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Limnogeology of Laguna Miscanti: evidence for mid to late Holocene moisture changes in the Atacama Altiplano (Northern Chile) *

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Abstract

Sedimentological, mineralogical and geochemical analyses of sediment cores from 9 m-deep, saline Laguna Miscanti, Chile (23 ° 44′S, 67 °46′W, 4140 m a.s.l.) together with high-resolution seismic profiles provide a mid to late Holocene time series of regional environmental change in the Atacama Altiplano constrained by ^{210}Pb and conventional ^{14}C dating. The mid Holocene was the most arid interval since the last glacial maximum, as documented by subaerial exposure and formation of hardgrounds on a playa surface. Extremely low lake levels during the mid Holocene appear consistent with lower effective moisture recorded at other sites along the Altiplano and in the Amazon Basin. Termination of this arid period represented a major shift in the regional environmental dynamics and inaugurated modern atmospheric conditions. The cores show a progressive upward increase in effective moisture interrupted by numerous century-scale drier periods of various intensities and durations that characterize a fluctuating late Holocene climate. In spite of chronological uncertainties, the major environmental changes seem to correlate with the available paleorecords from the region providing a coherent account of effective moisture variability in the tropical highlands of South America.

Introduction

Increasing evidence for abrupt and drastic moisture changes in tropical and subtropical latitudes during the Holocene (Wright *et al.*, 1993) contrasts with more uniform climatic conditions for the Holocene inferred from temperature proxy data in the high latitude areas of Greenland and Antarctica (e.g. Lorius & Oeschger, 1994). Particularly in South America controversy persists whether hydrological shifts are synchronous to the northern hemisphere and what are the ultimate causes and triggers of observed changes such as (i) increased moisture and vegetational shifts during the mid to late Holocene transition, (ii) variability in the intensity and frequency of El Niño events, and (iii) the extent and impact of the medieval climatic anomaly and the Little Ice Age (LIA). It is questioned whether they represent global (i.e. synchronous to the northern hemisphere), hemispherical or regional signals (Hansen *et al.*, 1984; Markgraf, 1993; Coltinari, 1993; Stine, 1994; Hansen *et al.*, 1994). One problem has been the scarcity of continuous, reliably-dated archives in South America. This is particularly the case for the tropical and subtropical Andes where the climatic and topograph-

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ic gradients are extreme. Comparison of records from different ecozones remains difficult until a network of time-series sites with improved chronological fidelity is available.

Recent results from areas adjacent to the Atacama Altiplano (18–28 °S) have elucidated the Holocene environmental history and the paleoclimate in the Central Andes. The mid Holocene was extremely dry both north and south of the Atacama. The lake level of Lago Titicaca increased rapidly around 3600 yr B.P., a pronounced dry episode occurred around 2200 yr B.P., and the modern level was reached about 1000 yr B.P. (Mourguiart *et al.*, 1992). A significant increase in effective moisture occurred around 3000 yr B.P. at the coast of the semiarid Chile at 32 °S, and more humid conditions than today are suggested around 1800 yr B.P. (Villagran & Varela, 1990). Increasing moisture during the late Holocene in Central Chile is attributed to a weaker Southeast Pacific Anticyclone (SPA), allowing the frontal winter precipitation to move further north (Villagrán & Varela, 1990). A positive correlation between El Niño events and dry conditions in the Central Andes area is suggested by snow accumulation rates in the Quelccaya ice (Thompson *et al.*, 1984; Thompson & Mosley-Thompson, 1987, 1989; Thompson, 1992) and the changes in lake Titicaca level (Martin *et al.*, 1993).

In this paper we summarize preliminary results from a broader research program aimed to develop coherent data sets of regional environmental dynamics along a transect of the Chilean Altiplano from 18 ° to 27 °S. Our study from Laguna Miscanti, a saline lake in the Atacama Altiplano (Fig. 1) provides geochemical and sedimentological data series of environmental change for the last few thousand years that display very little lag on a decadal time scale. Today, Laguna Miscanti is one of the largest and deepest lakes in the Atacama Altiplano. Compared to most of the shallower lakes such as Laguna Lejía, Salar Tuyaito, and Aguas Calientes II, desiccation periods were less pronounced, and the sedimentary record of Laguna Miscanti probably provides the most continuous archive since at least the late-glacial lake phase. The relatively humid late-glacial/early Holocene Tauca phase and the onset of the arid mid-Holocene climate are relatively well-documented for this area from lake sediments and geoarchaeological evidence (e.g. Nuñez, 1983; Messerli *et al.*, 1993; Grosjean, 1994; Grosjean & Nuñez, 1994; Nuñez, 1994; Messerli *et al.*, in press). Little is known about the transition from mid to the late Holocene, or the climatic changes during the last 3000 years, including a potential equivalent to a medieval climate anomaly or a Little Ice Age in the Atacama region. A comprehensive study of lake sediments can provide the needed resolution to decipher the environmental variability in tropical/subtropical South America. Palynological studies in these desert environments are hampered by the scarcity and low variability of vegetation. Glaciers do not exist in spite of continuous permafrost, and soil development is very slow.

Our proposed reconstruction of effective moisture for the last few millennia follows from the sedimentological, mineralogical and chemical criteria for sediment cores from Laguna Miscanti and on a seismic survey of the lake basin. Inferred changes in lake levels reflect changes in the effective moisture (precipitation/evaporation ratio), whereas changes in salinity must be interpreted in light of both water volume changes and chemical concentration and precipitation processes. Lake sediments, although lacking the annual resolution of ice cores, contain long time series and, because of their large geographical distribution allow regional transect studies. The hydrologically closed Altiplano lakes are highly sensitive to shifts in climate, biota, and hydrology. Their immediate response to environmental change is due to the relatively small size of the water reservoir, changes in bottom redox conditions, and pH, and a broad range of salinities, compositions and concentrations of chemical compounds. As a consequence lake sediments archive high resolution paleoenvironmental information which can only be decoded by the study of the sediments at microscale.

Paleoclimatic reconstructions and tests of global circulation models have utilized the high resolution records archived in lake sediments throughout the world and supply comparative models for this study (cf. Fritz *et al.*, 1987; Fontes *et al.*, 1985; Gasse & Fontes, 1989; Kelts & Talbot, 1990; Johnson *et al.*, 1991; Bradbury *et al.*, 1993).

Because of the lack of suitable terrestrial material, and the presence of reservoir effects, the dating of lake deposits in the Altiplano is often problematic. An accurate chronology will only result from the integration of various paleorecords and a critical evaluation of the different dating methods. This is not the goal of this paper. Here, we use the precise and sensitive lithological subfacies changes to characterize the mid and late Holocene effective moisture changes in the Atacama region, and discuss the paleoclimatic implications within the context of results from adjacent areas in Bolivia, Peru and Central Chile. We present for the first time data for upper Holocene lake sediments in

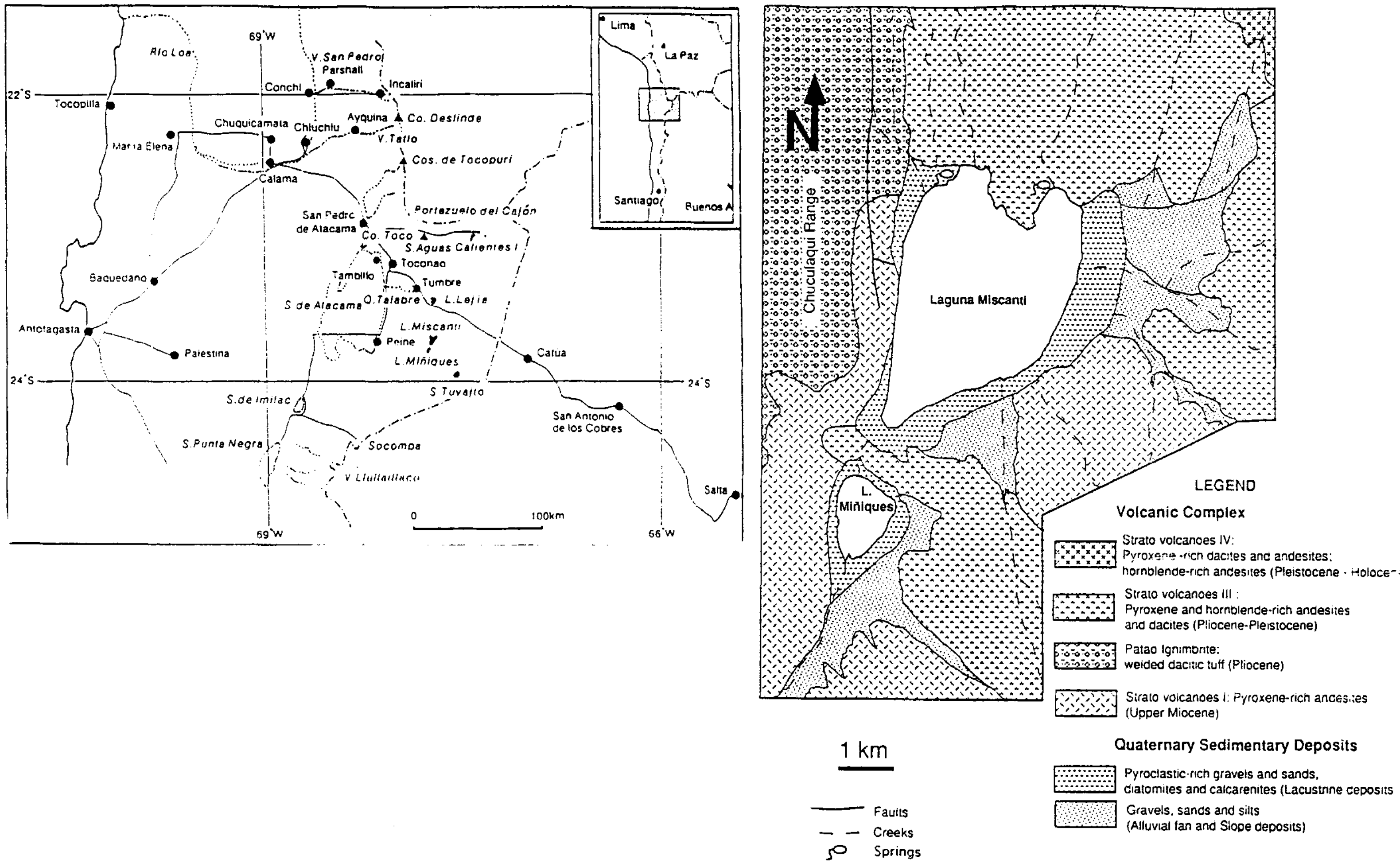

Fig. 1. Geographic and geological location of Laguna Miscanti. Geological units after Ramirez and Gardeweg (1982).

the North Chilean Altiplano that indicate less effective moisture during the mid Holocene followed by a lake level raise, and interrupted by several drier episodes.

