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Recent environmental changes in Laguna Mar Chiquita (central Argentina): a sedimentary model for a highly variable saline lake

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ABSTRACT

Laguna Mar Chiquita, a highly variable closed saline lake located in the Pampean plains of central Argentina, is presently the largest saline lake in South America (≈ 6000 km^2). Recent variations in its hydrological budget have produced dry and wet intervals that resulted in distinctive lake level fluctuations. Results of a multiproxy study of a set of sedimentary cores indicate that the system has clearly recorded these hydrological variations from the end of the Little Ice Age (≈ AD 1770) to the present. Sedimentological and geochemical data combined with a robust chronology based on ^{210}Pb profiles and historical data provide the framework for a sedimentary model of a lacustrine basin with highly variable water depth and salinity. Lake level drops and concurrent increases in salinity promoted the development of gypsum–calcite–halite layers and a marked decrease in primary productivity. The deposits of these dry stages are evaporite-bearing sediments with a low organic matter content. Conversely, highstands are recorded as diatomaceous organic matter-rich muds. Average bulk sediment accumulation rose from 0·22 g cm^{-2} year^{-1} in lowstands to 0·32 g cm^{-2} year^{-1} during highstands. These results show that Laguna Mar Chiquita is a good sensor of high- and low-frequency changes in the recent hydrological budget and, therefore, document climatic changes at middle latitudes in south-eastern South America. Dry conditions were mostly dominant until the last quarter of the twentieth century, when a humid interval without precedent during the last 240 years of the lake's recorded history started. Thus, it is an ideal system to model sedimentary and geochemical response to environmental changes in a saline lacustrine basin.

Keywords Central Argentina, Pb-210 chronology, recent climatic variability, saline lake sediments, sedimentation rates.

INTRODUCTION

Lakes interact with all components of the hydrological system: atmospheric water, surface water and groundwater (Winter, 1995). Endoreic regions, where water loss is almost entirely the result of evapotranspiration, are especially sensitive to changes in the hydrological balance, which are, in turn, the result of climatic fluctuations (Bradley, 1999). Closed lake basins are particularly suitable systems for palaeolimnological studies, because they are very sensitive to fluctuations in the precipitation–evaporation balance (P-E). These fluctuations in the hydrological cycle are reflected through variations in water levels, the chemistry and biology of the water column

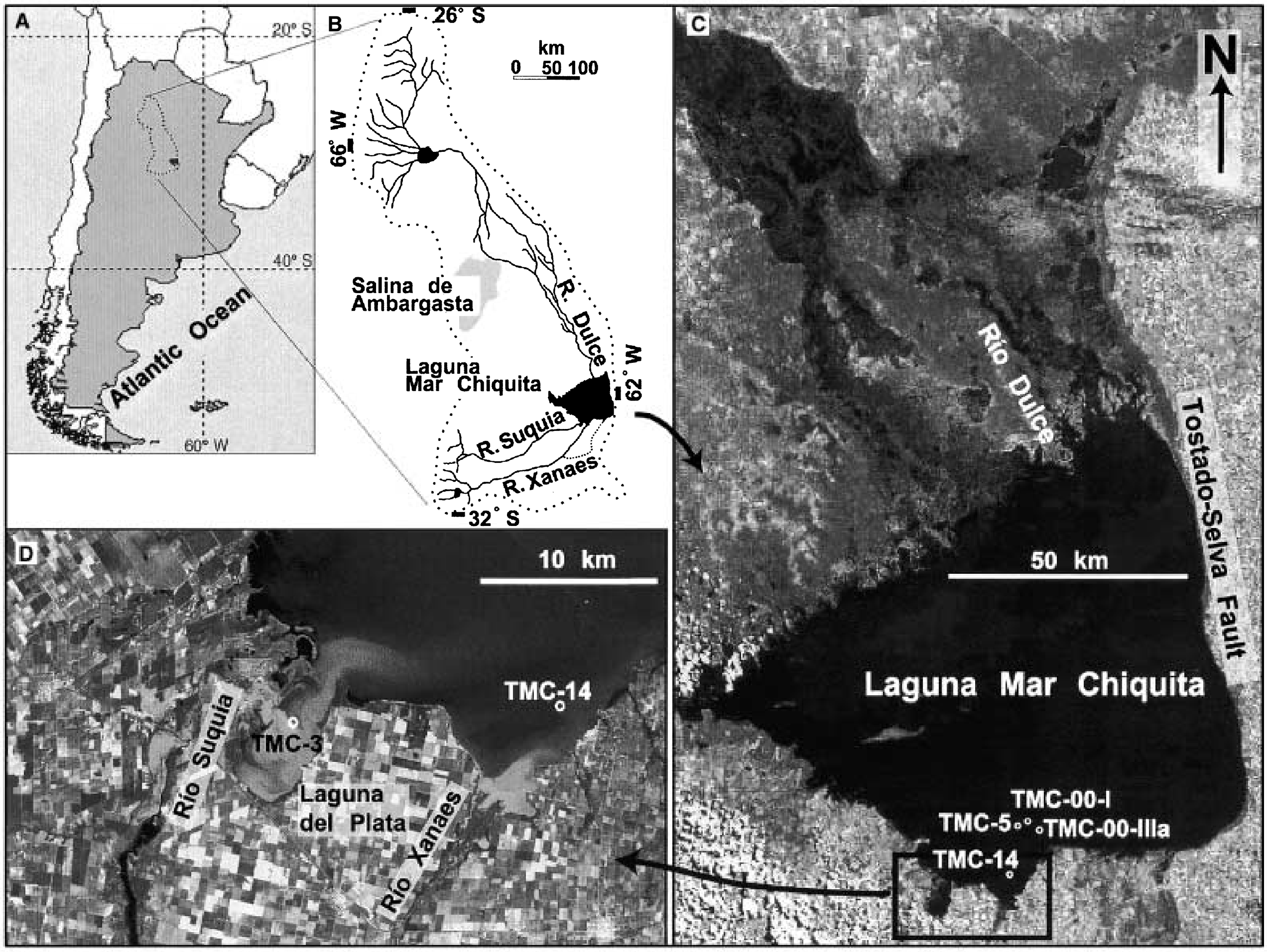

Fig. 1. (A) Map of Argentina showing the location of Laguna Mar Chiquita and its catchment area. (B) Detail of the drainage basin covering ≈ 37 500 km^2. (C) Satellite image of the lake in March 2001 with core locations. (D) Detail of the area indicated by the rectangle in (C) showing the Laguna del Plata with core locations. In November 1999, an extraordinary flood event produced the transport and dispersion of suspended sediments from Laguna del Plata into the main lake (lighter colours). Satellite images were obtained from http://conae.gov.ar.

and a variety of sedimentary processes, which are further recorded in the sediments (e.g. Newton, 1994; Li *et al.*, 1997; Pienitz *et al.*, 2000; Almquist *et al.*, 2001).

Laguna Mar Chiquita, a shallow saline lake located in central Argentina (Fig. 1A), provides a very attractive site to study the sedimentological and geochemical responses to dramatic lake level variations resulting from recent changes in the P-E balance. At present, the lake is at its maximum extension, being not only the largest saline lake in South America (≈ 6000 km^2) but also one of the world's largest saline lakes.

