeper sedimentary facies in El Peinado during the last few decades is coherent with the tree-ring evidence for increased precipitation during the last 3 decades in northwestern Argentina (Villalba et al., 1998). Rainfall records from central Chile (La Serena, 30°S) also show marked wet years at the end of the 19th century, followed by a decreasing trend to the present. The glaciers of the Río del Plomo (Mendoza, Argentina) show a similar pattern; they reached their maximum LIA extent at the beginning of the 20th century and have retreated since then. Marine records from Bahia Mejillones (23°S), off the coast of Chile, also show large changes associated with the 16th–19th century period (Ortlieb et al., 2000). A marked increase in paleoproductivity, increased upwelling, and colder waters during a 200-yr period centered around 400 cal yr BP have been interpreted as a reflection of environmental changes during the LIA.

The time-series from the three sites lack the resolution to decipher decadal variability; however, the time intervals represented by the different sedimentary units can be correlated with other high-resolution regional records (Fig. 8). The lake record suggests that changes in lake hydrology were time-transgressive and opposite in sign from the northern to the southernmost site. A change in lake hydrology at the end of the LIA ca. 1850 is coherent with other records from the Andes showing a regional pattern of climate change. Several mechanisms have been suggested to explain the paleohydrological variability and the rainfall fluctuations in the subtropical regions of the Altiplano at a decadal to century scale. High lake levels are interpreted in terms of strengthening of summer precipitation when the Intertropical Convergence Zone occupies a southernmost location; low lake levels are associated with increased winter precipitation and reduced summer rainfall (Argollo and Mourguiart, 2000). Both the Quelccaya ice cap cores and the Titicaca lake-level record demonstrate a general correlation between less effective moisture periods in the Altiplano and El Niño events (Thompson and Mosley-Thompson, 1987; Garreaud et al., this volume). Historical records provide evidence for more than 50 strong El Niño events during the last 500 years (Quinn, 1993), and some periods when strong El Niño events occurred: 1539–1578, 1600–1624, 1701–1728, 1792–1802, 1812–1832, 1897–1919, 1925–1932, and 1976–1987. Ortlieb (2000) re-evaluated the historical data and showed that many events reconstructed by Quinn (1993) may not have occurred and that the intensity of a number of events was probably lower than previously interpreted. The revised data do not provide a clear picture of former ENSO occurrences, particularly prior to ca. 1817, and show no conclusive evidence for more frequent and stronger El Niño events during the LIA. There is no obvious indication that global warming has had a significant effect on the ENSO activity (Enfield and Mestas-Nuñez, 2001). This may be related to the intrinsic problems of the historic data, but is also a reflection of spatial–temporal variability on the regional impacts of the ENSO system within South America. The strong correlation between wetter winters in Central Chile and northern Peru during El Niño is well established for the instrumental period, but the documentary record does not show such a correlation prior to 1817. Tree-ring chronologies show a stronger decadal mode of Pacific sea-surface temperature oscillations for the period 1600–1850 and a dominant interannual mode afterwards (Villalba et al., 2001). Both lines of evidence suggest a strong modification of the atmospheric circulation pattern that affected the teleconnections during the LIA. According to our chronologies for the three studied lakes, there is no clear indication that stronger ENSO events only occurred during the arid periods reconstructed from the lake records (Fig. 8).

In the southern Altiplano (El Peinado site), where winter snow is the dominant moisture source, arid periods could be linked to other extratropical mechanisms. The differences in paleohydrological evolution during the Late Holocene between Laguna Miscanti and Laguna del Negro Francisco have been explained by Grosjean et al. (1997) to reflect different moisture sources: tropical and Amazonian to the north, and a mixture of Pacific from the westerlies and south Atlantic to the south. Changes in the intensity of the westerlies is considered as the main cause for rainfall variability in the high Andes at 27°S. Changes in other mechanisms, such as convective summer storms and outburst of frontal winter precipitation, may also play a significant role (Grosjean et al., 1997). The track of South American anticyclones associated with cold surges can reach as far north as 20°S on the eastern side of the Andes (Marengo and Rogers, 2001). Although there is little relation between the occurrence of El Niño and polar-air outbreaks, cold fronts penetrate further north and lead to higher precipitation in central Chile when the South Pacific subtropical high is weaker and/or displaced northward (Aceituno, 1988). Schwalb et al. (1999) suggested that changes in cold fronts and 'cut-off' intensity and frequency could explain differences in the amount of precipitation between 23° and 27°S during the Holocene.

Garreaud et al. (2003) show that at the northern latitudes (Chungara and Miscanti), the rainfall variability responds to zonal wind anomalies that modulate summer-moisture transport from the eastern cordillera to the western Altiplano, with greater transport and more summer rainy days during La Niña events. Farther south, at El Peinado latitude, moisture responds to variations in the intensity and position of the South Pacific jet, with an increase in winter rainy days during El Niño events. The same general pattern of opposition in modern regional climate between the summer rainy areas to the north and the winter rainy ones to the south seems to hold for decadal-scale variability.