Geological and geographic setting

The modern lake

Laguna Miscanti (23 ° 44′S, 67 ° 46′W, 4140 m. a.s.l., Fig. 1) is with its modern 15.5 km^2 surface one of the largest and deepest lakes in the Atacama Altiplano. Like many other small lakes and salars (salt lakes) in this area, Laguna Miscanti sits in an endorheic basin. The three lakes in the area (Laguna Lejía, Miscanti and Miniques) as well as the Pampa Varela basin lie in Pliocene-Pleistocene tectonic basins along the Quebrada Nacimiento Fault (Fig. 1, Ramirez & Gardeweg, 1982). Groundwater flow along the fault system allows a limited drainage of the lake basins in spite of topographic closure. Concentrated brines and ephemeral salts are removed and prevent lakes from evolving into playa evaporite hardpans (Chong-Diaz, 1988; Grosjean, 1994). Today, Laguna Miscanti is the least saline lake in the region (5 g l^{-1} total dissolved solids, 6400 μS cm^{-1} electric conductivity) with a Na-(K-Ca-Mg)-SO_4-Cl brine and alkaline conditions (pH = 8.8). The water budget is mainly controlled by groundwater inflow from a large catchment area in the Cordón Puntas Negras (320 km^2) and by evaporation. The contribution of springs is very small, and seepage into Laguna Miniques is limited.

Lacustrine deposits blanket large areas around the lake. Former shorelines occur up to 20 m above the current lake level. Associated stromatolites yielded an age of 15 545 ± 250 ^{14}C yr B.P. (Table 1) suggesting a late-glacial age for this maximum. Alluvial fans underneath these late-glacial lake deposits are partially cut by shoreline wave action. These suggest that fans were active prior to the maximum late-glacial lake phase. Ground and lateral moraine deposits have been identified east of Laguna Miscanti in the Puntas Negras area between 4350 and 4900 m (Ramirez & Gardeweg, 1982). The precise age of the glaciation remains unknown. Based on the assumption that glaciers were triggered by moisture and not primarily by temperature, Messerli *et al.* (1993) proposed a late-glacial age, likely synchronous with the high lake levels in the area.

Modern sediments in Laguna Miscanti consist of carbonate and sulfate precipitates (magnesian calcite and gypsum), bioclasts (charophytes, diatoms and ostracodes) and organic matter from aquatic plants. Pleistocene to modern eruptions of volcanoes contributed glasses to the lake sediment composition. The amount of siliclastic input is very low due to the lack of surface inflow, although an aeolian component may be significant.

The climate in the Altiplano

Laguna Miscanti is located in an arid transition between two climatic regimes (Miller, 1976): the convective tropical summer rainfall (*Invierno Boliviano*) and the advective extratropical winter precipitation (*Invierno Chileno*). The dry-cold modern climate in the area is characterized by an annual mean air temperature of about 2 °C and precipitation rates of <200 mm yr^{-1}. Evaporation rates of about 2000 mm yr^{-1} (Linzor weather station) largely exceed precipitation. Due to this persistent aridity, glaciers are absent even in the continuous permafrost above 5600 m (Messerli *et al.*, 1993). Local wind systems are usually dominant in the boundary layer.

The influence of the Southeast Pacific Anticyclone (SPA) is significant year round, particularly with regard to its moisture blocking effect. Socaire station (3200 m, 30 km west of Laguna Miscanti) shows 50–90% of the rainfall between December and May. However, field observations, sequential LANDSAT (Vuille & Baumgartner, 1993) and NOAA/AVHRR images (Messerli *et al.*, in prep.) strongly suggest that winter precipitation has been underestimated. Three different synoptic mechanisms seem to explain moisture transport into the Altiplano at the latitude of 24 °S (Fuenzalida & Rutllant, 1986; Messerli *et al.*, in prep.): (i) frontal precipitation from the westerly circulation during winter (*Invierno Chileno*) brings moisture to the lower and the higher elevation areas, (ii) tropical summer precipitation (*Invierno Boliviano*) is usually related to a high-elevation anticyclonic flow with NE wind component at 24 °S and brings moisture exclusively to the higher elevation area, and (iii) drops of cold polar air masses (cut-offs from the polar front) collide as isolated cells with tropical warm-moist air at subtropical latitudes and bring moisture mainly during fall, winter and spring.

Although precipitation may be triggered by extratropical air masses as in the case with the cut-offs from the polar front, the isotopic signal of rainfall and snow was found to be predominantly continental (Aravena *et al.*, 1989; Grosjean *et al.*, in press). The mani-

Table 1. Conventional un-corrected ^{14}C ages from Laguna Miscanti sediment samples. The dates are not corrected for reservoir effect, which is probably about 3000–4000 years

Lab number	Depth (cm)	Sample	^{14}C age (yr B.P.)	$\delta^{13}C$ (‰ PDB)
Hv-19799	50	aquatic macrorest	4855 ± 155	−11.3
Hv-19800	119	aquatic macrorest	6025 ± 225	−12.4
Hv-19801	159	aquatic macrorest	6110 ± 350	− 9.3
Hv-19802	195	aquatic macrorest	8170 ± 220	− 9.8
Hv-19803	227	total organic fraction	8940 ± 545	− 8.3
Hv-19701	shoreline (+ 20 m)	Stromatolite (carbonate fraction)	15,545 ± 250	+ 6.4

festation of the El Niño-Southern Oscillation ENSO phenomenon in the Atacama Altiplano at 24 °S is still controversial (Pittock, 1980; Aceituno, 1988; Kessler, 1990; Martin *et al.*, 1993; Thompson *et al.*, 1992; Grosjean, 1994). This may be due to the extreme variability of rainfall at generally low levels measured at a few available stations, as well as to the lack of canonical ENSO events in this area.

Methodology

We used a high-resolution ORE-GEOPULSE (1–12 kHz) seismic profiling system with an EPC 9800 digital graphic recorder to test the continuity of the sediment layering in the basin of Laguna Miscanti. This seismic survey enabled us to locate the coring site, and to determine the representativeness of the sediment cores. A short core (50 cm) including the undisturbed sediment/water interface was sampled in the field at 0.5 cm intervals. Water, organic matter, and carbonate contents were determined by loss-on-ignition method (LOI; Dean, 1974) at 105 °C, 550 °C and 1000 °C. ^{210}Pb dating was performed at the LRC (University of Minnesota) using the Constant Rate of Supply (CRS) model. Conventional radiocarbon dates were obtained from six samples (4 aquatic macrorests, 1 stromatolite carbonate and 1 bulk organic matter) using standard techniques at the State Geological Survey, Lower Saxony, Hannover.

A 2.92 m long core was retrieved with a modified Livingstone piston corer (5 cm diameter) during December 1993. The core was documented photographically and described by lithology, color, grain size, fossil content and sedimentary structures. Subsamples were taken every 5 cm or less for petrographic microscope smear slides, mineralogical and chemical analyses. The mineralogical composition was determined using a Phillips PW 1050/65 x-ray diffractometer (CuKα source); magnesium content in calcite was calculated from XRD peaks after Goldsmith & Graf (1958). Total carbon content was measured with a Leco Carbon Analyser, and organic carbon by titration with $FeSO_4$ (Walkley-Black method). Sediment subsamples were digested in 1% HCl, heated at 60 °C for 1 h and centrifuged at 5000 rpm for 42 min. Sulfate concentrations were determined turbidimetrically (Lachat Autoanalyser), Na^+ and K^+ were measured by flame atomic absorption spectrophotometry FAA (Perkin Elmer Model 306). Inductively coupled argon plasma atomic emission spectroscopy ICAP-AES (Thermo Jarrel Ash ICAP 61) was used to determine concentrations of other cations.