This lake is an unusual site in South America because limnological studies started in the area as early as the end of the nineteenth century (e.g. Harperath, 1887; Von Grumbkow, 1890; Frank, 1915; Kanter, 1935; Seckt, 1945). A detailed list of previous work is compiled in Reati *et al.* (1997). The palaeoenvironmental changes proposed so far were based exclusively on historical and geomorphic–stratigraphic data (e.g. Carignano, 1999; Cioccale, 1999; Iriondo, 1999; Kröhling & Iriondo, 1999), whereas limnogeological studies were missing. Thus, this paper provides the first quantitative multiproxy study of the sedimentary record of Laguna Mar Chiquita and, consequently, of central Argentina. Historical and instrumental lake level data were combined with sedimentary facies in a well-dated sequence to evaluate the sedimentological and mineralogical response of the lake system to the last 100 years of documented lake-level changes. The observed relationship between lake-level fluctuations and sedimentary properties within an accurate chronological framework made it possible to develop a depositional model and to reconstruct older environmental changes in the lake.

SITE AND CLIMATE DESCRIPTION

Laguna Mar Chiquita is a terminal lake in a catchment area of ≈37 500 km^2 located in the subtropical pampean plains of central Argentina (30°54′S–62°51′W; Fig. 1A). The surrounding geology is composed of aeolian and fluvial sediments deposited since the Upper Pleistocene (Kröhling & Iriondo, 1999). Very low relief and gentle slopes characterize the north, west and south coasts of the lake, with the exception of some 0·3 to 4·0 m high isolated cliffs in the south. Comparatively higher shores are present in the east and are the result of Middle Pleistocene faulting (Kröhling & Iriondo, 1999). The area covered by wetlands, extending north of the lake, is significantly reduced during dry periods. Geomorphologic features, such as shorelines, indicate former water-level fluctuation. A highstand started in AD 1977 prevailing until today, with a present shoreline altitude of 71 m.a.s.l. (metres above sea level). Maximum length and width are 120 km and 80 km, respectively, whereas the maximum water depth is ≈10 m.

The lake is fed by three major rivers (Fig. 1B) and receives a substantial groundwater input. River basins drain part of the Gran Chaco (Río Dulce basin) and Sierras Pampeanas regions (Ríos Suquía and Xanaes basins). The Río Dulce alone has an average annual discharge of 3·0 km^3; whereas the Suquía and Xanaes rivers both have a total annual discharge of 0·7 km^3 (Reati *et al.*, 1997). The Río Suquía drains into a small lagoon, the Laguna del Plata (Fig. 1C and D), which is connected to the main lake only during highstands. Flooded deltas are present in the mouth of both the Suquía and Xanaes rivers.

Lake waters are alkaline chloride–sulphate sodium type, supersaturated in calcite and gypsum during lowstands and supersaturated in calcite and occasionally in gypsum during highstands (Martínez *et al.*, 1994). Table 1 presents the chemical composition of lake waters in November 1986 and January 1989. The chemical variability between both data sets was the result of a 1·3 m lake-level drop during this interval. Shallow depths and constant winds produce a well-mixed water column. A strong wind storm in November 1986 developed a completely mixed water body, as evidenced by the constant content of dissolved oxygen throughout the water column (Table 1). Conversely, in January 1989, bottom waters (6·9 m depth) were undersaturated in oxygen. This last situation is the most frequent in Laguna Mar Chiquita, with bottom sediments under reducing conditions because of the presence of sulphate-reducing bacteria that appear to trigger the development of oxygen undersaturation at the sediment/water interface (Martínez *et al.*, 1994).

Table 1. Major ionic average concentrations (mmol L^{-1}) during the present lake highstands.

	November 1986	January 1989
Water temperature (°C)	22·9	27·8
TDS (g L^{-1})	28·7	34·9
pH	8·3	8·5
HCO_3^- (mmol L^{-1})	3·9	3·4
CO_3^{2-} (mmol L^{-1})	0·5*	0·4
SO_4^{2-} (mmol L^{-1})	43·8	52·6
Cl^- (mmol L^{-1})	378·3	464·9
Na^+ (mmol L^{-1})	433·4	538·8
K^+ (mmol L^{-1})	3·4	3·6
Mg^{2+} (mmol L^{-1})	7·1	10·0
Ca^{2+} (mmol L^{-1})	7·1	8·6
O_2 (mg L^{-1})		
0·3 m water depth	9·5	7·8
2·0 m water depth	10·3	7·7
4·7 m water depth	–	0·1
6·9 m water depth	9·4	–

*A maximum value. A 1·3 m drop in lake water level was documented between November 1986 and January 1989 (data from Martinez, 1991). Oxygen contents were measured at three different water depths.

Austral summer precipitation and dry winters characterize the climate of the region. The most relevant feature during the summer circulation over South America is the South Atlantic Convergence Zone (SACZ). The Amazon basin is the principal source of moisture into central South America (Rao *et al.*, 1996). Meridianal low-level atmospheric circulation is the most important mechanism of transporting water vapour from the Amazon Basin into central northern Argentina and largely determines the hydrological balance of the region (Berri & Inzunza, 1993; Saulo *et al.*, 2000). The average air temperature during summer (December, January and February) is 24·5 °C and 11·5 °C in winter (June, July and August). Instrumental data from AD 1925–97 show that annual precipitation has varied from 303 to 1074 mm year^{-1}, which in turn defines wet and dry periods.

MATERIALS AND METHODS

A multiset of short cores (≈ 1·2 m long) was retrieved in November 1997 (TMC-5, TMC-14 and

TMC-3) and July 2000 (TMC-00-I, TMC-00-IIIa) using a hand corer beeker sampler. Most of the cores were collected in the deepest area of the lake close to the southern shore at 7–8 m water depth (Fig. 1C); however, core TMC-3 was retrieved at Laguna del Plata in front of the Río Suquía mouth (Fig. 1D).

Whole-core petrophysical properties (magnetic susceptibility and bulk density) were determined in cores TMC-00-I and TMC-00-IIIa using a Multi Sensor Track Core Logger (GeoTek®) at the Limnogeology Laboratory, ETH-Zurich, Switzerland. Lithological units were defined combining a detailed core description with smear slide observations. A lamination index (LI) was defined in a similar fashion to the bioturbation index of Behl & Kennet (1996). A value of '1' represents continuous laminae up to 2 mm thick; '2', diffuse or discontinuous 2–4 mm thick; '3', thin banded 4–10 mm thick; and '4', thick banded > 10 mm thick. X-ray radiographs were taken for selected intervals using a Minishot-Dual 150 (Fa. Andrex). Water content was determined in freeze-dried subsamples.

Total organic and inorganic carbon values (TOC and TIC respectively) were obtained by coulometry (Coulometric Inc.) in TMC-00-I. Mineralogical analysis included X-ray diffraction analyses and scanning electron micrographs of selected samples using a Jeol JSM840 scanning electron micrograph (SEM) coupled with an energy-dispersive X-ray (EDAX) analyser at the Department of Geology and Paleontology of the University of Geneva, Switzerland.

