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A 22,000 ^{14}C year BP sediment and pollen record of climate change from Laguna Miscanti (23°S), northern Chile

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Abstract

Lake sediments and pollen, spores and algae from the high-elevation endorheic Laguna Miscanti (22°45′S, 67°45′W, 4140 m a.s.l., 13.5 km^2 water surface, 10 m deep) in the Atacama Desert of northern Chile provide information about abrupt and high amplitude changes in effective moisture. Although the lack of terrestrial organic macrofossils and the presence of a significant ^{14}C reservoir effect make radiocarbon dating of lake sediments very difficult, we propose the following palaeoenvironmental history. An initial shallow freshwater lake (ca. 22,000 ^{14}C years BP) disappeared during the extremely dry conditions of the Last Glacial Maximum (LGM; 18,000 ^{14}C years BP). That section is devoid of pollen. The late-glacial lake transgression started around 12,000 ^{14}C years BP, peaked in two phases between ca. 11,000 and < 9000 ^{14}C years BP, and terminated around 8000 ^{14}C years BP. Effective moisture increased more than three times compared to modern conditions (~ 200 mm precipitation), and a relatively dense terrestrial vegetation was established. Very shallow hypersaline lacustrine conditions prevailed during the mid-Holocene until ca. 3600 ^{14}C years BP. However, numerous drying and wetting cycles suggest frequent changes in moisture, maybe even individual storms during the mid-Holocene. After several humid spells, modern conditions were reached at ca. 3000 ^{14}C years BP. Comparison between limnogeological data and pollen of terrestrial plants suggest century-scale response lags. Relatively constant concentrations of long-distance transported pollen from lowlands east of the Andes suggest similar atmospheric circulation patterns (mainly tropical summer rainfall) throughout the entire period of time. These findings compare favorably with other regional paleoenvironmental data.

Keywords: Holocene; Pleistocene; lake sediments; pollen; radiocarbon reservoir effect; Andes

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1. Introduction

The Central Andes and the Altiplano have become key regions for the study of late Quaternary

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climate change in South America. These regions are very arid today, but show large-scale and high amplitude moisture changes during late Pleistocene and Holocene. The Altiplano is currently located in the extremely dry transition zone between the tropical summer precipitation belt in the northeast (with Atlantic continental moisture sources), and the extratropical winter rainfall area in the southwest (with Pacific moisture sources). This high mountain desert is thus susceptible to small changes in effective moisture (precipitation minus evaporation) and may provide insight into changes in large-scale atmospheric circulation patterns of the past.

Among the variety of potential paleoclimatic archives in this area (Messerli et al., 1993), tropical ice cores from Bolivia (e.g., Thompson et al., 1998) and the sediments of the numerous endorheic basins with lakes and salt lakes (salars) on the Altiplano are the only archives that provide continuous paleoenvironmental records at a decadal, centennial and millennial-scale resolution back to the last ice age. However, most of the sediment records beneath modern lakes in Chile and Bolivia cover only the Holocene (Valero-Garcés et al., 1996; Abbott et al., 1997; Grosjean et al., 1997b; Mourguiart et al., 1998), whereas paleoclimatic conditions for the lateglacial are inferred from numerous lake sediment outcrops and fossil shore line deposits (Servant and Fontes, 1978; Grosjean, 1994; Grosjean et al., 1995; Servant et al., 1995; Wirrmann and Mourguiart, 1995; Sylvestre et al., 1999). The only lake sediment core spanning to pre-Last Glacial Maximum (LGM) times (TD1 from Lake Titicaca, Mourguiart et al., 1997) shows a hiatus between 18,000 and 14,000 ^{14}C years BP. Thus, the environmental history in the south central Andes since the LGM is drawn from a mosaic of information obtained from different archives and different localities. Consensus exists about a late-glacial/early Holocene paleolake transgression due to an increase in effective moisture by a factor of three compared to modern conditions. Sylvestre et al. (1999) divided the paleolake transgression in SE Bolivia into an earlier phase (Tauca Phase between 16,000 and 12,000 ^{14}C years BP) and a later phase (Coipasa Event between <9500 and 8500 ^{14}C years BP), whereas Geyh et al. (1998, 1999) established for lakes in adjacent Chile a ^{14}C reservoir effect-corrected chronology for lake level changes, placing the two paleolake phases (with a dry interval) between $<13{,}000$ and 8000 ^{14}C years BP. More arid conditions prevailed during the mid-Holocene (between ca. 8000 and 3600 ^{14}C years BP) when many lakes were shallow or disappeared, and the previously deposited sediments were exposed to the atmosphere and eroded (Valero-Garcés et al., 1996; Seltzer et al., 1998). Lake levels increased again in several steps, and modern conditions were finally established ca. 3000 ^{14}C years BP. Information about the conditions during the LGM is controversial (high or low lake levels?), and data on the pre-LGM humid 'Minchin Phase' (between ca. 35,000 and 22,000 ^{14}C years BP, Clapperton, 1993) are uncertain.

Laguna Miscanti and nearby Laguna Miñiques (23°45′S, 67°45′W, 4140 m a.s.l.) are the only relatively deep (10 m), brackish lakes in the arid Atacama Altiplano, and are thus the best candidates for uninterrupted deposition. Here, we present the first continuous lake sediment record from this area spanning the last 22,000 ^{14}C years BP. The sediment record also provides insight into the mechanisms of how environmental conditions changed from one stage to another. We also provide a detailed record of pollen (105 pollen and spore types) and other microfossils from the lake sediments, showing how the limnogeological changes compare with changes in the aquatic and terrestrial vegetation. This allows us to estimate the response lags between the hydrological cycle and vegetation patterns.

2. Methods and materials

A 7.95-m-long sediment core was obtained (October 1995, Livingstone piston corer) from 9.68-m water depth in the deepest part of Laguna Miscanti. The core was opened in the laboratory, photographed, described for lithology, texture, Munsell color, macrofossils and sedimentary structures. Subsamples for microscopic, mineralogical and geochemical analysis were taken every 10 cm (time resolution of ca. 100–200 years) or following major sediment changes. The mineralogical composition was determined using X-ray diffraction (XRD). Magnesium content of the calcite was calculated from XRD measurement of the lattice distances after

Goldsmith and Graf (1958). Following Müller et al. (1972), we interpret the carbonate mineral sequence 'low-Mg calcite' ⇒ 'high-Mg calcite' ⇒ 'aragonite' ⇒ 'dolomite' as increasing ionic Mg/Ca ratios and, most likely, increasing salinity. Sediment subsamples were digested in 0.1 N HCl (1 h at 60°C) in order to extract the authigenic mineral fraction. SO_4 was measured turbidimetrically (Lachat Autoanalyzer). Na and K were determined by flame atomic absorption (FAA; Perkin Elmer Model 306), other cations by inductively coupled argon plasma atomic emission spectrometry (ICP-AES; Thermo Jarrel Ash ICAP 61).

Laboratory preparation of pollen was made using a sample volume of 4 ml. One tablet containing 12,542 ($\pm$3.3%) spores of *Lycopodium* was added to each sample at the beginning of the laboratory treatment in order to determine pollen concentrations (Stockmarr, 1971). Pollen analysis was carried out by Jacqueline F.N. van Leeuwen. Literature used for the identification of pollen types included Graf (1986), Heusser (1971), Hooghiemstra (1984), and Markgraf and D'Antoni (1978).