Chronology

Radiocarbon dating of lake sediments in the Chilean Altiplano faces two major problems: the scarcity of terrestrial organic material and the importance of reservoir effects (Grosjean, 1994; Grosjean *et al.*, in press). Modern lake water in Laguna Miñiques contains about 45 pMC (percent modern carbon) and evidence for postsedimentary dissolution and reprecipitation of carbonates in the sediments were extensively found in Laguna Lejía outcrops (Grosjean, 1994). Our preliminary age model for Laguna Miscanti sediments is based on ^{210}Pb dates derived from the short core and correlated with the long core (Fig. 2), and six conventional radiocarbon dates (Table 1). The presence of lithological markers such as gypsum layers and color laminations allow a layer to layer correlation between the

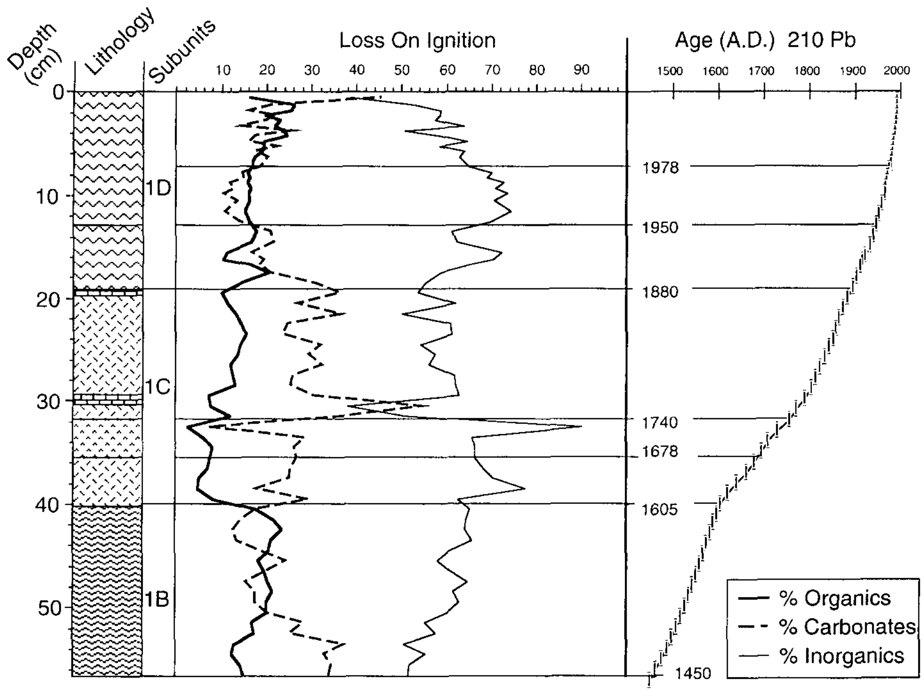

Fig. 2. Sedimentological units, Loss On Ignition parameters (% organic matter, inorganics and carbonate) and ^{210}Pb ages for the short core. Legend for lithology as in Fig. 5.

two cores. Besides the intrinsic temporal limitations of the method, the attempts to extrapolate the ^{210}Pb-based chronology face two main obstacles: (i) sedimentation rate is likely to have changed at century-scale considering the variety of facies, although overall it may have remained uniform (0.022 g cm^{-2} yr^{-1}); (ii) indurated carbonate hard grounds and erosive surfaces at the lower third of the core represent unknown time spans. Therefore, the extrapolated ages have to be considered as minimum ages. Considering the conventional ^{14}C age-depth relationship (Table 1), the reservoir effect for Laguna Miscanti is very significant, up to 3000–4000 years. Correlation of the main environmental changes in Laguna Miscanti with the significant changes in other Altiplano records helps to constrain chronological uncertainties, but also induces a circular argument. We consider that our core spans between the mid-Holocene to late-Holocene transition and the present. A detailed discussion of the chronological problems in the Altiplano, however, is not the focus of this paper and will be dealt with elsewhere.

Results

Seismic units

High resolution seismic profiles show a main basin with steep margins and a very flat bottom (Fig. 3.1), as well as a small subbasin in the NE separated by a lava flow. Acoustic penetration of sediments is about 15 m below a water layer of <10 m. Thicker sedimentary sequences in the western areas of the basin delineate an elongated N-S depocenter following the major fault lines (Figs 3.2 and 3.3).

We distinguish four main reflectors (Bt, M1, M2, M3) in Laguna Miscanti sediments that define four acoustic units (Table 2). Three major depositional units constitute the lacustrine fill of Laguna Miscanti Basin. The Lower Seismic Unit, LSU, encompasses the sediments between a bottom unconformity with the Pliocene volcanic and/or alluvial sediments (M3) and an irregular reflector with strong impedance contrast in the pelagic areas (M2) and in the littoral areas (M1). The LSU is characterized by well-stratified reflectors that gently drape the topography of the basin floor. Thickness of the LSU varies from 10 m in the western depocenter to 6 m in the eastern littoral areas, and

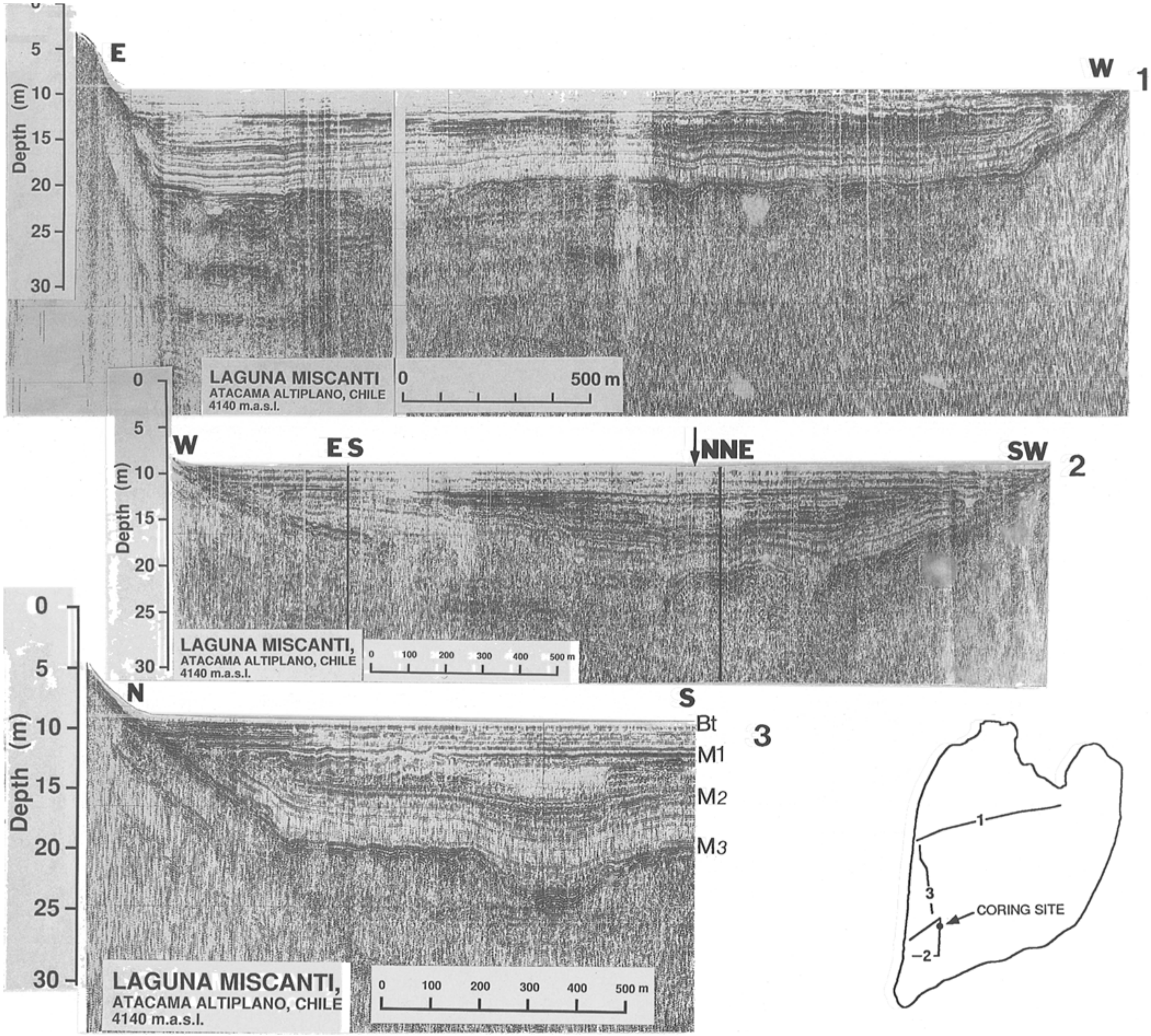

Fig. 3. Representative seismic profiles of Laguna Miscanti recorded at 1/16 sec. sweep, 1–7 Khz, 1/2 sec. shot interval and 100 lines/inch. Location of the profiles and coring site is shown in the inset map. The Livingstone core, indicated by an arrow in seismic profile 2, reached seismic reflector M1.

Table 2. Seismic reflectors and units described in Laguna Miscanti Basin

Reflector	Unit	Thickness	Depth	Description	Interpretation
Bt	Lake bottom		9 m	Continuous reflector throughout the basin with strong contrast with water	Surface sediments with relatively low water and organic matter content. Charophyte meadows in some places.
	Upper Seismic Unit (Bt to M1)	Constant throughout the basin: 2.5 m	9 to 11.5 m	Strong parallel reflectors traceable troughout the basin. Constant thickness	Continuous and relatively constant sedimentation during relatively high lake levels (Late Holocene, 0 to 2.8 Ka)
M1			11.5	Strong, continuous, regular with small amplitude irregularities and hummocky in the littoral areas	Low lake level stand about 3 ka BP : erosive surface developed in the littoral areas, specially in the western shoreline, and indurated aragonite hard-ground in the pelagial zones.
	Middle Seismic Unit (M1 to M2)	Average: 3.4 m; maximum 4.6 m in the western area; the unit slowly thins towards the east.	11.5 to 15 m (average)	Strong, irregular hummocky reflectors, non traceable throughout the basin and truncated at the littoral zones by M1	Variable but generally low lake levels during the Mid Holocene with non continuous sedimentation, and numerous subaerial exposure periods in the littoral zones.
M2			15 m	Strong, traceable throughout the basin	Disconformity and erosive surface in the littoral zones
	Lower Seismic Unit (M2 to M3)	Maximum thickness (western area) = 9.5 m; progressively thins towards the east till about 6.2 m.	15 - 24.5 m	Draped, strong, traceable and parallel reflectors with small hummockies that follow the M3 reflector	High Lake levels with relatively constant sedimentation (Late Glacial to Early Holocene).
M3			21.2 to 25 m	Strong, irregular and hummocky reflector, but traceable throughout the basin. This boundary is characterized by a ringing of the sonic signal indicative of high density contrast between the two sedimentary packages. Faulted in the NE subbasin.	Unconformity that represents the bottom of the lacustrine sequence.
	Below M3	very variable, but greater in the western area and the northeastern subbasin	below 21.2 to 25 m	Very irregular, non traceable but strong reflectors	Subaerial (alluvial, epiclastic) and/or volcanic deposits. Some V-morphologies may correspond to channels (Upper Pleistocene).