Radionuclides ^{226}Ra and ^{210}Pb were measured in cores collected in 1997 in continuous samples (taken every 2 cm) at the Instituto de Pesquisas Energéticas e Nucleares (IPEN, Sao Paulo, Brazil). All samples, previously dried at 60 °C, were passed through a 62·5 μm sieve and digested in concentrated HNO_3, 40% HF and 30% H_2O_2 for the radiochemical determination. The procedure included the initial precipitation of ^{226}Ra and ^{210}Pb with 3 M H_2SO_4, the dissolution of the precipitate with nitrilo-triacetic acid at basic pH, the precipitation of Ba(^{226}Ra)SO$_4$ in a solution of ammonium sulphate and the precipitation of $^{210}PbCrO_4$ in a solution of sodium chromate. The ^{226}Ra concentration was determined by gross alpha counting of Ba(^{226}Ra)SO$_4$ precipitate (Oliveira, 1993), and the ^{210}Pb was analysed through its decay product ^{210}Bi by measuring the gross beta activity of $^{210}PbCrO_4$ precipitate (Moreira, 1993). The chemical yields for both radionuclides were determined by gravimetric analysis of the precipitate. Ages were calculated using the CRS model (Noller, 2000). ^{210}Pb years AD are designated by an asterisk (e.g. AD 1953*). Bulk sediment accumulation (BSA) and organic accumulation rates (OAR) were obtained according to the method of Niessen *et al.* (1992).

A lake-level variation curve for the interval AD 1890–2000 was reconstructed combining historical data such as salinities, shoreline positions and photographs (Von Grumbkow, 1890; Doering, 1907; Frank, 1915; Kanter, 1935; Bertoldi de Pomar, 1953) with instrumental data of monthly lake-level elevation values for the AD 1967–2000 interval. The lake-level data are expressed as deviation from the 66·5 m.a.s.l. shoreline elevation that is an intermediate altitude between well-documented extreme high and lowstands. The altitude obtained is in agreement with the AD 1977 shoreline elevation, typical of an intermediate stage.

HISTORICAL AND INSTRUMENTAL RECORD OF RECENT LAKE-LEVEL CHANGES

The twentieth century history of the lake is characterized by conspicuous water-level fluctuations, which produced low and highstands (Fig. 2A) and substantial changes in lake water salinity. A lake-level curve was built using historical information for the period 1890–1967 (circles in Fig. 2A), and continuous instrumental data have been available since 1967. Low and high water stands are defined here as below or above the 66·5 m.a.s.l. water altitude (AD 1977), respectively, and are represented in Fig. 2A as negative or positive values in grey and black areas respectively.

The proposed lake-level curve starts in AD 1890, when an intermediate stage of the lake – a low highstand – can be proposed according to the lake's description by Von Grumbkow (1890). Low lake levels characterized almost the entire first three-quarters of the twentieth century, with salinities up to 360 g L^{-1} in AD 1911 (Frank, 1915), 251 g L^{-1} in AD 1951 (Bertoldi de Pomar, 1953) and 270 g L^{-1} in AD 1970 (Martinez, 1991). During these lowstands, the lake was never completely desiccated, even during extreme dry intervals with almost non-existent river supply. This resulted from the significant contribution of groundwater to the hydrological budget of the system, although this input has not been

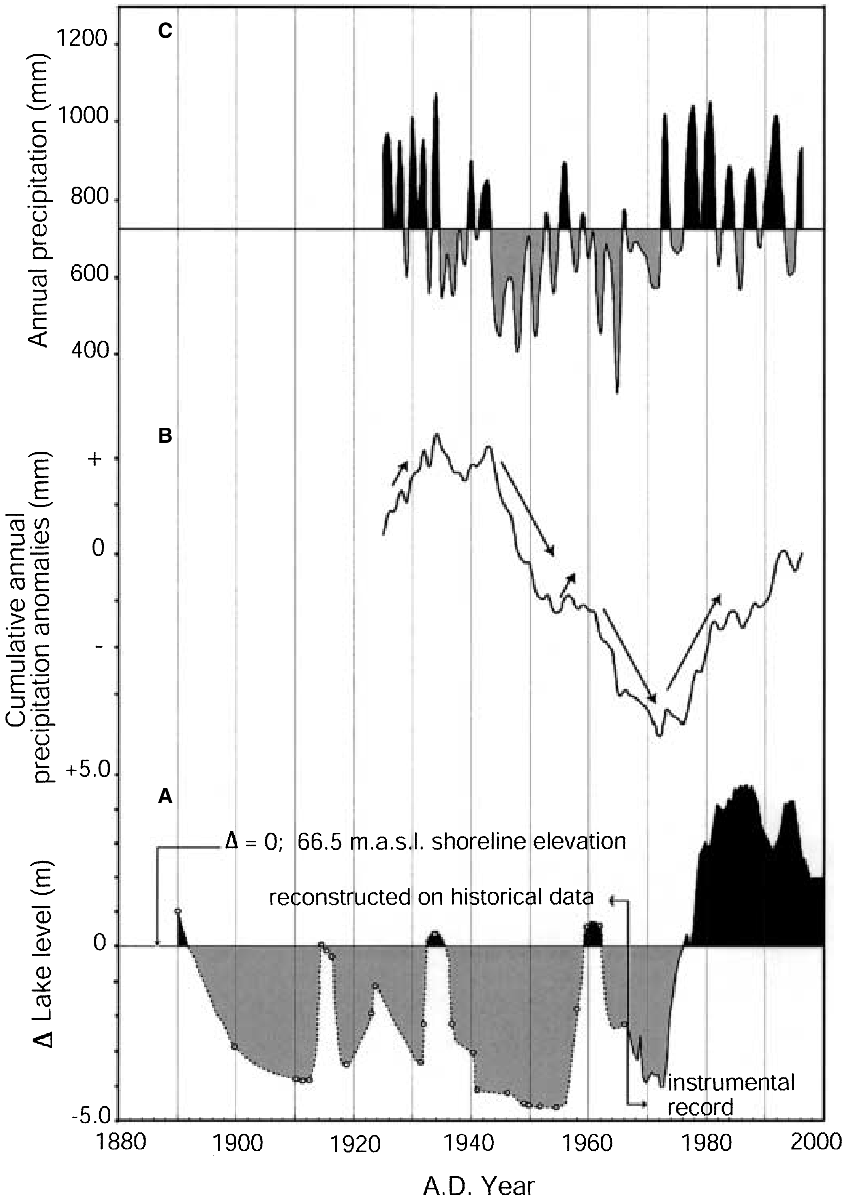

Fig. 2. (A) Lake-level curve for Laguna Mar Chiquita. The interval AD 1890–1967 was reconstructed from historical data (circles in dashed line). Instrumental records started in AD 1967. Δ lake level = 0 is an intermediate lake-level stage that matches the AD 1977 shoreline elevation. Positive values represent highstands (black areas), and negative values indicate lowstands (grey areas). (B) Cumulative annual precipitation anomalies. Upward trend: wet interval (anomalies above the average); downward trend: dry interval (anomalies below the average). (C) Annual precipitation for the AD 1925–96 interval. Values above average are in black and below average in grey.

quantified yet. Within this overall dry interval, short-term pulses of lake level rises occurred at AD 1915 (Frank, 1915), between ≈AD 1931 and 1935 (Kanter, 1935), as well as during AD 1959–61 (documented in photographs).

In AD 1972, the lake level started to rise, and a highstand has dominated from AD 1977 to the present. Comparatively lower salinities (e.g. 29 g L^{-1} in 1986; 35 g L^{-1} in 1989) were reported during this last and ongoing highstand (Martínez *et al.*, 1994). Within 5 years (i.e. AD 1977–82), the maximum depth increased from 4·0 to 8·6 m, the lake surface from 1960 km^2 to 5770 km^2 and the volume from 4240 km^3 to 21 400 km^3 (Reati *et al.*, 1997).