3. Physiogeographical setting of the site

Laguna Miscanti (23°44′S, 67°46′W, 4140 m a.s.l., Fig. 1) is a relatively large (13.5 km^2) 10-m deep lake with brackish (6.4–6.9 mS cm^{-1}), alkaline (pH 8.0–8.8), Na–(K–Ca–Mg)–SO_4–Cl brine. The catchment area (320 km^2) consists of Miocene to Holocene volcanic rocks (andesite and dacite), and Quaternary alluvial and glacial deposits. Laguna Miscanti is the first lake in a series of three basins along the Quebrada Nacimiento fault (Ramirez and Gardeweg, 1982). Although the basin of Laguna Miscanti is topographically closed, the lake seeps through a lava flow into Laguna Miñiques preventing the brine from reaching high concentrations (Chong Diaz, 1984). Fossil beach terraces, a well-developed delta complex in Laguna Miñiques, and fluvial terraces show that the three basins (Miscanti ⇒ Miñiques ⇒ Pampa Varela) were connected with surface outflow at times of maximum lake levels. Annual precipitation amounts to ca. 200–250 mm, mainly during austral summer (50–90%, 'Invierno Boliviano') with tropical continental moisture sources from the east side of the Andes. Potential evaporation (ca. 2000 mm $year^{-1}$) strongly exceeds precipitation rates. Mean annual air temperatures are estimated to be ~ 2°C. The lake sporadically freezes for several days during austral winter.

4. The lake level chronology

Establishing a radiocarbon chronology for lake level changes on the Altiplano is extremely difficult. Because terrestrial plant macrofossils are hardly found in the harsh environment, aquatic organic fractions (aquatic macrofossils and total organic fraction) and inorganic fractions (marl, carbonate of algal bioherms) are usually used for dating. All of our sites in northern Chile show a ^{14}C reservoir effect, which ranges between 10^3 and 10^4 years depending on the fraction used, and depending on the physical–chemical status of the lake (Geyh et al., 1998).

Terrestrial plant macrofossils were not found in the Laguna Miscanti core. The radiocarbon dates for bulk carbonates, total organic fractions, aquatic macrophytes (*Chara*, *Myriophyllum*, cf. *Ruppia*), and *Ruppia* seeds are compiled in Table 1. All of these fractions are potentially subject to reservoir corrections. The ^{14}C value of dissolved inorganic carbon compounds (DIC) in littoral waters of Laguna Miscanti is 82.5 ± 2.9 pM C (corresponding to 1550 $\pm$ 270 ^{14}C years BP), and living *Ruppia* dated at 1230 ± 250 ^{14}C years BP. The application of the bomb correction for the year of sampling (1993) results in a reservoir correction between -2200 and -2500 years for littoral fractions. Extrapolation of the uppermost ^{14}C data for benthic fractions (e.g., Characeae., 10-m water depth) suggests a reservoir correction of ca. -4000 years for deep water. This is consistent with the finding by Geyh et al. (1999) that reservoir corrections strongly depend on water depth and lake level changes. Sedimentological data are thus indispensable and help to estimate the reservoir correction in the past.

At the current state of research, we are not able to justify in detail the ^{14}C reservoir corrections for the late-glacial and Holocene Laguna Miscanti, because terrestrial plant macrofossils were not yet found. The

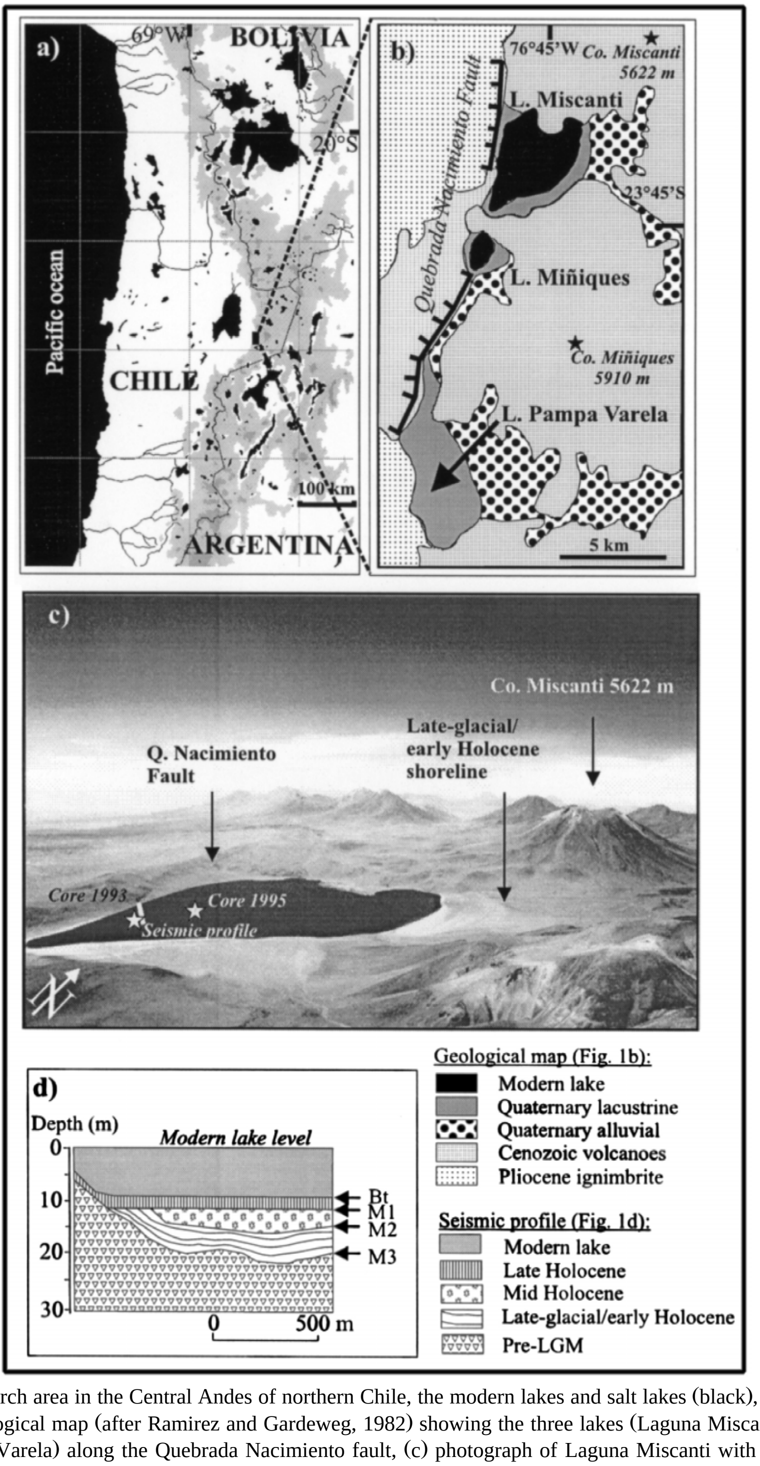

Fig. 1. (a) Shows the research area in the Central Andes of northern Chile, the modern lakes and salt lakes (black), and the areas above 4000 m a.s.l. (shaded), (b) geological map (after Ramirez and Gardeweg, 1982) showing the three lakes (Laguna Miscanti, Laguna Miñiques and paleolake Laguna Pampa Varela) along the Quebrada Nacimiento fault, (c) photograph of Laguna Miscanti with the coring site 1995, and (d) schematic seismic profile (after Valero-Garcés et al., 1996).