Table 3. Sedimentary facies and units described in the 2.91 m long core (Upper and Middle Seismic Units

FACIES	LITHOLOGY and MINERALOGY	COLOR	SEDIMENTARY STRUCTURES and BIOTA	INTERPRETATION
1.- Variegated, banded, charophyte-rich, calcitic diatomaceous muds	High Mg-Calcite (13-40 %); organic matter (3.5%); Siliciclastics (volcanic glass and fragmented diatoms)	Variegated brown, red, greenish, yellow	Laminated, gradual contacts. *Charophyte remains (calcite coated & uncoated).*	Brackish, calcite-producing lake with high *macrophyte productivity*
2.- Gray, banded, O.M. and charophyte-rich calcitic, diatomaceous muds	High Mg-calcite (average 10 %, but very variable), organic matter (13-20 %), siliciclastics (fragmented diatoms, volcanic glass; occasional quartz and lithic fragments)	Brown (10 YR 6/2) to gray (9, 8)	Banded to massive. Intercalated gypsum laminae. Macroscopic charophyte remains. Entire diatoms and occasional ostracods.	Brackish, calcite-producing lake with high organic productivity
3.- Gray calcitic diatomaceous mud	High Mg-Calcite (25%), organic matter (5 %); siliciclastics (opal, clay minerals)	Gray to yellow (5YR 6/4)	Banded to laminated	Brackish, calcite-producing lake with moderate organic productivity
4.- Gray aragonitic diatomaceous mud	Aragonite (< 25 %); organic matter (~ 3%); siliciclastics (fragmented diatoms, occasional quartz,	5 YR 7/1 to 9/1	-massive -laminated with organic matter and gypsum layers intercalated -intercalated up to 1 cm thick aragonite crusts	Saline, aragonite-producing lake with low organic productivity, relatively low lake level
5.- Laminated, variegated, calcitic diatomaceous mud	Mg-calcite (21-25%); organic matter (6-12 %)	Variegated, frequent brown and green.	Finely laminated	Brackish, calcite-producing lake with relatively high organic productivity
6.- Laminated, variegated, aragonitic diatomaceous mud	aragonite (23-27%); organic matter (~ 3%)	Variegated	Finely laminated	Saline, aragonite- producing lake with low organic productivity and absence of bottom disturbances.
7.- Black, laminated organic-rich diatomaceous muds	Carbonate (0-50%); organic matter (7% in aragonite units; 20% calcite units). Occasional dolomite. Alternance of brown to black organic rich layers with gray carbonate and ash layers	Brown to black	Banded, irregular lamination (1-2 cm)	High organic productivity periods related to fresher lake episodes
8.- Banded aragonite and diatomaceous muds	aragonite (18-25%); organic matter (<3%)	Gray and olive	euhedral prismatic aragonite crystals and entire diatoms	Saline, alternating phases of aragonite precipitation and diatom blooms; generally low organic productivity
9.- Gypsum	Few mm - thick laminae with gradual boundaries and composed of a mixture of: i) prismatic, euhedral crystals, and ii) lenticular crystals with numerous carbonate inclusions. Variable gypsum percentage, up to 60 %.	Gray to white	massive	Saline, sulfate-precipitating lake: intrasediment growth (clouded crystals) and water column formation (inclusion-free crystals)
10.- Tephra	Glass shards, lithic fragments (Clay mineral and calcite; microcrystalline quartz). lapilli, mafic minerals. Variable carbonate content (< 25%). Rounded, lens-shaped gypsum crystals (0.5 - 1 mm) and broken diatoms; occasional plant remains	Gray	Banded Inverse and normal grading	Ash fall pyroclastic deposits and epiclastic (reworked) deposits

pinches out to zero in the littoral areas where the LSU is truncated by the M1 reflector. We interpret these features as evidence for pelagial deposition during generally high lake levels. The LSU can be correlated to lacustrine sediments outcropping around the lake, representing the highest lake level stage during the Late Glacial.

The Middle Seismic Unit, MSU, (between reflectors M2 and M1) is characterized by irregular, poorly stratified reflectors with high amplitudes (Figs 3.1 and 3.3), indicating more heterogeneous littoral deposition interpreted as variable, but generally lower lake levels than before. The thickness of the MSU ranges between 3 to 5 m, and the top is also truncated by reflector M1. The strong reflector, M1, is a major unconformity representing an unknown span of time, likely as a desiccation surface.

The Upper Seismic Unit, USU, (between M1 and Bt) is characterized by various well-stratified reflectors, a uniform sediment thickness and an on-lap geometry over the lower seismic units in the littoral areas of the lake. We interpret the USU as deposition during higher lake levels than the previous unit, but lower than during the LSU. Our core penetrated the USU and reached M1, the strong seismic reflector characterized by irregularity and strong impedance contrast. The presence of aragonite crusts and irregular sedimentary contacts in the core sequence confirm the erosive nature of this limit and its interpretation as extremely low lake levels.

Sedimentary facies and geochemistry

Based on sedimentary textures and structures, lithology, mineralogy, color, and organic matter content, 10 subsurface sedimentary facies are distinguished in the cores studied from Laguna Miscanti (Table 3, Figs 2 and 4). The sediments are admixtures of three main components: (i) pyroclastic material (mainly silicic glass with rare lithic fragments, feldspar and quartz grains), (ii) authigenic minerals (magnesian calcite, aragonite, gypsum and traces of dolomite), and (iii) organic matter and bioclasts (carbonate-coated stems, oogonia and uncoated remains of charophytes, Ruppia seeds, diatoms and ostracodes).

Changes in carbonate mineralogy such as observed from the Miscanti core (Figs 5 and 6) track past ionic ratios and lake water salinity assuming the carbonates are primary precipitates (Müller & Wagner, 1978; Last, 1994). Small, prismatic aragonite and lens-shaped calcite crystals in the Miscanti sediments indicate rapid inorganic precipitation. Based mainly on observational data (Müller *et al.*, 1972), the mineral sequence: low-Mg calcite → high-Mg calcite → aragonite → dolomite is interpreted as increasing Mg/Ca ionic ratios in the precipitating solution and, most likely, increasing salinities. A molar Mg/Ca ratio in solution higher than 10 favors aragonite versus high-Mg calcite precipitation (Müller *et al.*, 1972). However, other factors such as alkalinity and sulfate concentration have a major influence on the specific carbonate mineral precipitated, and temperature of the solution plays a major role in controlling Mg content in high-Mg calcite (Müller & Wagner, 1978), but has a negligible effect on aragonite (Oomori *et al.*, 1987).

Gypsum occurs in Laguna Miscanti sediments as microcrystalline laminae and isolated crystals (Figs 7B and 7E). Most of the gypsum crystals in Miscanti contain occluded carbonate that indicates crystal growth within the sediment from interstitial brines. The presence of abraded and rounded gypsum crystals documents littoral reworking. Laminae mostly composed of prismatic, euhedral, star-shaped and lenticular gypsum crystals are likely the result of direct precipitation within the water column (Warren, 1982) or at the air-brine interface (Smoot & Lowenstein, 1991). Similar matrix-free prismatic crystals, 0.01–1 mm long occur in thin, well-sorted laminae 1–10 mm thick in Lake Tyrrell, Australia (Bowler & Teller, 1986) and in Lake Urmia (Kelts & Shahrabi, 1986).

We assume that our acid treatment digested completely the carbonate and sulfate fractions and that contribution from silicates and oxides is minor; therefore, chemical composition of the sediments mainly reflects ions of the carbonate fraction. Chemistry of the Laguna Miscanti sediments is mainly controlled by the carbonate mineralogy (Figs 8 and 9). Aragonite-rich sediments contain more Sr (1000–2000 $\mu g\ g^{-1}$) and generally less Mg (less 1000 $\mu g\ g^{-1}$) than calcite-rich sediments ($<1000\ \mu g\ g^{-1}$ Sr and about 1000 $\mu g\ g^{-1}$ Mg, Fig. 8). Correspondingly, Sr/Ca ratios are considerably higher in the aragonite-rich units. Calcites precipitated in Miscanti is a high magnesium variety (9–19 mol% $MgCO_3$). Mg content and Mg/Ca ratios are thus higher in the calcite-rich units (Fig. 9). Potassium and, more markedly, sodium content gradually decrease up core, suggesting a general trend towards decreasing salinities; however, due to the mobile character of these ions in the system, this trend could be caused by downward leaching in the core. Iron and Mn contents are higher in the calcitic than in the aragonitic sediments, which agrees with the known partitioning coefficient values