High and lowstand periods are synchronous with increasing and decreasing average regional precipitation respectively (Fig. 2B and C). Precipitation data for the interval 1925–50 correspond to only one station, whereas values from the most recent interval are averages from a wider area. The precipitation average from AD 1934 to 1972 is 653 mm $year^{-1}$; however, a noticeable increase in the average is observed for the period AD 1973–97 up to 810 mm $year^{-1}$. Cumulative precipitation anomalies for the period AD 1925–97 (Fig. 2B) show that positive anomalies (upward trend in the cumulative curve) were dominant until AD 1934. With some exceptions (i.e. from the middle to latest 1950s), negative anomalies

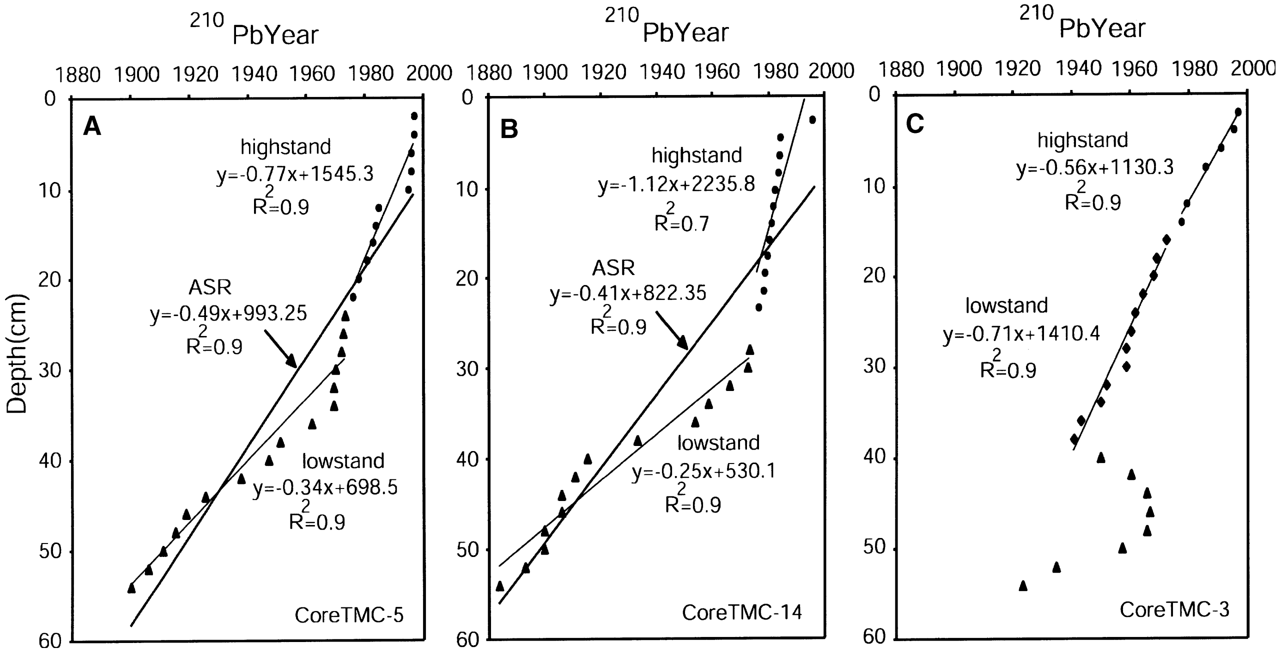

Fig. 3. ^{210}Pb age profile and sedimentation rates for high and lowstands, obtained from the slope of the best-fit linear equation. ASR, average sedimentation rate for the entire dated interval. (A) Core TMC-5 and (B) core TMC-14, both from the main lake, and (C) core TMC-3 from Laguna del Plata (see core locations in Fig. 1C and D).

(downward trend) occurred until AD 1972, when a well-defined reverse trend indicates the predominance of values above the average. The rise in the amount of precipitation agrees closely with the lake-level rise during the last decades and with increasing trends in the annual runoff of river discharges.

CHRONOLOGY AND SEDIMENTATION RATES

Two ^{210}Pb age profiles in the sediment cores from the main water body and an additional profile in the satellite lake (Fig. 1C and D) were used to develop a time–sediment depth chronological model (Fig. 3A–C) in cores retrieved in November 1997. This age model was used to link the sedimentary record to documented lake-level changes and also to estimate sedimentation rates for the different lake-level stands using linear regression.

The results show that sedimentation rates have changed according to variations in the lake-level altitude. The last highstand yields sedimentation rates of 0·77 and 1·12 cm year^{-1} (average value 0·94 cm year^{-1}) in the cores of the main lake, and 0·56 cm year^{-1} in the core from the satellite lake (Fig. 3A–C). This relatively lower value for the satellite lake is related to the influence of Río Suquía suspended sediments, which are transported out of the satellite lake towards the main basin during floods, as observed in satellite images (Fig. 1D). Sedimentation rates during lowstands (below 24 cm in Fig. 3A and B) are 0·25 and 0·34 cm year^{-1} (average value 0·30 cm year^{-1}) in the cores from the main water body. Conversely, the satellite lake exhibits higher sedimentation rates (0·71 cm year^{-1}) as it becomes disconnected from the main lake and traps fine fluvial sediments normally transported to the main lake.

Long-term average sedimentation rates were calculated for the cores retrieved in the main water body (ASR in Fig. 3A and B). Linear regressions were fitted to the whole sections measured by the ^{210}Pb method (0–54 cm) resulting in 0·41 and 0·49 cm year^{-1}. Older ages below 54 cm were obtained using the mean value of ASR (0·45 cm year^{-1}) and assuming constant rates. The obtained value is more representative of the sedimentation rate in the lake because high, intermediate and low lake-level stands were included in the ASR calculation. The chronological model was extrapolated further to cores collected in July 2000 (TMC-00-I and TMC-00-IIIa). Ages were corrected in these cores, according to the thickness of sediments accumulated during the last 2·6 years (i.e. from November 1997 to July 2000) at a rate of 0·94 cm year^{-1}. This extension