Table 1
Radiocarbon dates for total dissolved inorganic carbon compounds in the lake water TDIC, bulk carbonates, total organic fractions, aquatic macrophytes (*Chara*, *Myriophyllum*, cf. *Ruppia*), and *Ruppia* seeds from Laguna Miscanti

Lab. code	Sample ID	Location	Sediment depth (cm)	Material	^{14}C years BP	$\pm 1\sigma$	δ^{13}C
Hv-21635	938A	western shore	0	Live *Ruppia*	1230	250	−11.9
Hv-21636	938	western shore	0	TDIC	1550	270	0.8
Hv-19799	M50	core 1993	49–51	Aquatic plant macrofossil	4855	155	−11.3
Hv-19800	M119	core 1993	118–120	Aquatic plant macrofossil	6025	225	−12.4
Hv-19801	M159	core 1993	157–159	Aquatic plant macrofossil	6110	350	−9.3
Hv-19802	M195	core 1993	194–196	Aquatic plant macrofossil	8170	220	−9.8
Hv-19803	M277	core 1993	276–278	Total organic fraction	8940	545	−8.3
Beta-93202[a]	MIS-3	core 1995	53–55	*Ruppia* seeds	4970	60	−7.6
Beta-93203[a]	MIS-3	core 1995	203–205	*Ruppia* seeds	7470	60	−6.9
Beta-93204[a]	MIS-3	core 1995	276–278	Total organic fraction	8010	50	−14
Hv-21629	MIS-3	core 1995	285–287	Carbonate	8250	230	1.6
Beta-93205[a]	MIS-3	core 1995	515–517	Aquatic plant macrofossil	18,430	80	−7.3
Hv-21630	MIS-3	core 1995	521–523	Carbonate	18,010	360	6.4
Hv-21631	MIS-3	core 1995	604–606	Carbonate	11,705	310	−1.4
Beta-93207[a]	MIS-3	core 1995	664–666	Total organic fraction	22,540	100	−12
B-7220	1030C	Maximum lake level	Delta N	Carbonate	14,530	50	−3.3
Hv-19701	750	Maximum lake level	Shore S	Carbonate (algal bioherm)	15,545	250	6.4

[a] AMS dates.

first comprehensive reservoir-corrected radiocarbon chronology of regional lake level changes has recently been established for nearby Laguna Lejía 15 km north of Laguna Miscanti (Geyh et al., 1999). The mid- and late-Holocene reservoir corrections of Laguna Miscanti are discussed in Valero-Garcés et al. (1996). Because (i) the late-glacial/early Holocene lake history of Laguna Miscanti features in detail the characteristics of the lake evolution in Laguna Lejía (Grosjean, 1994; Geyh et al., 1999) and thus implies broad synchroneity, and (ii) rodent midden studies with reservoir effect-free ^{14}C dates support our reservoir-corrected lake level history and paleoclimatic evolution (Betancourt et al., 2000), we use the regional paleoclimatic history and the reservoir-corrected Laguna Lejía chronology as a strong comparative argument for the Miscanti chronology presented here and conclude the following.

The reservoir effect is likely minimal in the basal sediment section with shallow lake, because atmospheric admixtures to the carbon pool in the lake were likely dominant. Thus, we conclude that the beginning of the core reaches back to pre-LGM (around 22,000 ^{14}C years BP). The carbonate sample at 604 cm is interpreted as a maximum ^{14}C age with an unknown reservoir effect, and confirms earlier findings by Geyh et al. (1998) that the lake levels started to increase not before 12,000 ^{14}C years BP. The subsequent ^{14}C age inversion has also been observed in the nearby Laguna Lejía (Geyh et al., 1999) and suggests that, as expected, the reservoir correction increases with a rising lake level (for discussion, see Section 5). The reservoir-corrected ^{14}C chronology (synthesis, Fig. 2) suggests that the dry event (end of lake II and pollen zone 2) separating both paleolake phases was placed around 10,000 ^{14}C years BP, and that the lake transgression came to an end around 8000 ^{14}C years BP. The reservoir correction was likely small (around 1000 years) during the subsequent phase with a shallow lake, and increased gradually with increasing lake levels until modern conditions were established between ca. 3800 and 3000 ^{14}C years BP. It is worth noting that the different fractions used for ^{14}C dating yielded similar ages in Laguna Miscanti whereas in nearby Laguna Lejía, the ^{14}C ages for inorganic fractions were systematically higher than the ^{14}C ages of the organic fractions.