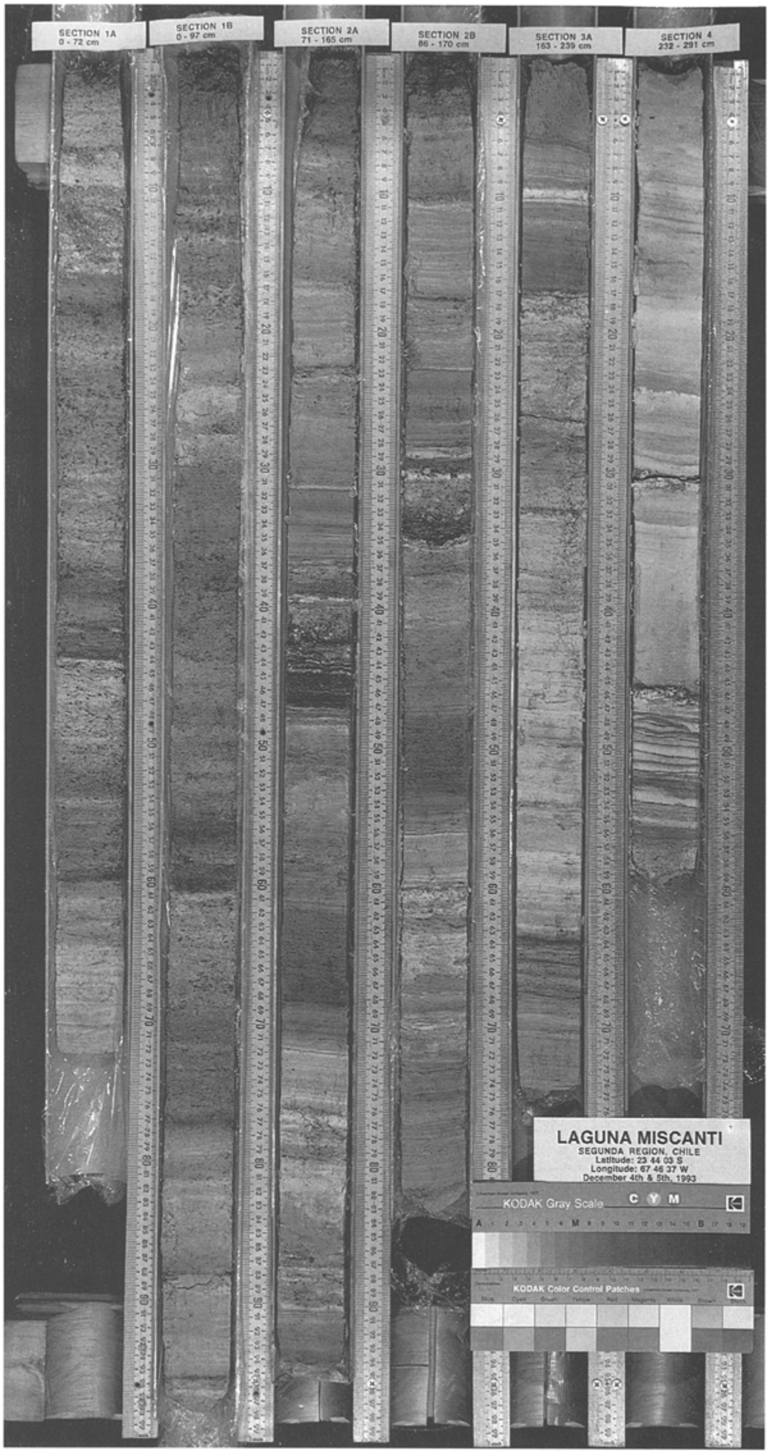

Fig. 4. Photograph of the Miscanti core. Correlation among the retrieved sections allows to reconstruct a 2.9 m continuous sedimentary sequence.

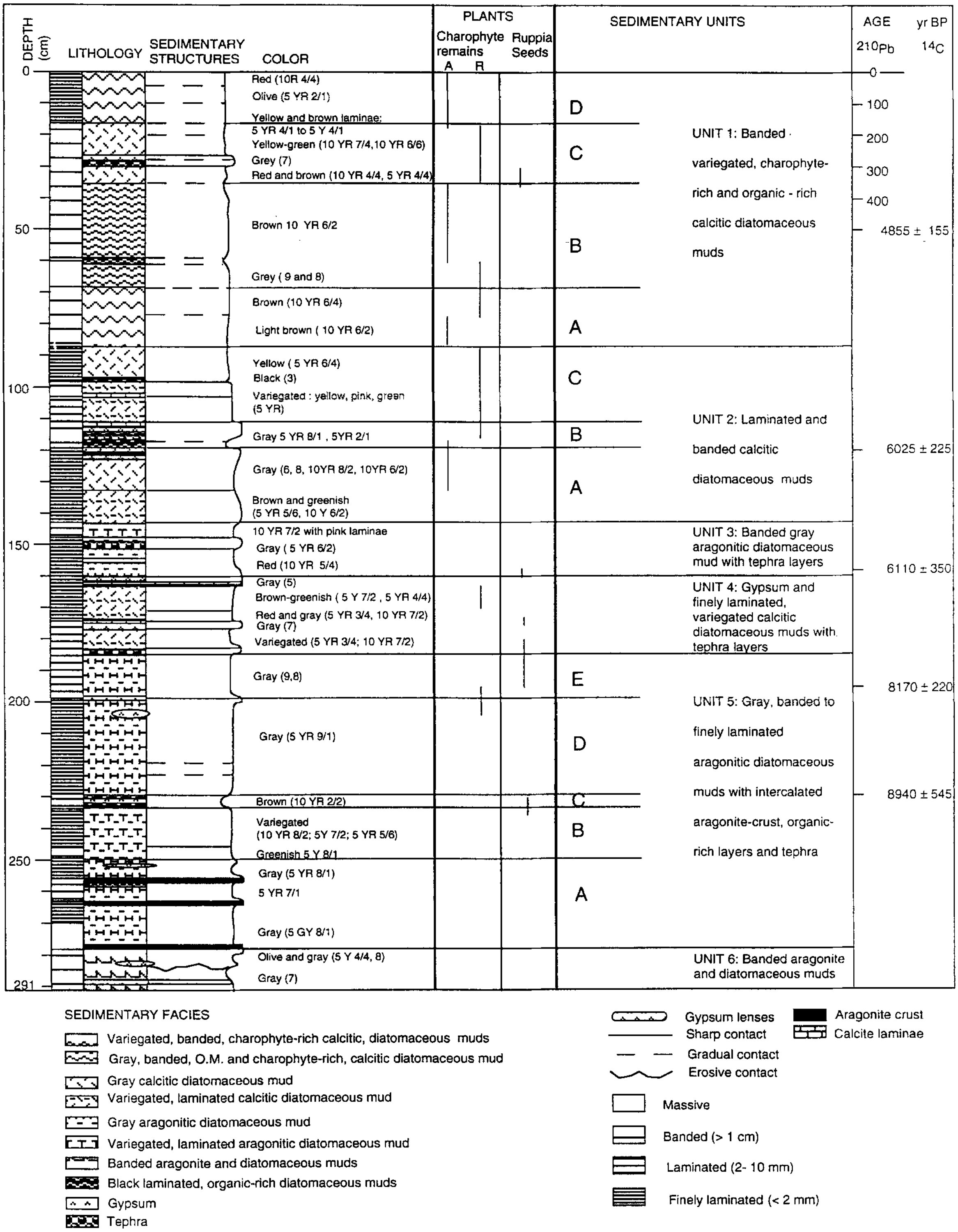

Fig. 5. Sedimentary facies and units defined in the Miscanti core. ^{210}Pb ages for the upper 50 cm are correlated from the short core. ^{14}C dates are uncorrected for reservoir effects.

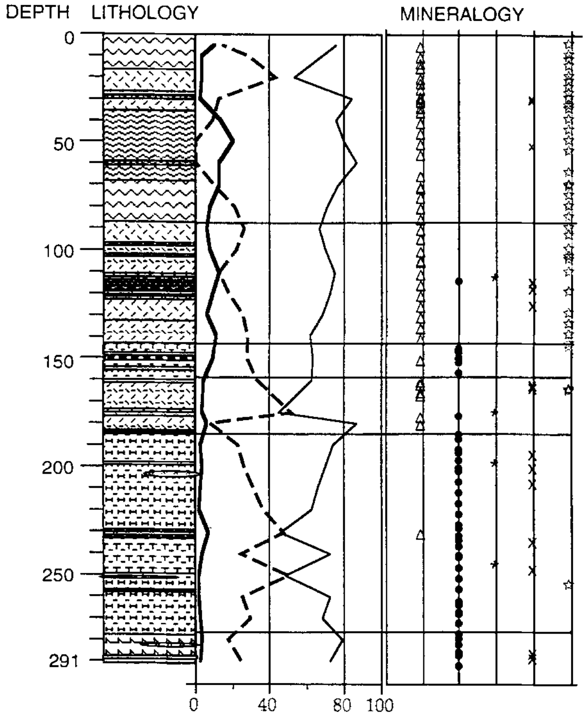

Fig. 6. Mineralogy (XRD), organic matter, carbonate and siliciclastic content of 60 samples from the Miscanti core. Relatively higher organic matter and variable carbonate content characterize units 1 and 2 with calcite as the only carbonate phase, whereas organic content is lower and carbonate content generally higher in unit 5 and 6, where aragonite is the only carbonate. Units 3 and 4 contain both carbonate phases. Legend for lithology as in Fig. 5.

greater than 1 for calcite (preferential enrichment of Mn and Fe in the solid phase; Veizer, 1983) and smaller than 1 for aragonite (Rainswell & Brimblecombe, 1977). Changes in redox potential may also contribute to this trend; in meteoric oxidizing waters, Fe and Mn are oxidized as Fe^{3+} and Mn^{3+} or Mn^{4+}, and the much larger radii of these cations hamper their inclusion in the carbonate lattice. In addition they are less soluble.

Authigenic carbonates, precipitated from the lake water during discrete periods of time, carry a momentary chemical lake water signature. Changes in lake water composition are tracked by changes in the mineral composition of the sediment (gypsum content and aragonite/calcite ratio) and the geochemical ratios (Engstrom & Nelson, 1991; Chivas *et al.*, 1993). Gypsum precipitation marks episodes of high water concentration, and aragonite precipitation occurs during more saline lake episodes with likely lower lake levels than calcite precipitation. Sr contents, Mg/Ca, Sr/Ca, and Na/Ca ratios and mol% Mg in calcite are higher during high salinity phases. High salinity phases characterized by gypsum precipitation correspond with smaller increases in Mg/Ca, and decreases in Sr/Ca and Mg/Ca ratio suggest refreshening of the lake water (Figs 6, 8 and 9). Caution is needed to recognize interstitial gypsum precipitation in previously deposited fresher water sediments.

Sedimentary units

We define 10 sedimentary facies in the Laguna Miscanti cores using lithology, color, grain size, fossil content, mineralogy, and sedimentary structures (Table 3). Each facies is interpreted as a depositional environment in the lake. Based on the presence of these facies, we divided the 2.92 m long core into six sedimentary units (Figs 4, 5 and 7), representing six phases of the lake history.