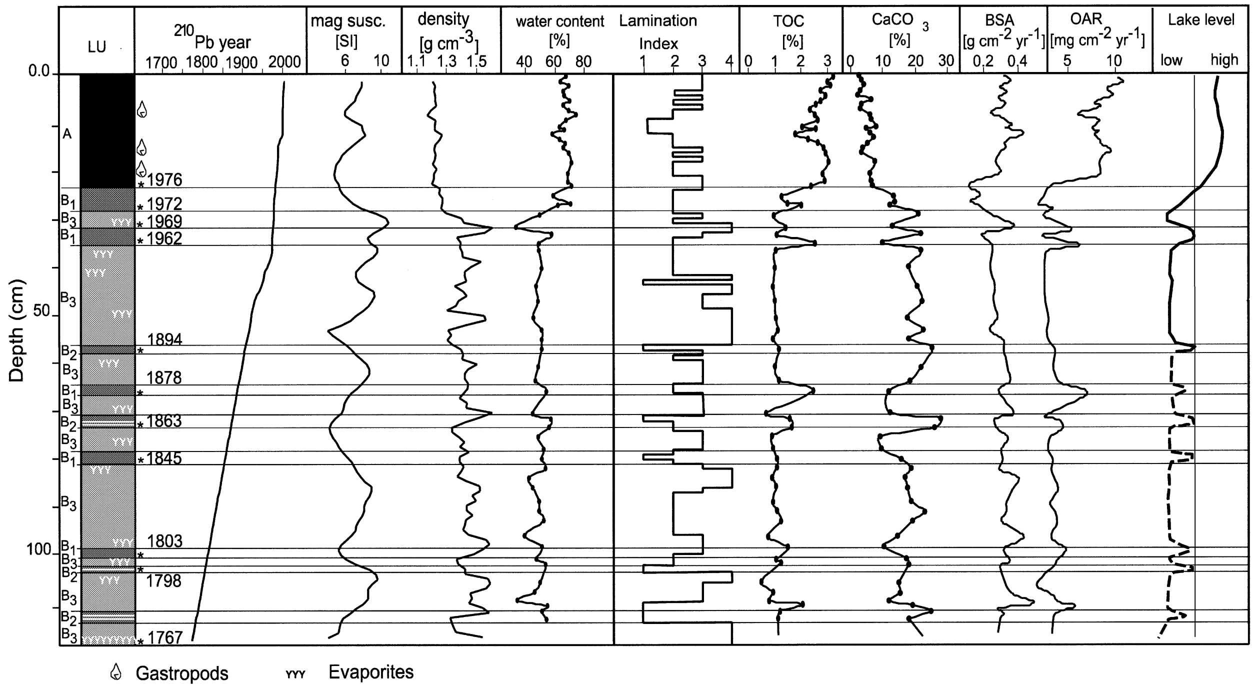

Fig. 4. Lithological units (LU) and position of evaporites. LU A, laminated to banded organic matter-rich muds. B_1, B_2 and B_3 are subunits within LU B (laminated to banded muds with evaporites). Chronological model and AD ^{210}Pb years (the corresponding level is indicated by *). Physical properties, lamination index, percentages of total organic carbon (TOC) and carbonates ($CaCO_3$). Bulk sediment accumulation (BSA) and organic accumulation rate (OAR). The reconstructed lake-level record before AD 1894* (dashed line) is entirely based on the developed sedimentary model.

was also validated by the comparison between the thickness of the most recently accumulated sediments in both sets of cores. The age of the bottom sediments was then estimated as AD 1767*.

A strong anomaly is present in the ^{210}Pb profile of core TMC-3 below the 36–38 cm level (Fig. 3C). These anomalous values coincide with the greatest droughts of the twentieth century which occurred during the 1940s, and are well documented in south-eastern South America's hydrology (e.g. Genta *et al.*, 1998). The core was retrieved in the satellite and shallower Laguna del Plata, which has been strongly affected during lowstands, such that the observed anomaly could be attributed to subaerial exposure of the satellite lake floor during those years.

PHYSICAL PROPERTIES AND SEDIMENTOLOGY

Whole-core measurements of magnetic susceptibility and density before opening the cores provided the first downcore information of different lithological units through depth. Although variations in magnetic susceptibility are quite small – ranging between 5 and 10 SI units – small fluctuations can be identified throughout the logged core (Fig. 4). In a similar fashion, density values varied between 1·2 and 1·5 g cm^{-3}, providing an almost mirror image of the observed changes in the water content of the sediments.

Overall, the Laguna Mar Chiquita cores mostly consist of banded and laminated dark and light muds and evaporites (Fig. 4). Photographs, X-ray radiographs and general features of the cored sediments are presented in Fig. 5. Endogenic components (diatoms, organic matter, calcite, gypsum, halite; Fig. 6A–F) dominate the sediment composition, with minor amounts of allogenic components of both aeolian and fluvial origin (e.g. quartz, feldspars, tourmaline, biotite, muscovite and clay minerals). Thin laminations and clustering of dominant laminae with different colours can be observed in the core but are better recognized in X-ray radiographs (Fig. 5).

Figure 4 summarizes the main sedimentological features of the cores that comprise two main lithological units (LU) A and B, which are also recognized in the physical properties. Unit A has distinctly lower density and higher water content than unit B. The uppermost part of the sedimentary record shows a distinctive dark colour

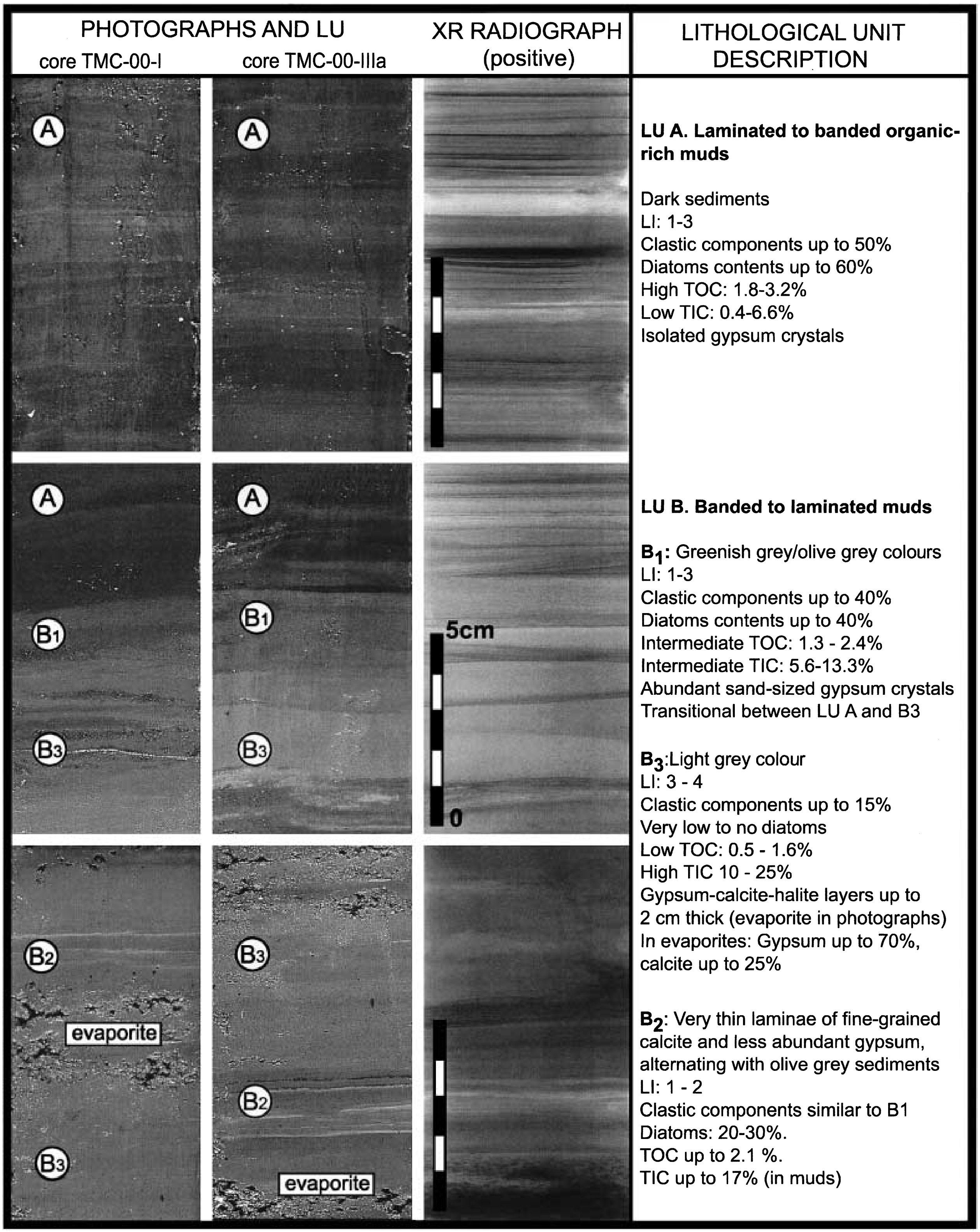

Fig. 5. Photographs, X-ray radiographs and descriptions of the lithologic units. Encircled letters designate individual lithologic units. X-ray radiographs from core TMC-00-IIIa.