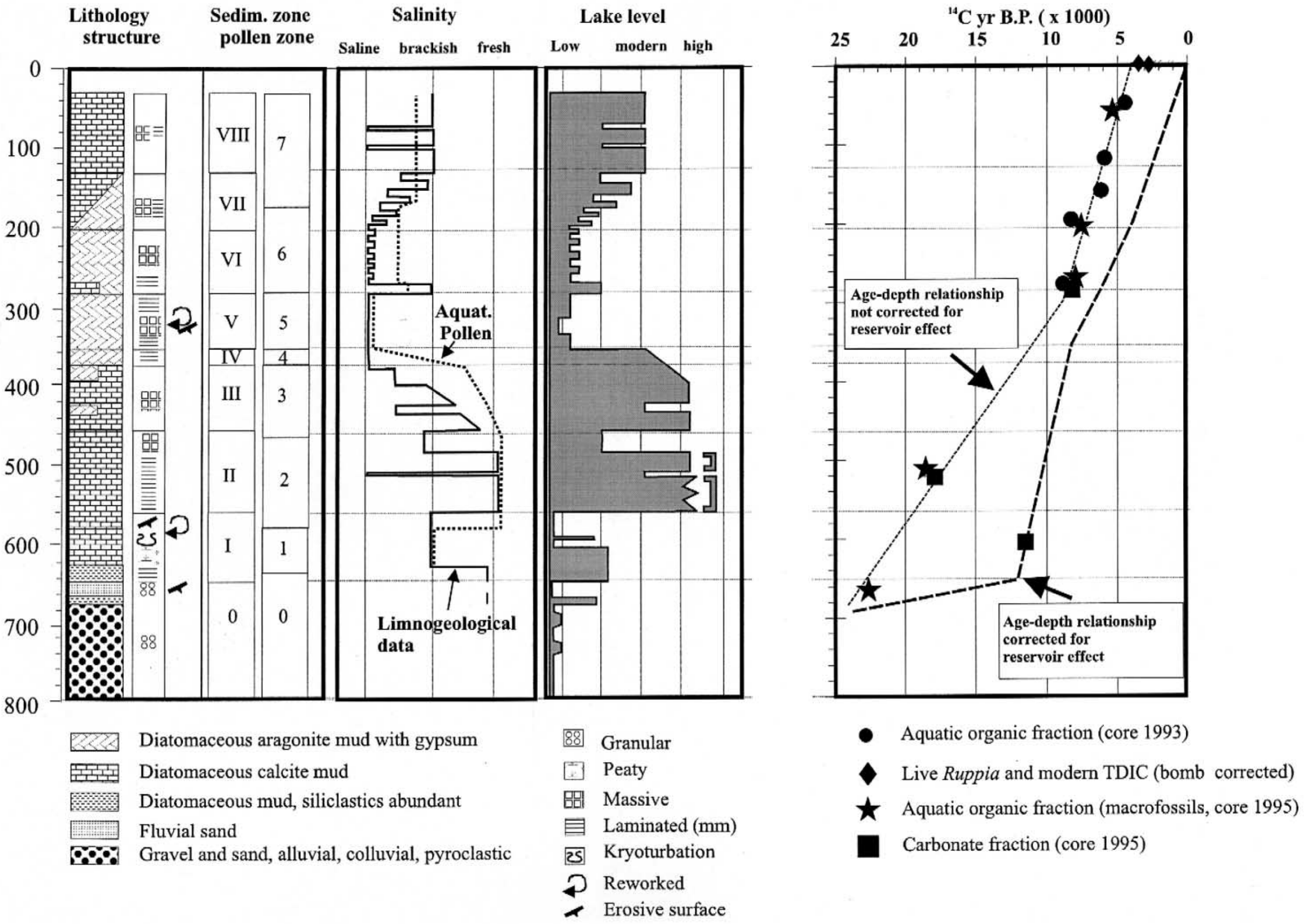

Fig. 2. Lithology, sediment and pollen zones, estimated salinity (inferred from aquatic pollen and limnogeological data), estimated lake levels, conventional and ^{14}C reservoir-corrected chronologies for Laguna Miscanti. The reservoir-corrected age–depth relationship is based on (1) measurements and estimates of the reservoir effect for modern and Holocene times, (2) on the reservoir-corrected lake level chronology of nearby Laguna Lejía (Geyh et al. 1999), and (3) on the regional palaoenvironmental history, which includes reservoir effect-free ^{14}C dates on terrestrial macrofossils and compares favorably with rodent midden studies (Betancourt, 1999, personal communication).

5. Results and discussion

5.1. Limnogeology

5.1.1. Zone 0: 7.95–6.46 m

The sediments of the lowermost zone (7.95–6.73 m, Fig. 3) consist mainly of alluvial pyroclastic coarse gravel and sand. Fe and Al oxide coatings suggest numerous drying and wetting cycles with fluctuating groundwater tables in a generally terrestrial environment, or in a littoral environment with episodic flooding by a very shallow lake. Towards the end of this zone (6.73–6.63 m), an initial shallow freshwater lake developed as suggested by banded (1 cm) to discontinuously laminated diatomaceous silt and decomposed organic aquatic macrofossils (C_{org}, 2–3.5%). Soluble ions (e.g., K, Na, B, SO_4) increase. However, the initial lake transgression was interrupted by a poorly sorted dark gray to black sand layer (6.63–6.46 m) with few gravel-size clasts. The seismic survey (Valero-Garcés et al., 1996, see also Fig. 1) suggests that this is the oldest lake transgression in this basin (reflector M3).

5.1.2. Zone I: 6.46–5.59 m

Zone I is characterized by the change to magnesian calcite precipitation (<5 mol% Mg in $CaCO_3$). Diatoms and aquatic macrophytes are abundant. Carbonate coatings of Characeae (?) are found in the lower section. High concentrations of decomposed plant macrofossils (C_{org}, 3.5–5.5%) in the upper section give the diatomaceous mud a peaty texture. While the Sr/Ca ratio is similar to modern conditions, the Mg/Ca and Ba/Ca ratios are significantly higher than today, suggesting salinity around modern levels, but higher water temperatures, probably due to still lower lake levels than today with better heating of the small water body, and not necessarily due to a higher air temperature. Measurements in different Altiplano lakes show that modern water temperatures are poorly correlated with air temperatures. Inwash of siliciclastic components remain high. A gypsum lens (at 6.00 m) and reworked granular calcite clasts (5.90–8.59 m) suggest fluctuating lake levels with short-term highly saline and very shallow conditions, beach erosion and maybe cryoturbation.

5.1.3. Zone II: 5.59–4.53 m

Subsequently, a ∼30-m deep, freshwater lake was established. Stratigraphic correlation shows that the lake level reached the prominent beach terraces and the level of overflow into Laguna Miñiques. In the center of the lake, banded (0.5–1 cm) to laminated (1–3 mm) green to greenish brown and brown diatomaceous calcite mud was deposited in a low-energy environment (sediment depth between 5.59 and 4.81 m). Gypsum is found in traces or is absent, plant macrofossils are very scarce. Sulfate, sodium, and boron levels are low. Calcite contains less than 5 mol% Mg, and Mg/Ca, Sr/Ca, Ba/Ca ratios are minimal, suggesting the freshest conditions of the entire paleolake history. This phase was likely the period with maximum lake levels up to 20 m above the current lake level, surface overflow to Laguna Miñiques and Pampa Varela, and an increase of the total water surface (all three lakes) from modern 15.3 to 38.2 km^2. This freshwater phase was interrupted (5.20–5.13 m) and terminated (4.81–4.53) by conditions with increasing salinity and lower lake levels, siliciclastic inwash and gypsum precipitation.

5.1.4. Zone III: 4.53–3.75 m

The sediments between 4.53 and 3.75 m consist of massive, fine-grained, light green carbonate mud, intercalated with gray gypsum-rich layers. Organic carbon is very low, macrophyte fossils were not found in the core. Inwash of siliciclastic silt continues, suggesting that water contributions from surface runoff still played a role. Magnesian calcite (5–10 mol% Mg in $CaCO_3$) remains the dominant carbonate phase. However, episodically (at 4.30 m) and in the top section of Zone III (between 3.90 and 3.75 m), co-precipitation with high amounts of aragonite was found, suggesting markedly increased salinity. Traces of aragonite are found in the entire Zone III. Gray gypsum-rich laminae and bands (1 mm–1.5 cm) are widespread. Interestingly, those layers with high amounts of aragonite and gypsum (e.g., 3.90 m) are free of siliciclastics, suggesting that high salinity was due to strong evaporation in a shrinking water body, at a time when surface runoff ceased.

The steady increase of most components (SO_4, B, K, Na, Mg, Sr) suggests continuous concentration of the brine due to evaporation in the endorheic lake system (still at high levels), maybe towards the end combined with a drop in lake level. In addition, increasing Mg/Ca and Sr/Ca ratios suggest increasing salinity, although variable but small admixtures