7. Conclusions

The paleohydrological reconstructions from a lake transect in the Altiplano show abrupt fluctuations during the last centuries. A significant paleohydrological change occurred in the three lakes at the end of the 19th century, coeval to the termination of the LIA. However, the inferred changes in water balance were of different sign. In Chungará and El Peinado a drier period began, while in Miscanti, conditions seem to have become more humid. An intense drought period is present in all the records but they show different patterns in northern Chile (Chungará), Atacama (Miscanti) and the southern tip of the Altiplano (El Peinado). In Chungará, the arid period was shorter and occurred during AD 1880–1950, and it was punctuated by a more humid period between AD 1905 and 1935. In Miscanti, the arid period terminated at the end of the 19th century, but it had lasted longer. In El Peinado, conditions were wetter during the 17th–19th centuries and the arid period occurred prior to the 17th century. Other high-resolution records from the region (ice caps, historical documents, dendrochronological and lake records) show abrupt paleohydrological and paleoclimatic changes synchronous to the onset and termination of the LIA. Although there exist local differences and dating uncertainties, the LIA stands out as a significant though complex climatic event in the Andean Altiplano. The discrepancies between the northern and southern Altiplano records during the LIA may reflect distinct responses to external forcing in two areas with different climatic regimes.

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References

Aceituno, P., 1988. On the functioning of the southern oscillation in the South American sector, Part I: surface climate. Mon. Weather Rev. 116, 505–524.

Aravena, R., Suzuki, O., 1990. Isotopic evolution of river water in the northern Chile region. Water Resour. Res. 26, 2887–2895.

Aravena, R., Suzuki, O., Peña, H., Pollastri, A., Fuenzalida, H., Grilli, A., 1999. Isotopic composition and origin of the precipitation in northern Chile. Appl. Geochem. 14, 411–422.

Aravena, R., Warner, B.G., MacDonald, G.M., Hanf, K.I., 1992. Carbon isotope composition of lake sediments in relation to lake productivity and radiocarbon dating. Quat. Res. 37, 333–345.

Argollo, J., Mourguiart, P., 2000. Late Quaternary climate history of the Bolivian Altiplano. Quat. Int. 72, 37–51.

Dean, W.E., 1993. Physical properties, mineralogy, and geochemistry of Holocene varved sediments from Elk, Lake, Minnesota. In: Bradbury, J.P., Dean, W.E. (Eds.), Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States. GSA Special Paper 276, Boulder, CO, pp. 135–157.

Dettinger, M.D., Battisti, D.S., Garreaud, R.D., McCabe Jr., G.J., Bitz, C.M., 2001. Interhemispheric effects of interannual and decadal ENSO-like climate variations on the Americas. In: Markgraf, V. (Ed.), Interhemispheric Climate Linkages. Academic Press, San Diego, CA, pp. 1–16.

Enfield, D.B., Mestas-Nuñez, A.M., 2001. Interannual to multidecadal climate variability and its relationship to global sea surface temperaratures. In: Markgraf, V. (Ed.), Interhemispheric Climate Linkages. Academic Press, San Diego, CA, pp. 17–30.

Fritz, P., Suzuki, O., Silva, C., Salati, E., 1981. Isotope hydrology of groundwaters in the Pampa del Tamarugal, Chile. J. Hydrol. 53, 161–184.

Garreaud, R., Vuille, M., Clement, A.C., 2003. The climate of the Alliplano: observed current conditions and mechanisms of past changes. Palaeogeogr. Palaeoclimatol. Palaeoecol. S0031-0182(03)00269-4.

Geyh, M.A., Schotterer, U., Grosjean, M., 1998. Temporal changes of the ^{14}C reservoir effect in lakes. Radiocarbon 40, 921–931.

Grosjean, M., 1994. Paleohydrology of the Laguna Lejía (north Chilean Altiplano) and climatic implications for late-glacial times. Paleogeogr. Paleoclimatol. Paleoecol. 109, 89–100.

Grosjean, M., Valero-Garcés, B., Geyh, M.A., Messerli, B., Schreier, H., Kelts, K., 1997. Mid and Late Holocene Limnogeology of Laguna del Negro Francisco, northern Chile, and its paleoclimatic implications. Holocene 7, 151–159.

Grosjean, M., Geyh, M.A., Messerli, B., Schotterer, U., 1995. Late Glacial and early Holocene lake sediments, groundwater formation and climate in the Atacama Altiplano 22-24°S. J. Paleolimnol. 14, 242–252.