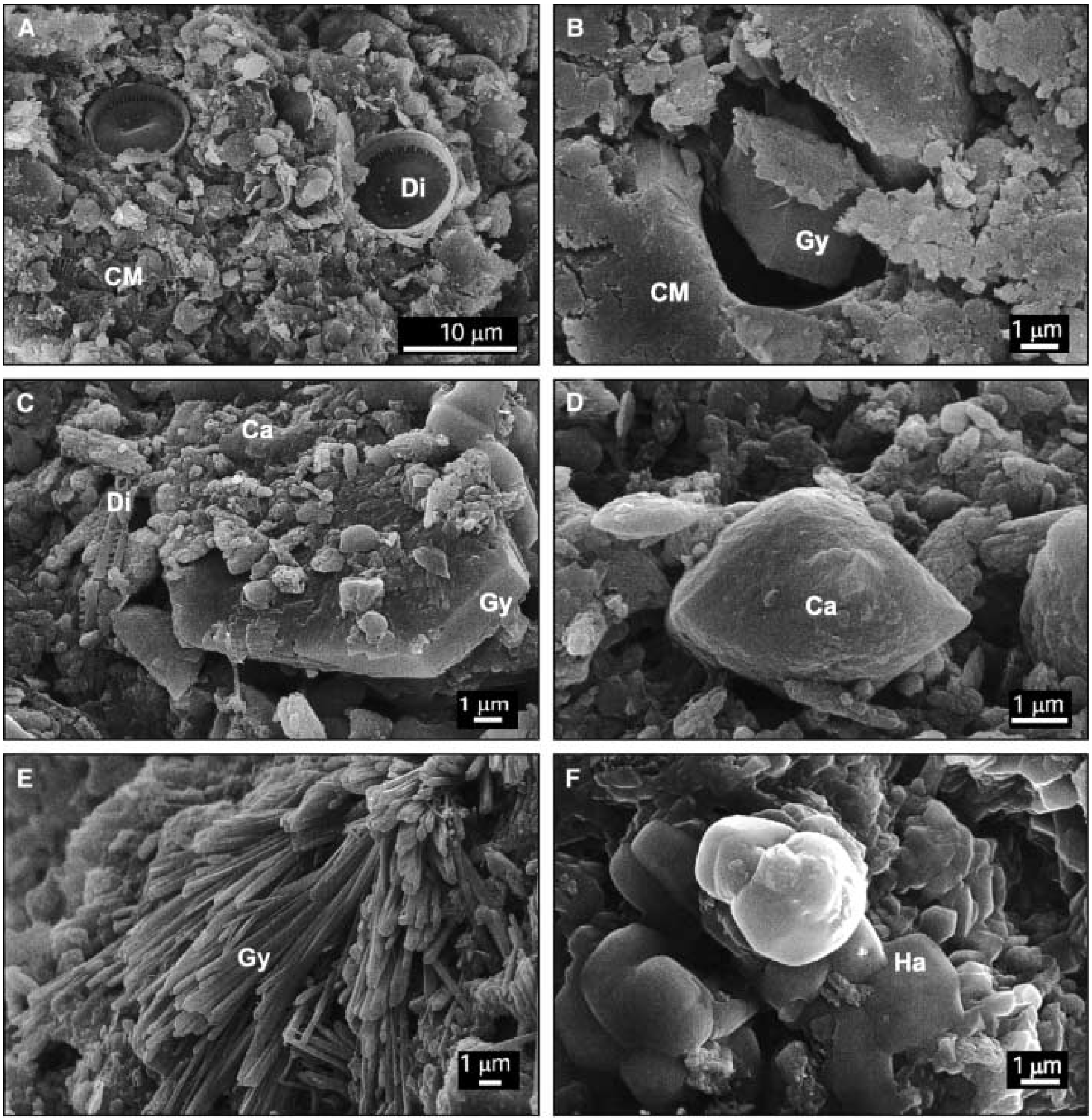

Fig. 6. SEM photomicrographs of lithologic units. (A) LU A, organic matter-rich sediments including diatoms (Di) and aggregates of clay minerals (CM). (B) LU A, crystal of gypsum with a tabular habit embedded in a clay matrix. (C) Subunit B_2, tabular gypsum (Gy) with calcite (Ca) crystals on the surface and diatom frustules (Di). (D) Subunit B_2, authigenic calcite (Ca) displaying sharp crystal edges. (E) Subunit B_3, gypsum (Gy) crystals with prismatic acicular habit within the evaporitic layers. (F) Subunit B_3, cubic crystal of halite (Ha) showing dissolution textures.

associated with organic matter enrichment and low carbonate content. Unit B, below unit A, includes evaporitic layers (gypsum, calcite and halite) and a downward increasing content of calcium carbonate.

Unit A – Laminated to banded organic-rich muds

This unit comprises the uppermost 23 cm of sediments in the deepest part of the lake. The sediments are greyish black and olive grey/black, and are mainly composed of biogenic components with diatom percentages up to 60% (Fig. 6A). The clastic fraction comprises up to 50% of this unit and contains silt, clay and scarce sand grains. Endogenic crystals of gypsum (Fig. 6B) with frequent dissolution textures are dispersed in the mud. TOC contents are the highest of the analysed core (1·8–3·2%), whereas $CaCO_3$ percentages are the lowest (0·4–6·6%). Alternating light and dark sediments with variable organic matter contents result in thin laminations and thin-banded intervals (LI ranges from

1 to 3) highlighted by the X-ray radiographs (Fig. 5). Gastropod shells (*Littoridina* sp.) are concentrated at different levels within the sediments (Fig. 4). The Pb-210 age model indicates that this unit was deposited after AD 1973, therefore corresponding to the last very well-documented highstand of the lake.

Unit B – Banded to laminated muds with evaporites

This unit comprises the sediment interval between 23 cm and the bottom of all analysed cores coinciding with an evaporite crust that prevented further core penetration. It can be subdivided into three additional subunits, B_1, B_2 and B_3.

B_1

The sedimentological and mineralogical features of subunit B_1 are very well defined in the transition from the uppermost organic matter-rich sediments to evaporite-rich and TOC-poor subunit B_3 (see photographs in Fig. 5). These sediments are characterized by LI ranging from 1 to 3. Diatoms and clastic components, each reaching 40%, are accompanied by abundant sand-sized euhedral gypsum crystals ($\approx$ 5%) dispersed in a mud matrix. TOC ranges from 1·3% to 2·4% and carbonate from 5·6% to 13·3%. The age model indicates that the deposition of the uppermost subunit B_1 corresponds to the transition from low to high lake stands between AD 1972 and 1976 and during the documented short-term rising pulse at AD 1959–61. These sediments are also present at three deepest core levels, which correspond to AD 1878*, 1845* and 1803*.