Unit 6 (292–278 cm depth). This unit is composed of white banded aragonite muds (1 cm thick), olive diatomaceous muds (2–3 mm thick, Facies 8) and intercalated gypsum layers (Facies 9). The white muds consist of 3–5 μm long euhedral aragonite prisms (50–80%) and entire diatoms (20–50%). Diatoms make up the bulk of the olive laminae. Bedding is irregular, with internal erosive surfaces. The two gypsum layers consist of <200 μm long, inclusion-free, very angular crystals and star-shaped aggregates. The top of Unit 6 is a 1.5 cm cracked aragonite crust. Unit 6 belongs to the Middle Seismic Unit (Fig. 3) and is capped by a strong seismic reflector (M1) interpreted as an erosive surface developed during extremely low lake level.

We interpret unit 6 as deposition in an environment dominated by inorganic mineral precipitation due to extremely rapid concentration of the brine in a shallow playa lake. The olive laminae suggest short-term fluctuations with diatom blooms during higher lake levels. The relatively high Mg/Ca and Ba/Ca ratios and the large variability of these ratios support the interpretation of saline but fluctuating conditions. The relatively low Fe and Mn concentrations also suggest low lake levels with oxidizing lake bottom conditions (Figs 8 and 9). We propose a much drier climate than today with extremely high evaporation rates, interrupted by more humid conditions on an annual to decadal scale, and/or possibly single heavy storm events that filled

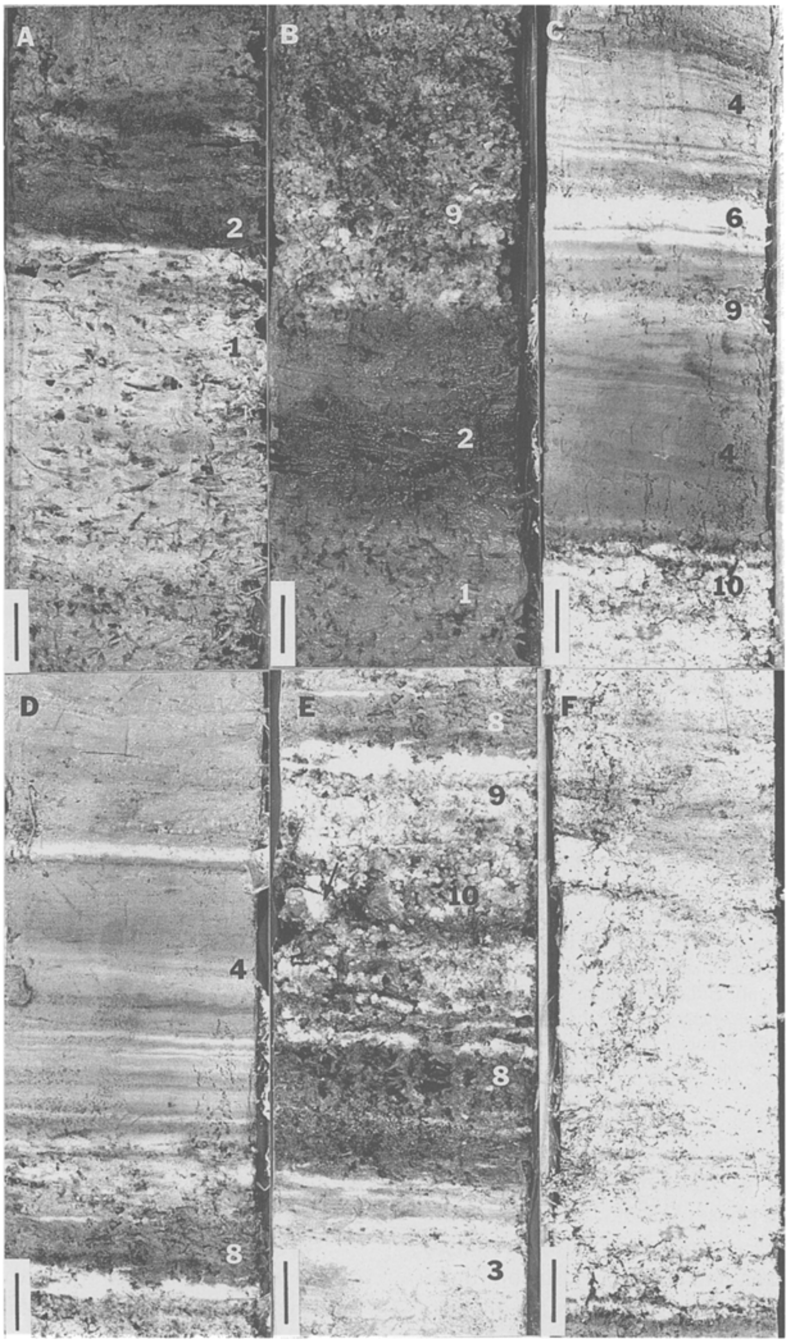

Fig. 7. Sedimentary facies described in the upper calcitic sedimentary units (A, B, D, and E) and in the lower aragonitic sedimentary units from Miscanti core (C and F). A. Variegated, banded, charophyte-rich calcitic, diatomaceous muds (facies 1) and gray, banded, O.M. and charophyte-rich, calcitic diatomaceous muds (facies 2). Section 1A: 39–51 cm (subunit 1B). B. Gypsum – rich layer (facies 9) overlies organic-rich (facies 2) and charophyte rich (facies 1) layers. Section 1A: 10–21 cm (subunit 1C). C. Transitional units: from top to bottom: variegated, laminated, calcitic diatomaceous muds (facies 4, Unit 3), aragonite and dolomite-rich diatomaceous muds (facies 6, Unit 4); gypsum layer (facies 9, Unit 4), variegated, calcitic muds (facies 4, Unit 4), tephra deposit (facies 10, Unit 4). Section 3A: 8–21 cm). D. Black, laminated, calcitic organic-rich diatomaceous muds (facies 8) and gypsum layers (facies 9, subunit 2B) overlain by variegated, laminated, calcitic diatomaceous mud (facies 4, subunit 2C). Section 2A: 29–41 cm. E. Sedimentary facies in Subunit 2B; from top to bottom: black laminated, organic-rich diatomaceous mud (facies 8), gypsum layer (facies 9), coarse tephra deposit (facies 10) with large volcanic clasts (arrow); organic-rich calcitic diatomaceous muds (facies 8) and gray calcitic diatomaceous muds (facies 3, subunit 2A). Section 2A: 38–51 cm. F. Gray aragonitic diatomaceous muds (facies 5) from subunit 5E; section 3A: 19–32 cm. Scale bars = 1 cm.

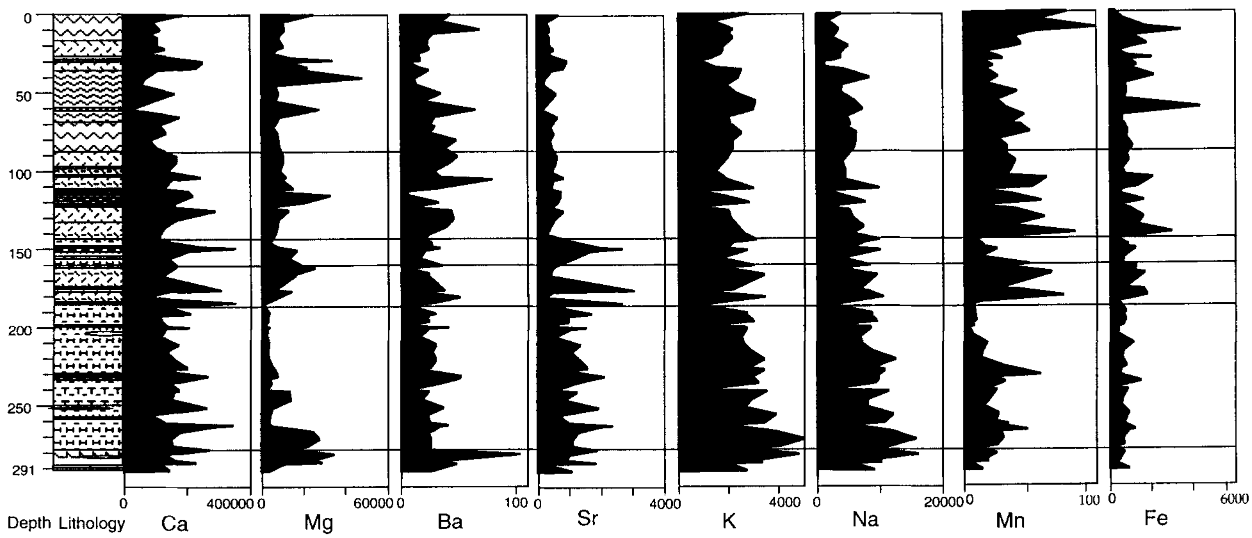

Fig. 8. Chemical composition ($\mu g\ g^{-1}$) of the sediments from Laguna Miscanti.