Grosjean, M., van Leeuwen, J.F.N., van der Knaap, W.O., Geyh, M.A., Ammann, B., Tanner, W., Messerli, B., Valero-Garcés, B., Veit, H., 2001. A 22000 ^{14}C yr B.P. sediment and pollen record of climate change from Laguna Miscanti (23°S), northern Chile. Glob. Planet. Change 28, 35–51.

Hardy, D.R., Vuille, M., Braun, C., Keimig, F., Bradley, R.S., 1998. Annual and daily meteorological cycles at high altitude on a tropical mountain. Bull. Am. Meteorol. Soc. 79, 1899–1913.

Kelts, K., 1988. Environments of deposition of lacustrine petroleum source rocks: an introduction. In: Fleet, A.J., Kelts, K., Talbot, M.R. (Eds.), Lacustrine Petroleum Source Rocks. Geol. Soc. Spec. Publ. 40, pp. 3–26.

Kelts, K., Talbot, M., 1990. Lacustrine carbonates as geochemical archives of environmental change and biotic/abiotic interactions. In: Tilzer, M.M., Serruya, C. (Eds.), Large Lakes, Ecological Structure and Function. Springer, pp. 288–315.

Kull, C., Grosjean, M., 1998. Albedo changes, Milankovich forcing, and late Quaternary climate change in the central Andes. Clim. Dyn. 14, 871–881.

Li, H.C., Ku, T.L., 1996. δ^{13}C-δ^{18}O covariances as paleohydrological indicator for closed-basin lakes. Paleogeogr. Paleoclimatol. Paleoecol. 133, 69–80.

Luckman, B.H., Villalba, R., 2001. Assessing the synchroneity of glacier fluctuations in the western Cordillera of the Americas during the last millennium. In: Markgraf, V. (Ed.), Interhemispheric Climate Linkages. Academic Press, San Diego, CA, pp. 119–141.

Marengo, J.A., Rogers, J.C., 2001. Polar air outbreaks in the Americas: assessments and impacts during modern and past climates. In: Markgraf, V. (Ed.), Interhemispheric Climate Linkages. Academic Press, San Diego, CA, pp. 31–52.

Messerli, B., Grosjean, M., Bonani, G., Bürgi, A., Geyh, M., Graf, K., Ramseyer, K., Romero, H., Schotterer, U., Schreier, H., Vuille, M., 1993. Climate change and natural resource dynamics of the Atacama Altiplano during the last 18,000 years: a preliminary synthesis. Mt. Res. Dev. 13, 117–127.

Meyers, P.A., 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. Chem. Geol. 114, 289–302.

Ortlieb, L., 2000. The documentary historical record of El Niño events in Peru: an update of the Quinn record (sixteen through nineteenth centuries). In: Diaz, H., Markgraf, V. (Eds.), El Niño and the Southern Oscillation: Variability, Global and Regional Impacts. Cambridge University Press, Cambridge, pp. 207–295.

Ortlieb, L., Escribano, R., Follegati, R., Zuñiga, O., Kong, I., Rodriguez, L., Valdés, J.Guzmán,N., Iratchet, P., 2000. Recording of ocean-climatic changes during the last 2000 years in a hypoxic marine environment of northern Chile (23°S). Rev. Chil. Hist. Nat. 73, 221–242.

Prieto, M.R., 1994. Reconstrucción del clima de América del Sur mediante fuentes históricas. Estado de la cuestión. Rev. Mus. Hist. Nat. San Rafael (Mendoza) XII, 323–342.

Prieto, M.R., Herrera, R., Dussel, P., 1998. Clima y disponibilidad hídrica en el sur de Bolivia y noroeste de Argentina entre 1560 y 1710, Los documentos españoles como fuente de datos ambientales. Bamberg. Geogr. Schr. 15, 35–56.

Prieto, M.R., Herrera, R., Dussel, P., 1999. Historical evidences of streamflow fluctuations in the Mendoza river, Argentina, and their relationships with ENSO. Holocene 9, 473–481.

Quinn, W.H., 1993. The large-scale ENSO event, the El Niño, and other important features. Bull. Inst. Fr. Et. Andines 22, 13–34.

Roche, M.A., Bourges, J., Cortes, J., Mattos, R., 1992. Climatology and hydrology of the Lake Titicaca basin. In: Dejoux, C., Iltis, A. (Eds.), Lake Titicaca: a Synthesis of Limnological Knowledge. Kluwer Academic, Dordrecht, pp. 120–130.

Rozanski, K., Araguas-Araguas, L., 1995. Spatial and temporal variability of stable isotope composition of precipitation over the South American continent. In: Ribstein, P., Francou, B. (Eds.), Aguas Glaciares y Cambios Climáticos en los Andes Tropicales. ORSTOM-UMSA-SENAMHI-CONAPHI, pp. 65–75.