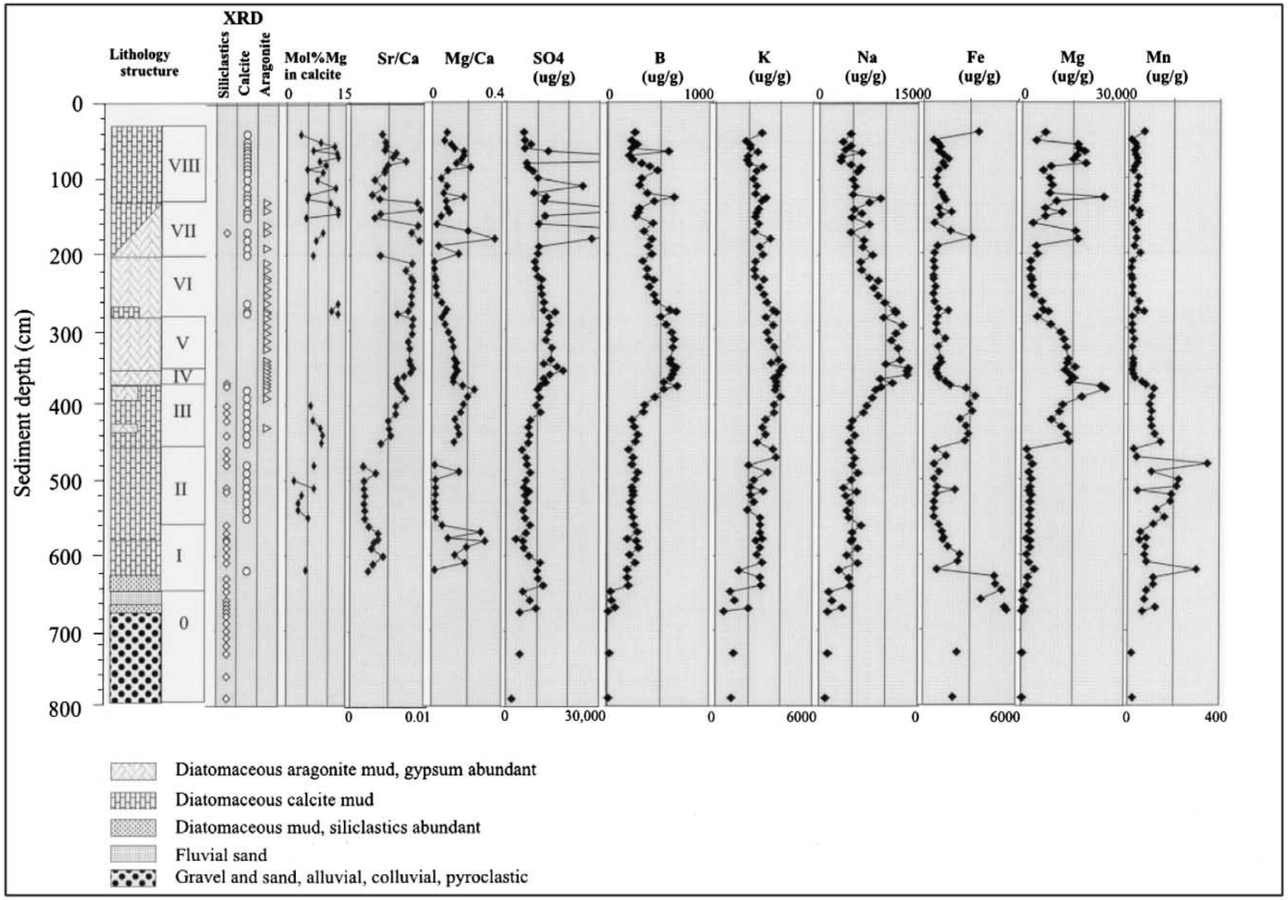

Fig. 3. Sedimentary zones, selected mineralogical composition and concentrations of chemical compounds in the sediments of Laguna Miscanti.

of aragonite (Sr partitioning is higher in aragonite than in calcite) limits the interpretation. XRD analysis shows traces of ankerite (which is consistent with high Fe concentrations of the HCl-soluble fraction), suggesting at least partly anoxic conditions in the deepest part of the lake, and thus still very high lake levels.

The surface overflow to Laguna Miñiques was probably no longer active during most of the time. This is in line with the geochemical data, which suggest remarkable stability and/or slowly, but steadily increasing trends. However, the century-scale sampling interval (10 cm) does not account for the marked decadal-scale (?) variability as suggested by the numerous well-defined centimeter-size grayish gypsum-rich layers observed by eye and in thin sections. These layers may reflect fluctuations of the lake level around the threshold of overflow, turning the lake back and forth from an open to a closed system.

5.1.5. Zone IV: 3.75–3.55 m

This zone is marked by the switch from calcite to aragonite precipitation, suggesting increasing salinity. This is consistent with the presence of gypsum and dolomite in the basal layer, although dolomitization may be a post-sedimentary effect. The diatomaceous aragonite mud consists of green and pink, millimeter-scale laminae and gray bands. Siliciclastic detrital grains disappear, which we interpret as the termination of surface runoff. The lake became exclusively groundwater-fed, and started to behave like an endorheic system with very limited subsurface seepage along the Quebrada Nacimiento fault into Laguna Miñiques. SO_4, Na and B concentrations reach the absolute maximum. So do Sr and the Sr/Ca ratio, the Mg concentration remains very high.

5.1.6. Zone V: 3.55–2.80 m

Aragonite, with traces of dolomite, is the dominant carbonate phase. Silicate debris is absent, and sulfate concentration is very high, suggesting highly saline conditions in a groundwater-fed lake, fast turn-over rates and shallow water depth. The light to medium gray massive aragonite mud is intercalated with red, green, pink and brown millimeter-size laminae except in the section between 3.44 and 3.13 m, where laminae are absent. Organic carbon is minimal ($< 3\%$) and macrophyte fossils are absent. K, Na, B, Mg, Mg/Ca and Sr/Ca remain at maximum levels.

We interpret these sediments as deposits in a very shallow, hypersaline lake with low organic productivity and reworking of littoral sediments. Sub-aerial exposure of the sediments as it is observed in the 1993 core (Valero-Garcés et al., 1996) was not likely in the deepest part of the lake at the 1995 site, because crusts and hard-pans were not found in this core (Fig. 1).

5.1.7. Zone VI: 2.80–2.04 m

The beginning is marked by a short interval (2.80–2.68 m) of high magnesian calcite (> 10 mol% Mg in $CaCO_3$) and aragonite co-precipitation, macrophyte growth and higher organic productivity in the lake. The light to dark brown calcite–aragonite mud is finely laminated and contains *Ruppia* seeds. We interpret these sediments as deposits during a multi-decadal period of increased effective moisture when a moderately saline and deeper lake was established. Subsequently, the lake switched back to deposition of massive gray aragonite, very low organic carbon contents and absence of plant macrofossils between 2.68 and 2.04 m. Pink, gray and brown laminae are found at 2.56, 2.52–2.49, 2.30–2.26, and 2.16–2.14 m.

5.1.8. Zone VII: 2.04–1.32 m

Zone VII shows the transition from the very shallow saline lake to the modern lake. The sediments consist of five cycles, each of them beginning with a basal freshwater facies (laminated to massive diatomaceous calcite with many plant macrofossils) followed by a more saline facies (calcite and aragonite co-precipitation, sometimes gypsum, few or missing plant macrofossils). The cycles and rapidly changing (decadal scale) environments are best seen in the changing sedimentary facies at the centimeter-scale, but also reflected in the high geochemical variability of the sediments (lattice space of calcite, Mg/Ca, Sr/Ca, SO_4), while the B concentration steadily decreases. The cycles suggest that the modern lake was established due to several individual moisture pulses back and forth, and not in a steady linear process.

(a)