B_2

This very thinly laminated lithology (LI 1–2) is mainly formed by fine-grained calcite, whereas gypsum is less abundant (Fig. 6C and D). These discrete laminae alternate with olive grey organic matter-rich layers (see photographs in Fig. 5) that contain up to 2·1% TOC and abundant sand-sized crystals of gypsum. The percentage of diatoms in this lithology ranges from $\approx$20% to 30%. B_2 occurs four times in the lower half of the core, and only the 56–59 cm level (AD 1894*) can be linked to the reconstructed lake-level curve. This comparison indicates that the B_2 sediments correspond to an intermediate stage of the lake during short-term lake level rises.

B_3

This lithology is the most abundant. It is mainly composed of thin to thick-banded sediments (LI 3–4) that contain evaporitic layers up to 2 cm thick (Fig. 5), consisting of a calcite–gypsum–halite mineral assemblage (Fig. 6E and F). Gypsum occurs mainly as 10 to 500 μm tabular and lenticular crystals and, less commonly, as smaller than 12 μm prismatic acicular crystals. Cubic halite crystals show frequent dissolution textures. These evaporitic layers display high bulk density values and corresponding lower water contents (Fig. 4). B_3 sediments are characterized by the lowest organic matter values (0·5–1·6%) and the maximum calcium carbonate content (up to 25%). The percentage of diatoms is remarkably low throughout this lithology, almost disappearing within the evaporites. The age model indicates that the deposition of B_3 corresponds to lowstand intervals of the lake before AD 1972. Furthermore, the evaporitic layers correspond to years of documented extremely low lake levels.

DISCUSSION

The Laguna Mar Chiquita sedimentary model

The significant correlation between lithological units, sedimentation rates, TOC and recent lake-level changes allows the formulation of a sedimentary model that reflects the documented fluctuations in the hydrological balance of the lake (Fig. 7). The associated variation in salinity during lake-level changes controls both the amount of primary producers in the lake (Reati *et al.*, 1997) and the precipitation of authigenic minerals, resulting in distinctive organic-rich or evaporite-rich lacustrine facies. The vertical variations in the content of TOC and TIC (authigenic calcite) shown in Fig. 4 are the effects of this variability in the lake-water composition. Sediment lamination and banded sediments at a millimetric scale are produced by variations in organic matter content as a result of intra-annual changes in the productivity cycle of the lake, and are also preserved as a result of anoxia at the sediment–water interface. Some intervals of the cores, however, are mostly dominated by either light (dominantly dry periods) or dark laminae (dominantly wet periods). The clustering of laminae is in turn a response to changes in organic matter production that are related to long-term fluctuations in lake level.

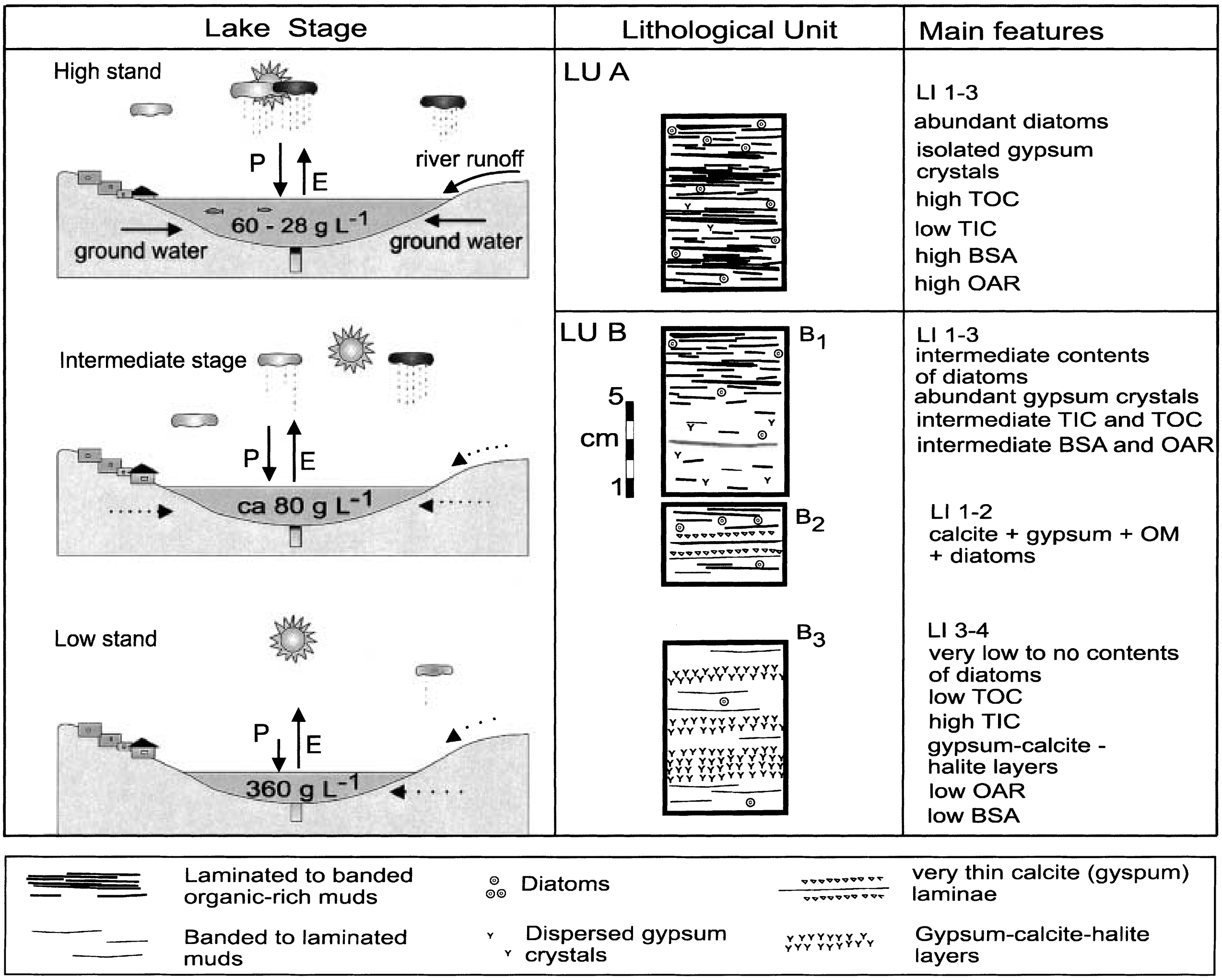

Fig. 7. Model representing lake-level changes and the associated sedimentary record. P-E arrows indicate precipitation (P)–evaporation (E) balance; the relative length of the arrows indicates the predominance of either P or E. Higher river runoff and groundwater inputs are indicated by solid arrows, whereas dotted arrows indicate comparatively low inputs. Lake-water salinities are in g L^{-1}. The main features of the distinctive lithologic units are also summarized. BSA, bulk sediment accumulation; OAR, organic accumulation rate; TOC, total organic carbon; TIC, total inorganic carbon; LI, lamination index.

Authigenic processes are dominant in the lake. The presence of calcite throughout the lithological units results from the permanent supersaturation of lake waters with respect to calcite, even during the most dilute stages of the lake, as reported by Martinez (1991). Isolated gypsum crystals appear to be associated with supersaturated bottom waters. Prolonged intervals with a negative hydrological balance result in comparatively more concentrated waters promoting the precipitation of carbonates associated first with gypsum and finally halite.