Ruttlant, J., Fuenzalida, H., 1991. Synoptic aspects of the central Chile rainfall variability associated with the Southern Oscillation. Int. J. Climatol. 111, 63–76.

Schwalb, A., Burns, S., Kelts, K., 1999. Holocene environments from stable isotope stratigraphy of ostracods and authigenic carbonate in Chilean Altiplano Lakes. Palaeogeogr. Palaeoclimatol. Palaleoecol. 148, 153–168.

Talbot, M.R., 1990. A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates. Chem. Geol. 80, 261–279.

Talbot, M.R., Kelts, K., 1990. Paleolimnological signatures from carbon and oxygen isotopic ratios in carbonates from organic carbon-rich lacustrine sediments. In: Katz, B.J. (Ed.), Lacustrine Basin Exploration - Case Studies and Modern Analogs. Am. Assoc. Petr. Geol. Mem. 50, Tulsa, OK, pp. 99–112.

Thompson, L.G., Mosley-Thompson, E., 1987. Evidence of abrupt climatic change during the last 1,500 years recorded in ice cores from the tropical Quelccaya ice cap, Peru. In: Berger, W.H., Labeyrie, L.D. (Eds.), Abrupt Climate Change, Evidence and Implications, NATO ASI Series C, Vol. 216. Reidel, pp. 99–110.

Thompson, L.G., Mosley-Thompson, E., Dansgaard, W., Grootes, P.M., 1986. The Little Ice Age as recorded in the stratigraphy of the tropical Quelccaya Ice Cap. Science 234, 361–364.

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

Valero-Garcés, B.L., Delgado-Huertas, A., Navas, A., Ratto, N., 1999b. Large ^{13}C enrichment in primary carbonates from Andean Altiplano lakes, Northwest Argentina. Earth Planet. Sci. Lett. 171, 253–266.

Valero-Garcés, B.L., Grosjean, M., Schwalb, A., Schreir, H., Kelts, K., Messerli, B., 2000a. Late Quaternary lacustrine deposition in the Chilean Altiplano (18°-28°S). In: Gierlowski-Kordech, E., Kelts, K. (Eds.), Lake Basins through Space and Time. Am. Assoc. Petr. Geol. Studies in Geology 46, pp. 625–636.

Valero-Garcés, B.L., Delgado-Huertas, A., Navas, Ratto,N., Edwards, L., 2000b. Paleohydrology of Andean saline lakes from sedimentolgal and isotopic records, northwestern Argentina. J. Paleolimnol. 24, 343–359.

Valero-Garcés, B.L., Grosjean, M., Schwalb, A., Geyh, M., Messerli, B., Kelts, K., 1996. Limnogeology of Laguna Miscanti: evidence for mid to late Holocene moisture changes in the Atacama Altiplano (northern Chile). J. Paleolimnol. 16, 1–21.

Valero-Garcés, B.L., Grosjean, M., Schreier, H., Kelts, K., Messerli, B., 1999a. Holocene lacustrine deposition in the Atacama Altiplano: facies models, climate and tectonic forcing. Palaeogeogr. Palaeoclimatol. Palaeoecol. 151, 101–125.

Villalba, R., 1990. Climatic fluctuations in northern Patagonia during the last 1000 years as inferred from tree-ring records. Quat. Res. 34, 346–360.

Villalba, R., 1994. Tree-rings and glacial evidence for the Medieval Warm epoch and the Little Ice Age in Southern South America. Clim. Change 30, 1–15.

Villalba, R., Dárrigo, R.D., Cook, E.R., Jacoby, G.C., Wiles, G., 2001. Decadal-scale climatic variability along the extratropical western coast of the Americas: evidence from treering records. In: Markgraf, V. (Ed.), Interhemispheric Climate Linkages. Academic Press, San Diego, CA, pp. 155–172.

Villalba, R., Grau, H.R., Boninsegna, J.A., Jacoby, G.C., Ripalta, A., 1998. Tree-ring evidence for long term precipitation changes in subtropical South America. Int. J. Climatol. 18, 1463–1478.

Vuille, M., 1999. Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the southern oscillation. Int. J. Climatol. 19, 1579–1600.

Vuille, M., Ammann, C., 1996. Regional snowfall patterns in the high, arid Andes (South America). Clim. Change 36, 413–423.

Vuille, M., Bradley, R.S., Keimig, F., 2000. Interannual climate variability in the Central Andes and its relation to tropical pacific and Atlantic forcing. J. Geophys. Res. 105, 12447–12460.

Vuille, M., Hardy, D., Braun, C., Keimig, F., Bradley, R.S., 1998. Atmopsheric circulation anomalies associated with 1996/1997 summer precipitation events on Sajama Ice Cap, Bolivia. J. Geophys. Res. 103, 11191–11204.