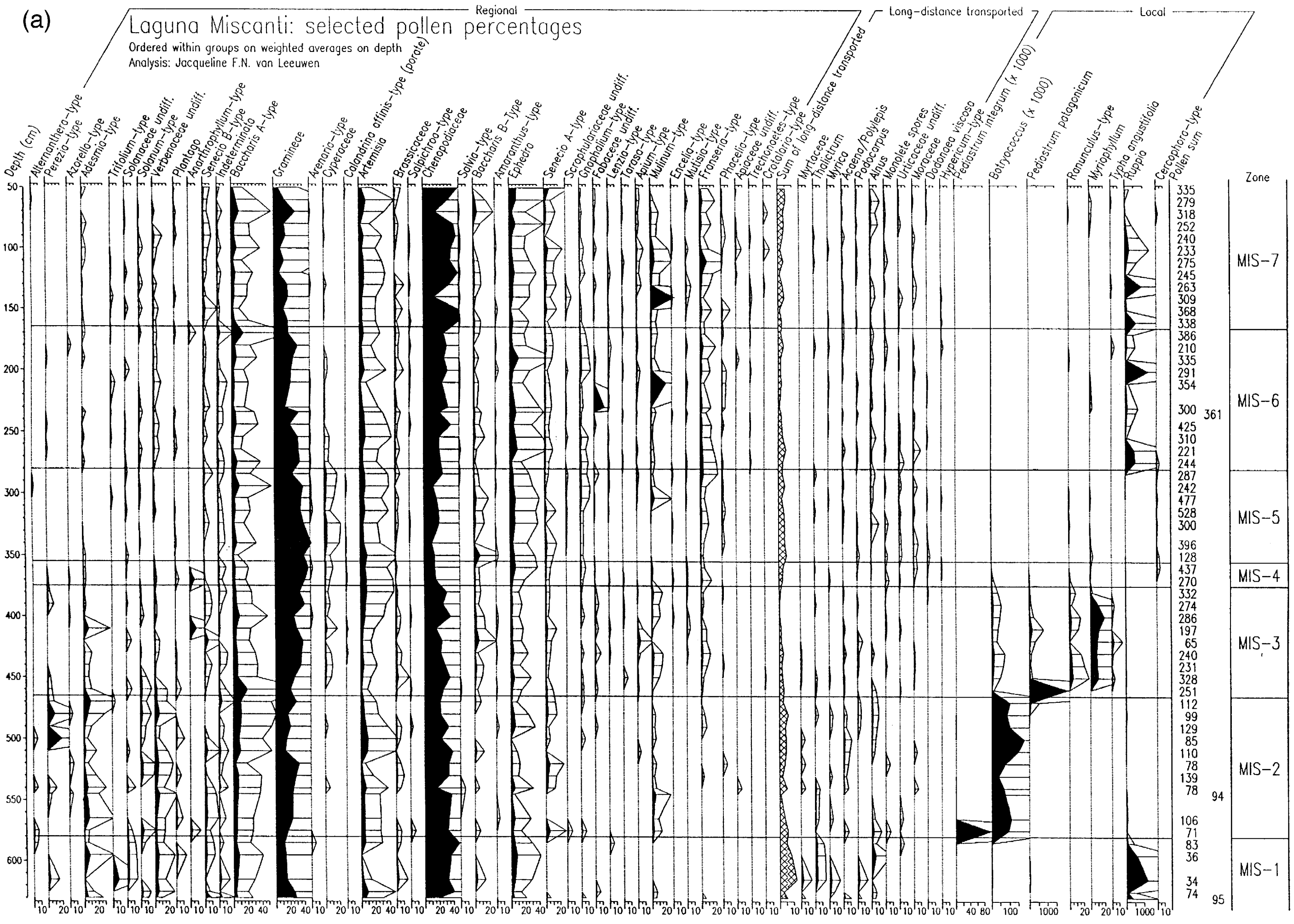

Fig. 4. (a and b) Continuation: terrestrial regional and long-distance transported pollen and aquatic pollen and spores in the sediments of Laguna Miscanti.

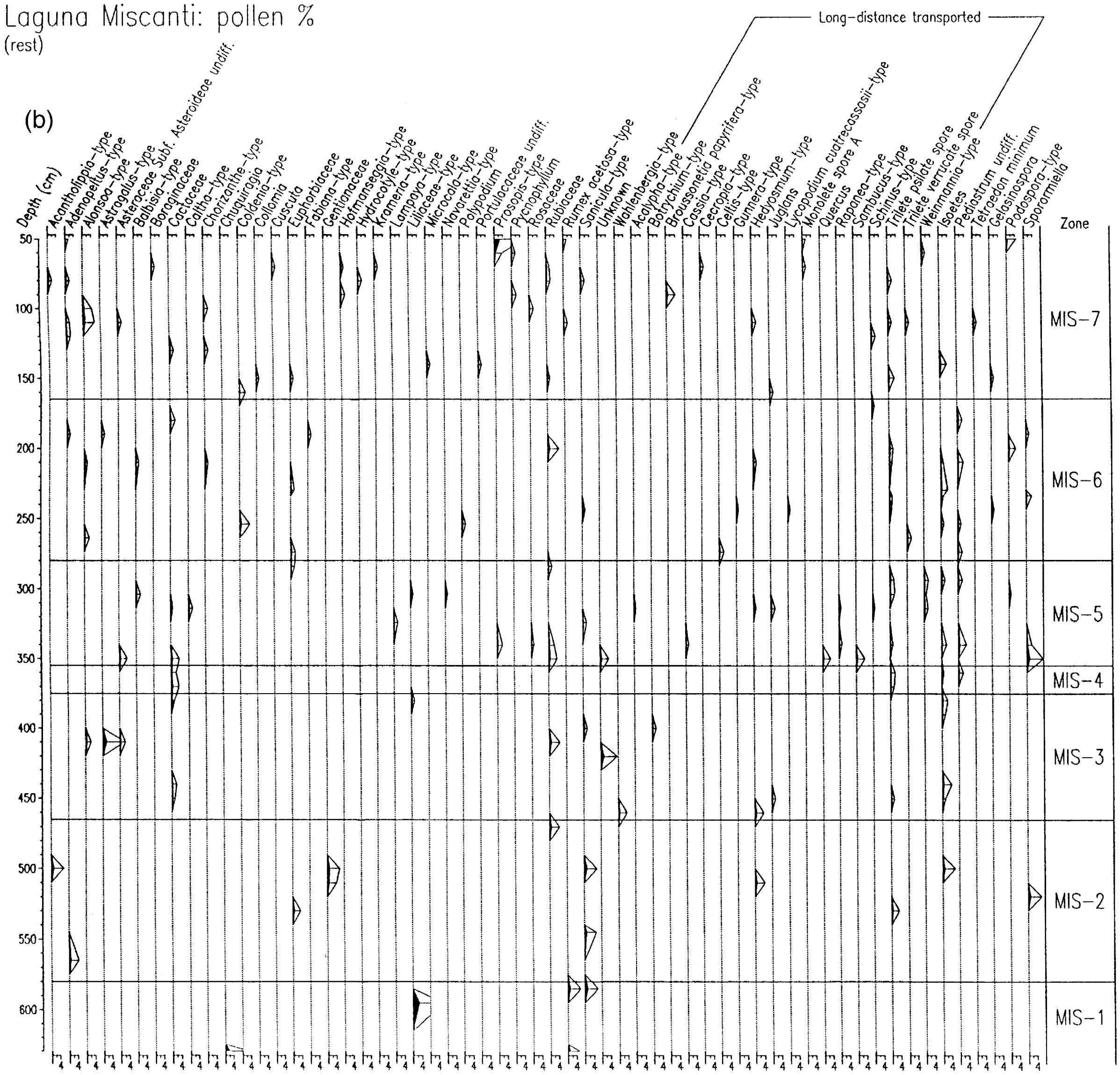

Fig. 4 (*continued*).

5.1.9. *Zone VIII: 1.32–modern*

Zone VIII shows the characteristics of the modern 10-m deep lake with sedimentation of light gray and brown laminated or massive diatomaceous calcite mud, low and high magnesian calcite precipitation (3–12 mol% Mg), variable but generally relatively high organic carbon concentration (1.5–10% C_{org}) and macrophyte fossils (Characeae fragments sometimes coated with calcite, and *Ruppia* seeds). However, gypsum precipitation and high B concentration at 1.00 and at 0.75 m suggest short-term decreasing lake levels and higher concentrations of the brine. The dry interval between 0.20 and 0.30 m (Valero-Garcés et al., 1996) is not shown in this core.

The uppermost 2.80 m of this core display the main features of our 1993 core (mid- and late-Holocene sediments, Valero-Garcés et al., 1996), showing that the sediments are representative for larger parts of the basin.