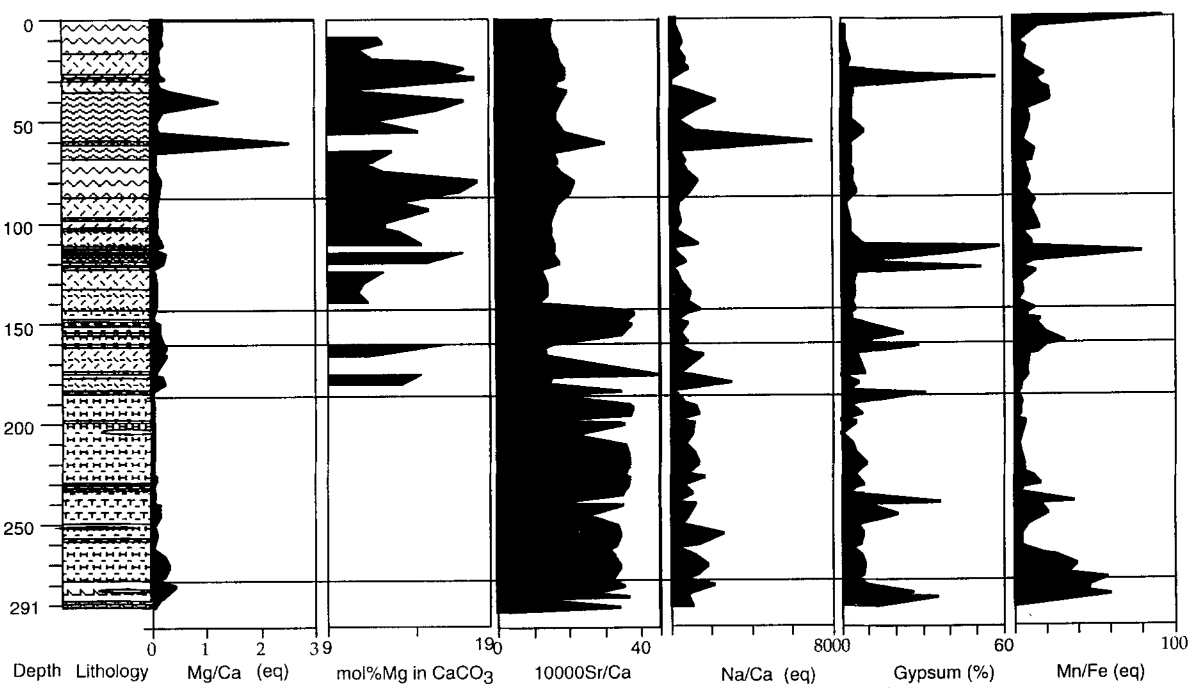

Fig. 9. Chemical ratios and gypsum content of the sediments from Laguna Miscanti.

the lake basin with water for a few months or years.

Unit 5 (278–183 cm). This unit consists of gray, banded to laminated aragonitic diatomaceous muds (Facies 4 and 6), with intercalated aragonite crusts in the lower part, organic-rich layers (Facies 7) and interbedded gypsum and tephra layers (Facies 9 and 10). Unit 5 is divided from bottom to top into the following subunits: 5a (278 - 249 cm): gray massive to banded muds (Facies 4) with two aragonite crusts. Subunit 5a corresponds to the M1 seismic reflector; 5b (249 –233.5 cm): variegated and laminated muds (Facies 5); 5c (233.5–229.5 cm): brown organic-rich laminated muds with occurrence of both, magnesian calcite and aragonite

(Facies 7); 5 d (229.5–198.5 cm): gray laminated muds (Facies 4) with interbedded gypsum layers (Facies 9); 5e (198.5 cm–183 cm): gray banded muds (Facies 4; Fig. 7F).

We consider the aragonite hard grounds (Subunit 5a) as evidence for extremely low lake levels and subaerial conditions. This Subunit corresponds to the strong reflector M1 in the seismic survey (Fig. 3; Table 1). The subsequent aragonite muds (Subunit 5b) are free of hard grounds indicating that the lake never dried out completely after this episode. The low variability and the decreasing trend of Mg/Ca and Ba/Ca ratios suggest a higher buffer capacity due to the larger water volume in the lake. The presence of magnesian calcite and high organic matter content with *Ruppia* seeds at 230 cm (Subunit 5c) indicates a short-term fresher episode. The high Mn concentrations in these sediments could result from an increase of Mn^{2+} in the calcite lattice due to more reducing conditions at the bottom of the lake, although Fe does not show this effect (Figs 8 and 9). Laminae and lenses of gypsum in Subunit 5d indicate highly concentrated brines due to persistently high evaporation rates.

In general we propose for Unit 5a slight increase of effective moisture compared to Unit 6, but still significantly more arid conditions than today. The fluctuations in effective moisture were still large enough to drive the lake system from a playa lake environment to a shallow brackish lake.

Unit 4 (183–160 cm). This unit is characterized by a switch from aragonite to calcite precipitation in the lake. The sediments consist of variegated, finely laminated calcitic diatomaceous muds with charophyte macrorests and *Ruppia* seeds (Facies 3). A feldspar-rich tephra layer (Facies 10) marks the lower limit of Unit 4. At the top, a gypsum layer (Facies 9) indicates the transition from the calcite-precipitating Unit 4 to the aragonite-precipitating Unit 3 (Fig. 7C). The predominance of fine-grained calcite crystals in Unit 4 gives evidence for rapid inorganic precipitation of carbonate. A switchback to aragonite precipitation occurred at 175 cm sediment depth, and – as it happens with similar changes at 160 and 112 cm – is accompanied by a marked drop in organic matter, Fe and Mn contents.

We interpret the changes in the carbonate mineralogy and biota as a significant decrease in lake water salinity which likely correlates with higher lake levels. As expected, the gypsum content is generally very low (Fig. 6). Fe and Mn reach a relative maximum (Figs 8 and 9), suggesting high organic productivity in the lake and reduced oxygen transport into the bottom waters due to limited mixing of the water column in the deeper lake. The switches from calcite to aragonite precipitation are preceded by or synchronous to increased gypsum precipitation. This suggests that the change in the carbonate mineralogy is related to a concentration of the brine and an increase in Mg/Ca ratio as a result of calcium sulfate precipitation during more arid periods.

For Unit 4 we propose a higher lake level and less saline conditions than before due to increased effective moisture in the region. The general climatic conditions were probably close to those of today. However, we infer from the changes in the carbonate mineralogy that there were still major fluctuations in the moisture regime. Because of generally higher lake levels, Laguna Miscanti did not dry out during the most arid periods of this period, but the system oscillated between a calcite and an aragonite precipitating lake.

Unit 3 (159–143 cm). The sediments consist of gray banded (Facies 4) to variegated and laminated aragonitic diatomaceous mud (Facies 6, Fig. 7C). Macrophytes are not present. The decreasing Fe and Mn concentrations (Fig. 8) suggest lower rates of organic matter decay and/or better mixing of oxygen in the waters of a shallower lake. Calcite and aragonite co-occur in a coarse grain layer (150 cm depth) composed of carbonate-coated grains, volcanic fragments and more abundant organic matter. The detrital nature of the layer at 150 cm indicates littoral reworking, and the mineralogical and chemical analogies with Unit 4 point to a short period of less saline conditions.

For Unit 3, we propose a depositional environment similar to that at the end of Unit 5: a shallow saline lake that could have reached gypsum-precipitating stage (155 cm) as a result of a short period of increased aridity or calcite-precipitating stage (150 cm) during short moister periods.

Unit 2 (143–87 cm). Unit 2 represents the onset of magnesium calcite precipitation in the lake. This unit is composed of: (i) alternating decimeter-thick variegated calcitic diatomaceous muds (Facies 5) in the lower part (Subunit 2A); (ii) a black laminated organic-rich and gypsum-bearing layer (123 cm–110 cm, Subunit 2B, Facies 7; Figs 7D and 7E), and (iii) gray calcitic diatomaceous muds (Facies 3) in the upper Subunit 2C (Fig. 7D). Diatoms are usually well preserved, and the gypsum content is very low in these calcitic sediments. The Sr/Ca and Mg/Ca ratios in the calcites are very constant and lower compared to the phases with gypsum co-precipitation (Fig. 9), suggesting brackish (i.e. less saline) conditions with relative stability of the water chemistry over longer periods of time. Subunit 2B represents a relatively higher salinity stage with gypsum and aragonite precipitation.

Unit 1 (87 cm–0 cm). Very abundant macrophyte and charophyte remains and calcite mineralogy characterize this unit. Four subunits are defined from bottom to top: Subunit 1A is composed of variegated, banded charophyte-rich calcitic diatomaceous muds (Facies 1); Subunit 1B encompasses organic-rich calcitic diatomaceous muds (Facies 2 and 7; Fig. 7A); Subunit 1C groups gray calcitic diatomaceous muds (Facies 3) and gypsum layers (Facies 9; Fig. 7B), and Subunit 1D is composed of finely laminated variegated, charophyte-rich calcitic diatomaceous muds (Facies 1). The mineralogical, chemical and biological features define an environment in the lake similar to the present one, slightly less saline than during Unit 2. The high Mn and to some extent Fe contents and the abundance of macrophytes and charophytes indicates higher organic productivity, generally less saline conditions and higher lake levels than before.

Short-term climatic changes might have been buffered by the larger water volume, but lake level and salinity fluctuations occurred. Relatively higher salinities during Unit 1A are suggested by the high mol% Mg in calcite and high Sr/Ca ratios (Fig. 9). Unit 1B is characterized by the highest organic matter content in the core (up to 13%; Fig. 6), giving evidence for a phase with high macrophyte productivity, higher lake level and lower salinity. A low macrophyte productivity and higher salinity period during deposition of Subunit 1C is indicated by low organic carbon content, higher Mg content in calcite and high Sr/Ca ratios. This period of relative high lake levels close to today's and brackish waters was interrupted by a period of significantly higher salinity (30–25 cm interval in the long core and 32–40 cm in the short core, Figs 6 and 2 respectively) with lower organic matter content, precipitation of gypsum and increased Sr/Ca, Mg/Ca ratios. Precipitation of gypsum marked an abrupt transition from brackish to saline conditions correlated with a reduction of the lake volume. Modern conditions inaugurated with deposition of Subunit 1D.