The sedimentary record of documented lowstands ($E \gg P$) is characterized by banded sediments, comparatively lower sedimentation rates, evaporites (Fig. 6E and F) and the lowest contents of TOC and diatom remains (subunit B$_3$). Average BSA is 0·22 g cm^{-2} year^{-1}, and the OAR is 3·28 mg cm^{-2} year^{-1}, which are both below the average rates during highstand intervals (Fig. 4). Lake-level drops increase the salinity, promoting the development of gypsum–calcite–halite layers and resulting in a marked drop in the amount of living organisms (blue-green and green algae, bacteria, diatoms, *Artemia salina*, etc.). The ^{210}Pb chronological model indicates that the uppermost level of evaporites at $\approx$30 cm corresponds to AD 1970*, when the amount of total dissolved solids was 270 g L^{-1}. Other well-developed evaporitic layers were formed in AD 1951* at 251 g L^{-1} (Bertoldi de Pomar, 1953), during the long drought of the 1940s and in AD 1911*, when the reported salinity was 360 g L^{-1} (Frank, 1915).

Transitional stages of the lake ($\approx E = P$) are clearly recorded by increasing TOC, decreasing carbonate values, a comparatively higher amount of diatom remains (subunit B_1) than in low water stands and sand-sized gypsum crystals dispersed in the mud. Some short-lived lake-level rises are recorded as an abrupt increase in TOC associated with very thin laminae of calcite (LI 1–2) and subordinated gypsum (Fig. 6c-d) on the top (subunit B_2).

High lake levels ($P \gg E$) are recorded as thinly laminated to banded sediments, increasing contents of both TOC and diatom remains (LU A; Fig. 6A and B) and higher sedimentation rates. The average BSA rate (Fig. 4) for this interval is 0·32 g cm^{-2} $year^{-1}$ with a maximum of 0·43 g cm^{-2} $year^{-1}$ during the highest lake water level (1984–85*). Carbonate minerals are scattered throughout unit A, which has the lowest carbonate content in the core. The presence of gypsum crystals (Fig. 6B) confirms episodic supersaturation of gypsum, at least in the bottom water. OARs reach maximum values within this unit (from 6·09 to 10·91 mg cm^{-2} $year^{-1}$) confirming that the highest primary productivity occurs during highstands. The uppermost organic-rich sediments deposited during the last highstand (LU A) are very distinctive and occur in distant sites, thus providing an excellent correlation level among cores. The coincidence of higher lake stands and higher organic matter contents shows that the hydrological stage of the lake plays a major role in controlling biological processes. Human impact in the catchment area cannot be ruled out as an additional factor increasing the most recent productivity. However, only the uppermost 23 cm (younger than AD 1976*) displays the highest TOC contents despite human settlements, intensive deforestation and agricultural activities that started as far back as the end of the nineteenth century.

Environmental changes in the last 240 years

The combined historical, instrumental, chronological and sedimentological data presented here indicate that the Laguna Mar Chiquita basin is a sensitive system for recording annual and even seasonal variations in the P-E balance for this region of south-eastern South America. Substantial changes in the hydrological balance produce lake-level fluctuations, defining extreme stages of the lake (i.e. high and lowstands) that have been clearly identified in the sedimentary record.

When the results for the dated most recent sediments are extrapolated to the lowermost evaporitic layer at the base of the core (AD 1767* in Fig. 4), a negative water budget can be inferred for this interval. This evaporitic layer is present at the base of all the retrieved cores, indicating the occurrence of an extensive drought that can be further inferred from the 1760s Jesuit cartography (Furlong Cardiff, 1937), which shows minor and isolated water bodies instead of the present shape of the Laguna Mar Chiquita. Moreover, this extreme lowstand can be associated with the end of the Little Ice Age (LIA), which has recently been proposed to have affected the Mar Chiquita area (Cioccale, 1999; Kröling & Iriondo, 1999). Conversely, rising lake levels synchronous with the LIA have been described in the Andean region of north-western Argentina, pointing towards different regional sources and/or magnitudes of moisture for both sites (Valero-Garcés *et al.*, 2000).

More humid conditions can be inferred for the end of the eighteenth century (below 100 cm in Fig. 4), followed by negative hydrological budgets in particular during the first half of the nineteenth century. Additionally, the development of B_1 and B_3 (between 60 and 100 cm) became more frequent towards the last half of the century, indicating short-term lake-level rises and a comparatively positive hydrological budget during this interval (i.e. AD 1845*, 1863*, 1878* and 1894*). This is supported by dendrochronological records near the upper catchment of the Rio Dulce showing slow tree growth during the early nineteenth century followed by a more positive trend in growth until AD 1860 (Villalba *et al.*, 1998). Thus, these two independent reconstructions show a similar sequence and magnitude of events.

The uppermost 54 cm of the core was deposited during the twentieth century. Dry conditions and consequently low lake levels prevailed during the first three-quarters of the century, with short intervals with positive hydrological budgets during 1915, 1932 (not clearly recorded in the sediments) and the most significant during 1959–61. The last 25 years include the highest historically documented lake level of Laguna Mar Chiquita.

The recorded variations in the Laguna Mar Chiquita hydrological balance during the twentieth century are synchronous with other hydrological changes observed in the discharge rate of south-eastern South American rivers, as well as in the dendrochronological records west of the lake (Villalba *et al.*, 1998). Long dry intervals throughout the first three-quarters of the twentieth century and a recent increasing trend in stream flows have been reported in the Río de la Plata basin (García & Vargas, 1998; Genta *et al.*, 1998; Depetris *et al.*, 2003). In the same basin, the recent wet interval is also recorded by an enlargement of the Pantanal of Mato Grosso (Brazil), one of the world's largest wetlands (Tucci & Clarke, 1998).

The triggering mechanism of this very recent increase in precipitation in the low plains of southern South America is not yet well understood. It has been suggested that the increase in precipitation in the subtropical area of Argentina may be caused by the enlargement of the meridianal transport of humidity from the tropics to the south (Villalba *et al.*, 1998). Additionally, there is evidence that the increasing trend of discharges in the Río de la Plata basin is associated with anomalies in sea surface temperatures of global extent (Robertson & Mechoso, 1998). The synchronous behaviour of Laguna Mar Chiquita water-level changes and the instrumental record of fluvial discharge variations in south-eastern South America highlight the sensitivity of the lake to environmental changes at a continental scale.

CONCLUSIONS

Contrasting hydrological situations have been historically documented and partially instrumentally recorded for the Laguna Mar Chiquita region. The switch between extreme regimes has triggered lake-level changes, which in turn exert an influence on the processes that occur in the lake system. Low and high lake levels promote either evaporite precipitation or enhanced primary productivity respectively. These different conditions are distinctively recorded as evaporitic-rich or organic-rich sediments and allow the construction of a sedimentological model for a fluctuating saline lake.

The combination of the well-developed chronological and sedimentological models allowed the definition of a lake-level curve for the last 240 years covering the substantial hydrological changes that occurred at and after the end of the LIA. The palaeolimnological record of Laguna Mar Chiquita shows that dry conditions dominated this region from the end of the LIA until the beginning of the last quarter of the twentieth century. However, several short-term wet intervals can be identified as rising lake levels within this dry phase (i.e. during the end of the eighteenth century, second half of the nineteenth and during the first three-quarters of the twentieth century). Wetter conditions produced the most recent highstand, which began 25 years ago and is the largest to occur during the 240 years of lake history.

These results show that Laguna Mar Chiquita is a good sensor of high- and low-frequency changes in the recent hydrological budget and, therefore, climatic changes at middle latitudes in south-eastern South America. Thus, the sedimentary and mineralogical changes observed in this modern system provide an excellent analogue for the interpretation of older sections of the record, which can also be extended to other lacustrine basins.

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