In summary, the siliciclastic sediments of zone 0 (between 7.95 and 6.46 m) belong to the prelacustrine terrestrial phase below seismic reflector M3 (Fig. 1). The sediments of Zones I–III (between 6.46 and 3.75 m) feature the characteristics of the late-glacial/early Holocene paleolake transgression with maximum lake levels (sediments between the seismic reflectors M3 and M2). As found in Laguna Lejía (Grosjean, 1994) and in southern Bolivia (Sylvestre et al., 1999), the paleolake transgression is divided into two phases interrupted by a dry event. Mid-Holocene aridity is evidenced in the shallow saline lake-saline pan sediments of Zones V and VI (between 3.75 and 2.04 m), when the lake level was ca. 10–11 m lower than today, and the paleolake sediments were truncated in the littoral zone (sediments between M2 and M1). After a transition period with several moisture pulses (Zone VII), modern conditions were established during late-Holocene times (Zone VIII, sediments between M1 and Bt).

5.2. Pollen stratigraphy

The pollen diagram of Laguna Miscanti (Fig. 4a and b) allows the reconstruction of aquatic and terrestrial vegetation of the past. The aquatic vegetation (both macrophytes and algae) provides information about salinity and relative water depth. According to Ybert (1992), who studied several lakes in the Titicaca area, *Ruppia* is dominant in brackish water, *Myriophyllum* is dominant in water 0.4–4 m deep, *Pediastrum* in water 4–10 m deep, and *Botryococcus* in water > 10 m deep. Past vegetation near the lake is reconstructed mainly based on pollen concentrations (Fig. 5). The pollen-climate model for the Atacama region by Graf (1992) remains debatable and is, in some cases, contradictory for the pollen assemblage in Laguna Miscanti. We divided the core in eight zones according to major changes in the pollen assemblage.

5.2.1. Pollen zone 0: (7.95–6.30 m)

The sediments are devoid of pollen, suggesting an environment not suitable for pollen preservation (oxidation) and/or too dry and cold for aquatic and terrestrial vegetation.

5.2.2. Pollen zone 1: (6.30–5.80 m)

Abundance of *Ruppia* suggests brackish conditions. Low pollen concentrations of high Andean plants indicate little terrestrial vegetation near the lake, consisting mainly of small shrubs (*Adesmia*-type, Verbenaceae undiff.), few herbs and Gramineae. The high proportion of long-distance transported pollen from the east side of the Andes suggests low pollen production in the surroundings and thus low effective moisture. Interestingly, the aquatic vegetation record compares at centennial scale with the lake history inferred from limnogeological data (cf. at 5.90 m, *Ruppia* disappears when the limnogeological data suggest subaerial exposure).

5.2.3. Pollen zone 2: (5.80–4.65 m)

The short phase of *Pediastrum integrum* followed by *Botryococcus* and the virtual absence of aquatic macrophytes suggest rapidly increasing water depths to more than 10 m deep (after Ybert, 1992). The local terrestrial vegetation remained scarce, however, slightly increasing with time. Concentrations of long-distance pollen from the east side of the Andes remain close to modern values suggesting that the atmospheric circulation pattern did not change fundamentally. This strengthens the view of intensified tropical summer precipitation (‘Invierno Boliviano’) during that time (Markgraf, 1993; Grosjean et al., 1995; Clayton and Clapperton, 1997; Betancourt et al., 2000). The vegetation change lags with about 10 cm (century-scale) behind the lake level increase as found in the limnogeological data. The pollen record does not show the abrupt drop of the lake level at around 4.80-m sediment depth.

5.2.4. Pollen zone 3: (4.65–3.75 cm)

The short phase of *P. patagonicum* followed by the aquatic macrophytes *Myriophyllum* and *Ranuculus*-type suggest a drop in the lake level from maximum levels (shallower than ~ 10 m). The composition of the aquatic vegetation still hints to fresh water conditions. Abruptly increasing overall pollen concentrations suggest rather well-developed terrestrial vegetation and thus relatively high effective

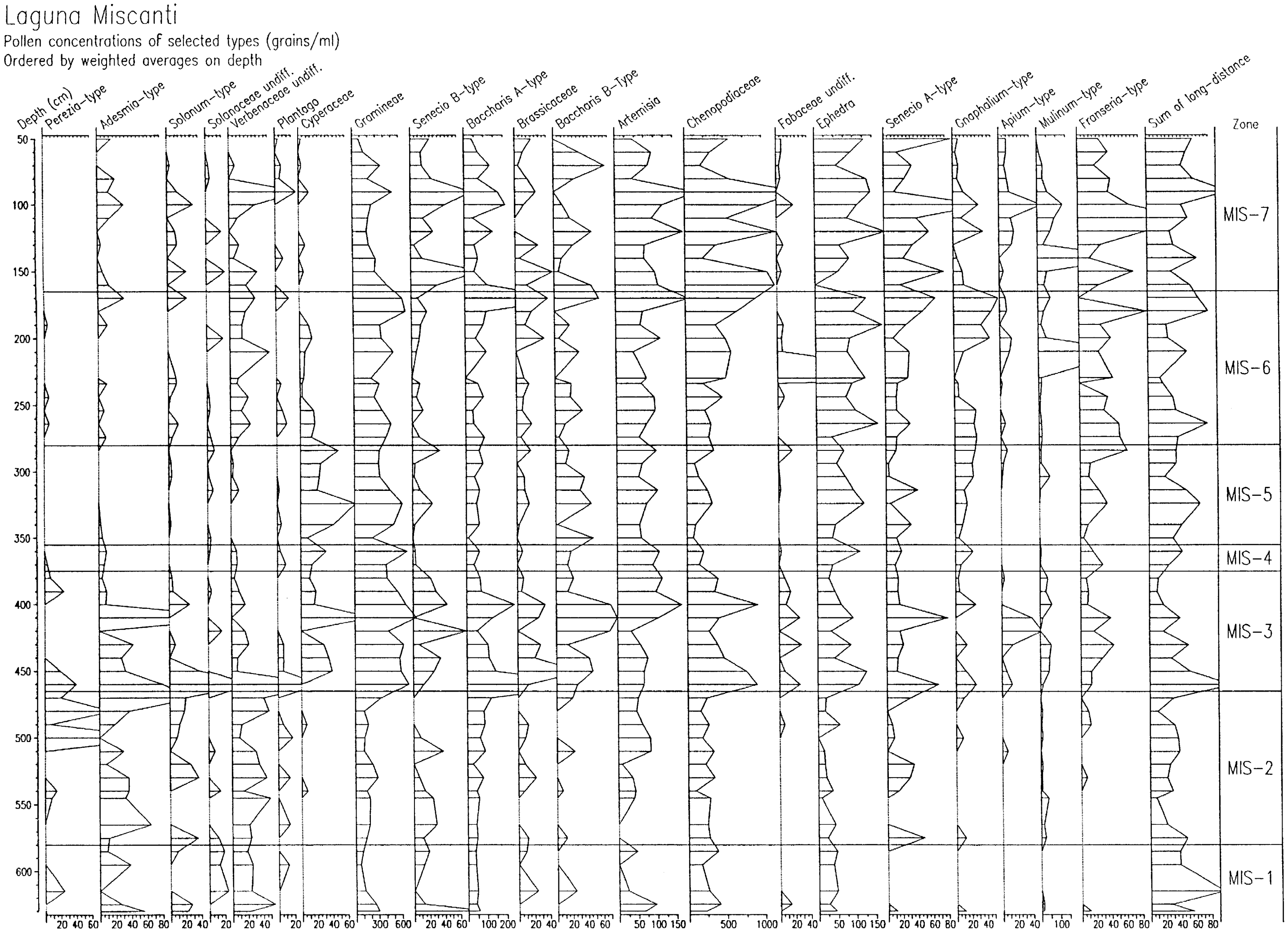

Fig. 5. Pollen concentrations (selected types) in the sediments of Laguna Miscanti.

moisture. Gramineae dominated locally, accompanied by various small shrubs and herbs (*Senecio* A-type, *Senecio* B-type, *Baccharis* A-type, *Baccharis* B-type, Brassicaceae, Fabaceae undiff.). A shore vegetation was also developed (Cyperaceae, *Apium*-type). Abundant Chenopodiaceae pollen arrived likely from lower elevation (below ca. 3500 m a.s.l.) where they are abundant today.