Discussion and regional implications

Based on the analysis of the lake sediments and radiocarbon chronologies using the available ^{210}Pb and hypothesizing that the major environmental changes along the Altiplano are synchronous, we reconstruct a scenario of effective moisture history for the mid and late Holocene in the Laguna Miscanti region (Fig. 10). Low lake levels and extensive aragonite deposition suggest an arid climate with severe droughts during the time of deposition of Unit 6. This decreasing effective moisture trend led to a period of frequent subaerial exposures, erosion of littoral sediments and formation of playa hardgrounds during a period of lake levels about 10 m lower than today. A general increase in effective moisture raised lake level progressively during Unit 5, although climatic fluctuations where frequent and waters remained saline. Eventually, waters became fresh enough to switch from aragonite to calcite precipitation during Unit 4, but this general trend to increased effective moisture was interrupted during Unit 3, representing a relatively short arid period. The modern chemical conditions in Laguna Miscanti depositional system started with the onset of Unit 2 with high Mg-calcite as the only carbonate phase precipitated. Finally, higher lake levels and less saline conditions prevailed during Unit 1, with some short term arid episodes.

Comparison with Altiplano Holocene paleorecords suggests that the major abrupt transitions recorded in the Laguna Miscanti sedimentary sequence are coherent. The sediments of Laguna Miscanti, according to regional chronologies (Grosjean, 1994) and the ^{14}C age of the stromatolites on the highest shoreline ($15\,545 \pm 250$ yr B.P.), span the entire Late Glacial-Holocene period. The seismic reflector M1 represents the most extreme period of low lake levels, with subaerial exposure and erosion. Linearly extrapolated chronologies from the ^{210}Pb dating would project a minimum age of 3000 yr B.P. for this low effective moisture episode, while the conventional ^{14}C dating would suggest an early Holocene (8000–9000 yr B.P., uncorrected dates) maximum age. An early Holocene age for this extremely arid phase is in disagreement with the well documented presence of the humid late-glacial/early Holocene Tauca phase near this area (Nuñez, 1983; Messerli *et al.*, 1993; Grosjean, 1994; Grosjean & Nuñez, 1994). Based on the minimum (^{210}Pb method) and the maximum (conventional ^{14}C dates) constraints, at this stage of our research we pro-

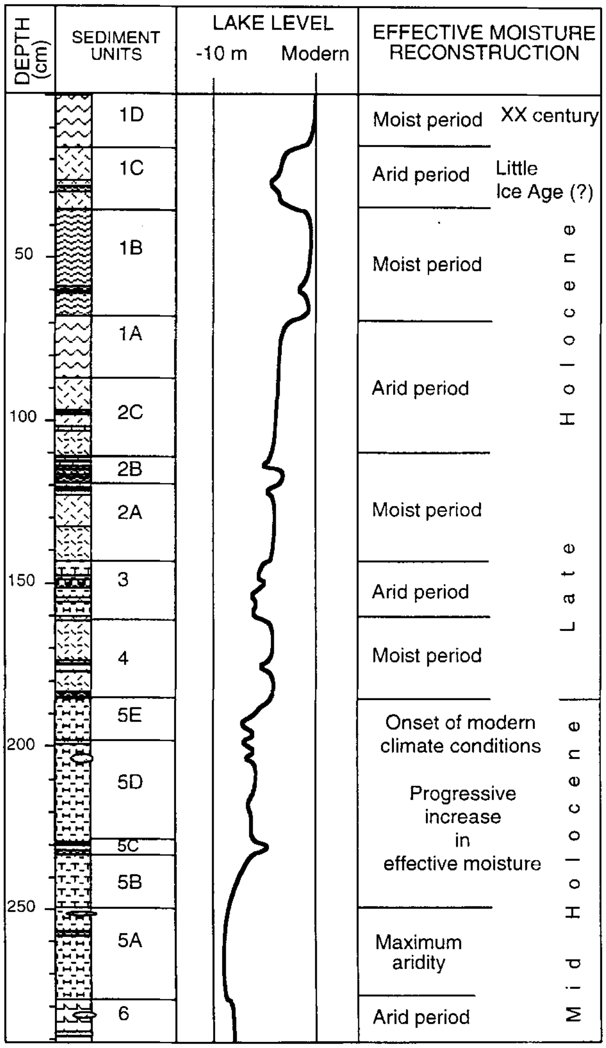

Fig. 10. Summary of the interpreted lake level changes in Laguna Miscanti during the mid and late Holocene and effective moisture reconstruction. Lake level interpretation is qualitative, assuming: (i) a range between – 9 m (subaerial exposure during unit 5A), and 0 m (the modern high lake level) and (ii) a generally increasing trend in lake levels.

pose a mid Holocene range of *c.* 8000 to 4000 years BP for this most arid period.

The conventional ^{14}C age-depth relationship suggests a reservoir effect of up to 3000 to 4000 years. Assuming the same reservoir effect during phases with similar lake levels than today, the progressive increase in lake level (upper part of Unit 5 and Unit 4) would have started at about the end of the mid Holocene (4000 yr BP). We correlate the subsequent increase in effective moisture with the well characterized mid to late Holocene transition in the Central Andes. The rapid mid to late Holocene transition at about 4000 yr BP has been interpreted as a step-over change from warm environments without El Niño episodes to the present cooler background climate interrupted by El Niño every few years (Markgraf *et al.*, 1991; Enfield, 1992). Although the El Niño system may be older (Nicholls, 1989), the increased variability and large moisture increase at subtropical latitudes observed from about 5000 yr BP in the circum-South Pacific areas may indicate when the system kicked in after 18 000 yr BP (McGlone *et al.*, 1992). Markgraf *et al.* (1991) and Villagrán & Varela (1990) compiled evidence for increased frequency of El Niño/Southern Oscillation events that brought moisture to lower latitudes, in particular to Central Chile, during the late Holocene. For Lake Titicaca, drastic lake level rises apparently took place around 3900 yr B.P., and are linked to changes in the El Niño-Southern Oscillation (ENSO) System (Mourguiart *et al.*, 1992; Martin *et al.*, 1993). The effect of the ENSO on the mid to late Holocene transition in the Atacama area is still unconclusive.

The progressive increase in effective moisture in the region was responsible for higher lake levels in Laguna Miscanti and less saline waters that eventually led the system to cross a chemical threshold and become a calcite-producing system. This trend to progressively higher lake levels coincides with the ostracode-inferred record for Lake Titicaca (Mourguiart *et al.*, 1992). This reconstruction indicates that lake Titicaca level did not rise regularly after its lowest level around 7500 yr BP, and that prior to 3900 BP levels were considerably lower than today, and started to rise between 3900 and 3000 yr BP. In Laguna Miscanti, a transition to moister conditions is defined by the onset of a calcite-producing system (Unit 2A) and the higher organic carbon content of Unit 2B. This increase in effective moisture after about 4000 years B.P. is well characterized in the Amazon Basin, and points to a general strengthening of the tropical precipitation belt. It is uncertain how much of the increase in winter precipitation - as observed in coastal central Chile by Villagrán & Varela (1990) – accounted for the increase in the lake level of Laguna Miscanti.

Drier conditions for a few centuries are indicated by the deposition of Subunit 2C and 1A. Due to the uncertainties of our age model for the long core we cannot strictly correlate the two episodes of abrupt water level drop in lake Titicaca dated at 2300 and 1300 yr B.P. (Martin *et al.*, 1993), a dry period at about 1400 yr B.P. in the Quelccaya Ice Cap (Thompson *et al.*, 1984;

Thompson *et al.*, 1992), or the archeological accounts of Andean cultures with our environmental reconstruction for Laguna Miscanti. However there is a clear link between the late Holocene period of increased effective moisture and the human occupation in the area. After the abandonment of the area during the early Holocene, the Miscanti region and the Quebrada Tulan were resettled at about 3400 yr B.P. (Grosjean & Nuñez, 1994; Nuñez, 1994) which would correlate with the increase of the lake level in Laguna Miscanti (Unit 4).

Our 500 year time-series from the Laguna Miscanti short core currently lacks the resolution to decipher decadal variability, however, the time intervals represented by sedimentary subunits can be tentatively correlated with the high resolution record from the Quelccaya ice cap cores (Thompson *et al.*, 1984; Thompson & Mosley-Thompson, 1987, 1989). Precipitation deduced from the thickness of annual ice core layers was higher during the period AD 1500–1750 and extremely reduced afterwards until AD 1860. In the Miscanti short core, according to the ^{210}Pb chronology, these two phases are also present (Fig. 2): the period of increased precipitation as deduced from increased charophyte and macrophyte productivity (Subunit 1B) lasted from about AD 1350–1650; the following drier period (Subunit 1C, AD 1650–1850) ended at about the same time as in the Quelccaya ice core. The relationship of these events with the European Little Ice Age (LIA) is still in debate. The transition from the LIA to the warmer conditions of the current century occurred over a 2–3 year period centered on AD 1880 (Thompson & Mosley-Thompson, 1987) and is one of the most abrupt changes detected in the Quelccaya ice cores. According with the ice cap record, the last 100 years are characterized by reduced wind velocities, increased annual snow fall and increased annual mean temperatures. The termination of the LIA may correspond to the transition from Subunit 1C to 1D, which suggest increased effective moisture and higher macrophyte productivity in the lake.

Concluding remarks

The Laguna Miscanti sedimentary sequence provides a century scale resolution time series of environmental change for the last few millennia in the tropical South American Altiplano. The occurrence of extremely low lake levels during the mid Holocene confirms the regional significance of this dry period documented in other sites of the Altiplano. The end of this lower effective moisture period represented a major change in the regional environmental dynamics and inaugurated modern atmospheric conditions. Since then, effective moisture increased in general but was punctuated by numerous drier periods of various intensity and duration.

Although both the Quelccaya ice cap cores and the lake Titicaca lake level record suggest a general correlation between less effective moisture periods in the Altiplano and El Niño events, it remains unknown, whether changes in atmospheric circulation such as latitudinal shifts of the tropical summer rainfall belts or changes in the frequency of El Niño events were responsible for the changes in the Atacama Altiplano. A transect of high resolution and accurately dated records from the area and more detailed studies of the modern atmospheric conditions in the Altiplano during El Niño events should provide the regional extent of atmospheric circulation changes and the nature of the climatic teleconnections. Clearly, the more detailed paleoecological studies must be interpreted within the context of the highly variable lithological facies types.

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