5.2.5. Pollen zone 4: (3.75–3.55 m)

In this transitional period, aquatic vegetation disappeared gradually suggesting that the lake level and effective moisture decreased markedly. This feature agrees with the conclusions inferred from the limnogeological data.

5.2.6. Pollen zone 5: (3.55–2.80 m)

The virtual absence of aquatic vegetation suggests that the lake was very shallow or even periodically dry at the coring location. Cyperaceae hint to patches of wetlands and mires, probably at the bottom of the lake. Pollen concentrations suggest that the local vegetation remained well developed and rich in Gramineae, but Chenopodiaceae from lower elevation declined markedly. Coprophilous fungal spores (*Cercophora*-type) indicate that grazers (mainly wild camelids), attracted by the few remaining mires, concentrated near the lake only during this period. We suggest that this was the only site with available water resources in a fully arid and hostile environment. The reservoir-corrected chronology (see Section 4) suggests an age between ca. 8000 and 6000 ^{14}C years BP for this zone, which is clearly earlier than the beginning of camelid domestication after 4800 ^{14}C years BP (Hesse, 1982).

5.2.7. Pollen zone 6: (2.80–1.65 m)

Abundant *Ruppia* and the absence of *Botryococcus* and *Pediastrum* suggest saline conditions in the lake. Cyperaceae in littoral wetlands decrease and were likely flooded by the rising lake level. Gramineae-rich vegetation near the lake remained well developed. Increasing Chenopodiaceae suggest that vegetation at lower elevation recovered gradually and became rather well developed towards the end of this period.

5.2.8. Pollen zone 7 (1.65–0.50 m)

The pollen assemblage reflects the onset of modern conditions with a brackish lake (*Ruppia*) and a relatively well-developed terrestrial vegetation with local Gramineae and Chenopodiaceae from lower elevations. This compares favorably with the limnogeological data.

Interestingly, some of the changes in the sediments and in the pollen assemblages are out of phase by ca. 10 cm (corresponding to ~200 years). During the initial lake phase (late-glacial times, zone 1), the terrestrial vegetation lags significantly behind the increasing lake level. We consider cold temperature and/or migration lags or other effects as possible explanations. Aquatic plants, on the other hand, respond very sensitively to abrupt high amplitude decadal-scale changes in the water budget of the lake (e.g., at 5.30, 4.30 and 2.80 m), whereas terrestrial vegetation does not seem to show such short-term oscillations. During environmental changes with overall lower rates of change (although the internal structure of the change may be complex) such as the onset of modern conditions, the limnogeological and land vegetation changes seem to be broadly in phase. However, many questions (e.g., water storage in the catchment) remain open.

6. Paleoclimatic discussion and conclusion

Sediments and pollen from Laguna Miscanti confirm the picture of regional late Pleistocene and Holocene environmental changes drawn from a broad variety of paleoclimatic archives and sites.

At the millennial scale, the paleoenvironmental conclusions from the limnogeological data compare favorably with those obtained from terrestrial and aquatic pollen. However, there are phase lags (in both directions) at the centennial time scale, which we attribute to different sensitivities in the bio–geo–hydrosphere, to storage and buffer processes in the catchment and maybe also migration lags of terrestrial plants. Whereas several paleoclimatic studies emphasized the potential of inorganic sediment components (geochemistry, mineralogy, depositional environment) in the Atacama Desert, the potential of pollen has been largely underestimated so far. We demonstrate that 105 different pollen and spore types may be distinguished. The environmental interpretation, however, remains to be developed for many of them. Quantitative studies of recent pollen (pollen-environment transfer-functions) are needed.

Based on the limnogeological data, the assemblages of aquatic and terrestrial pollen, and on the ^{14}C reservoir-corrected chronology, we propose the following late Pleistocene/Holocene paleoenvironmental reconstruction.

Although sediments in other lake basins on the Altiplano and the Sajama ice core recorded an extended pre-LGM wet–cold period with paleolake transgressions (Minchin Phase, between ca. 35,000 and 23,000 ^{14}C years BP, Clapperton, 1993; Mourguiart et al., 1997; Thompson et al., 1998), Minchin sediments are missing in the Miscanti basin. The reason is not known.

In Laguna Miscanti, conditions were relatively dry with extremely low sedimentation rates, or even with a depositional hiatus during the LGM. This compares favorably with the low lake level found in the Titicaca area (TD1 core, Mourguiart et al., 1997). In addition, the Sajama ice data suggest maximum desiccation of the lakes in Bolivia around 21,000 cal years BP (18,000 ^{14}C years BP, Thompson et al., 1998).

The Miscanti data add to the picture that the paleolake transgression in the Chilean part of the Central Andes did not start prior to 13,000 or 12,000 ^{14}C years BP. In addition, the Sajama ice data suggest that soluble and insoluble aerosol concentrations decreased significantly after 14,000 cal years BP (after ca. 12,000 ^{14}C years BP), suggesting that open water covered the previously exposed salt flats. The chronological discrepancy with the SE Bolivian paleolake history established by Sylvestre et al. (1999), (for discussion, see Geyh et al., 1999) remains unresolved for the moment. Interestingly, the Miscanti sediments show the dry event with a short-term decreasing lake level around 10,000 ^{14}C years BP. It is suggested that this was a regional event (Sylvestre et al., 1999) and not a local phenomenon as previously thought in Laguna Lejía (Grosjean, 1994). Long-distance transport of pollen from the east side of the Andes support earlier results (Markgraf, 1993; Grosjean et al., 1995; Clayton and Clapperton, 1997; Betancourt et al., 2000) that strengthened tropical summer precipitation with continental (and ultimately Atlantic) moisture sources was the reason for the increase in effective moisture on the Altiplano during latest late-glacial and early Holocene times (between ca. 12,000 and 8000 ^{14}C years BP).

Laguna Miscanti shows also the characteristic features for the extremely arid mid-Holocene climate (between ca. 8000 and 3600 ^{14}C years BP). As it was found in other Altiplano lakes (Grosjean et al., 1997b) and alluvial deposits (Grosjean et al., 1997a), the dry conditions were interrupted by short-lived, abrupt moisture changes (decadal to centennial scale?) or even individual storms (daily scale), leaving distinct wetting and drying cycles in the sediments. However, it is worth noting that the small water body of the shallow mid-Holocene lake responded very speedily to small climatic changes, whereas comparable climate fluctuations were likely buffered and masked in the much larger water body of the late-glacial/early Holocene paleolake.

The mid-Holocene coprophilous fungal spores suggest concentration of herbivores (Camelids) around the lake. As it is observed in nearby archaeological sites (Grosjean et al., 1997b), the mid-Holocene arid conditions resulted in the generation of pronounced ecological refuges with a high concentration of animals and people around particular sites where resources were still locally available, whereas the overall regional population and animal density was very low.

Our Miscanti core confirms earlier findings by Valero-Garcés et al. (1996) in the same lake showing that the onset of modern climatic conditions was a non-linear process with several steps back and forth, involving more than five individual moisture pulses over several centuries.

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