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Holocene paleoclimatic reconstruction based on the Lagoa Dourada deposits, southern Brazil

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ABSTRACT

The Lagoa Dourada is a circular-shaped pond formed on the Furnas Formation (Devonian of the Paraná Basin), filled by late Pleistocene - Holocene sediments. It lies in the hydrographic basin of the Guabiroba River, a tributary of the Tibagi River situated in the Campos Gerais region of the State of Paraná, southern Brazil. The pond is about 200 m in diameter and the maximum water depth is 5.4 m. Geological, chemical, textural and mineralogical studies on a core sample of the sediments collected from the Lagoa Dourada, 12.2 m thick, was obtained for investigations of paleoenvironmental changes as well as to provide additional data to support previous reconstructions based on palynomorphs and diatoms. Within the period recorded in the core, the pond has been filled by sandy material introduced by springs at the northern edge of the pond as well as by muddy material brought in by floodwaters of the Guabiroba River. Thus, the sandy layers could be interpreted as evidence of drier climates with consequent diminution of fluvial overflow, but with maintenance of the sandy deposits coming from springs. The occurrence of euhedral pyrite in the sediments, locally associated with gypsum, may indicate periods of increase in the organic matter content or an increase in the water salinity, what could be related to greater evaporation under drier paleoclimate regimes. Three "cycles" defined by an increase in the total carbon content of the sediments of the pond were observed. These cycles seem to correspond to an increase in the isotope ratio $^{13}C/^{12}C$ ($\delta^{13}C$). Several hypotheses can be suggested to explain the presence of these "cycles", including the alternation of wetter or drier climatic phases. The convergence of the sedimentological data obtained during this study with previous microfossil paleoclimatic (pollens and diatoms) indicators and radiocarbon dating suggests that a drier paleoclimatic phase occurred around 8720±150 years B.P. The evidence for a second drier phase in more recent times is less consistent. This subsequent phase could correspond to the drier phase in southern and southeastern Brazil between 5000 and 3000 years B.P. as suggested by other paleoclimatic studies.

KEYWORDS **Pond sedimentology. Holocene paleoclimatology. Carbon isotopes.**

INTRODUCTION

Lagoa Dourada is a circular-shaped pond situated in the Vila Velha State Park (25°14'20"S, 50°02'35"W), in the district of Ponta Grossa, Paraná State, southern Brazil (Fig. 1). The pond is about 200 m in diameter, and has a maximum water depth of 5.4 m (Fig. 3). It is filled by at least 12.2 m of late Pleistocene and Holocene sediments.

Many paleoenvironmental studies (for example Behling, 1997; Ledru et al., 1998) have shown that the region of the pond was submitted to alternating wetter and drier climatic phases at the end of the Pleistocene and during the Holocene, as a consequence of global long-term climatic changes as well as by short-term changes comparable to the El Niño.

Additionally, paleoclimatic changes are also believed to cause alteration in the vegetation cover with savannahs and open fields advancing over the forests during drier periods with the contrary occurring during periods of wetter climate. These changes in the vegetation may have caused variations in the palynological and diatom content of the sediments as well as in the sand and clay mineralogy, isotope ratios and total amount of sedimentary carbon.

The geological and sedimentological studies carried out at Lagoa Dourada focused on possible additional evidence for paleoenvironmental variations at the end of the Pleistocene and during the Holocene. The two principal objectives of these investigations were: 1) to provide geological support for the interpretation of the results of previous microfossil studies on the sediments of the pond (palynomorphs: Lorscheitter and Takeda, 1995; diatoms: Moro, 1998; Moro and Bicudo, 1998); 2) the definition of paleoenvironmental changes from mineralogical and isotope studies.

GEOLOGICAL AND GEOGRAPHICAL CONTEXT

Lagoa Dourada is situated in the hydrographic basin of the Guabiroba River, a tributary of the upper reaches of the Tibagi River, which flows through the Segundo Planalto Paranaense (Second Paraná Plateau). This plateau is one of the compartments of the stepped relief of the State of Paraná (Fig. 2), occurring at elevations between 1100 and 800 m and having a gentle westerly slope.

The source area of the Lagoa Dourada sediments is the watershed of the Guabiroba River. Locally present are the Furnas Formation (Devonian; whitish arkosean sandstone with kaolinitic cement), the Ponta Grossa Formation (Devonian; shale and fine sandstone) and rocks at the base of the Itararé Group (Carboniferous; red to reddish sandstone, conglomeratic lenses, diamictite, rhythmite, mudstone and shale). Some Mesozoic diabase dykes also occur in the area (Fig. 1).

A typical feature present in the area are the *furnas*, a kind of sinkhole understood as collapse shafts similar to the dolines, but formed in terrigenous sandstone, in this case the Furnas Formation (Devonian) that takes its name from these landforms. The *furnas* result from underground erosion along brittle structures to form tunnels the ceilings of which may collapse to form the depressions (Maack, 1956; Soares, 1989). Lagoa Dourada is considered to be a silted-up *furna*, that developed by the invasion of the floodwaters of the Guabiroba River (Melo et al., 2000).

The climate in the region of the Segundo Planalto Paranaense has well-defined thermal seasons. The average temperature of the hottest month (February) is 21.2ºC, and of the coldest (July) is 13.3ºC, with annual average temperature of 18ºC (Maack, 1981). The average precipitation (period 1954-1998) is 1542 mm per year. Rains are well distributed throughout the year, with a subtle decrease from April to August.

Clear fields of woody-grassy savannah type dominate the hilltops and hillsides in the region of the pond and its surroundings, whereas *Araucaria* woods appear as riparian forests or isolated coppices (Moro, 1998).

Hydrologic regimen of the Lagoa Dourada

When the Guabiroba River is at its normal or low flow, the Lagoa Dourada receives groundwater from several springs situated along its northern edge. During the floods of the Guabiroba and Tibagi rivers that can occur throughout the year (Melo et al., 2000), the fluvial water flows backwards and forwards through a channel some 200 m long that connects the Lagoa Dourada to the river. This mechanism floods the pond with muddy water.

The hydrologic regimen of Lagoa Dourada influences the geometry and composition of its sedimentary deposits (Fig. 3). The water depth is greater at the northern end of the pond, where the constant stream spring water maintains the water limpid even during times of flooding, thus avoiding the decanting of the fine particles in suspension. Sandy material predominates at the bottom closer to the northern edge of the pond, whereas elsewhere there is a predominance of muddy material.

PREVIOUS STUDIES ON THE SEDIMENTS OF THE LAGOA DOURADA

Lorscheitter and Takeda (1995) gave the results of the palynologic study of the lower 5.68 m from the same core used in this account. They concluded that the low pollen concentration at the end of the Pleistocene (period before 11000 years B.P.) showed that semi-arid conditions prevailed, whereas the more frequent presence of arboreal elements and diversification indicated a more humid climatic regime between 11000 and 8000 years B.P. They also identified an even more accentuated climatic wetting above 8000 years B.P., when *Araucaria* first appears in the pollen spectrum.

The studies of Moro (1998) and Moro and Bicudo (1998) concluded that the more elucidating parameters towards the interpretation of the paleoclimatic and hydrologic variations in the Lagoa Dourada region were the water content percentage, the available phosphor, the alkaline inorganic cations (Ca^{++}, K^{+}, Mg^{++}), and the percent-

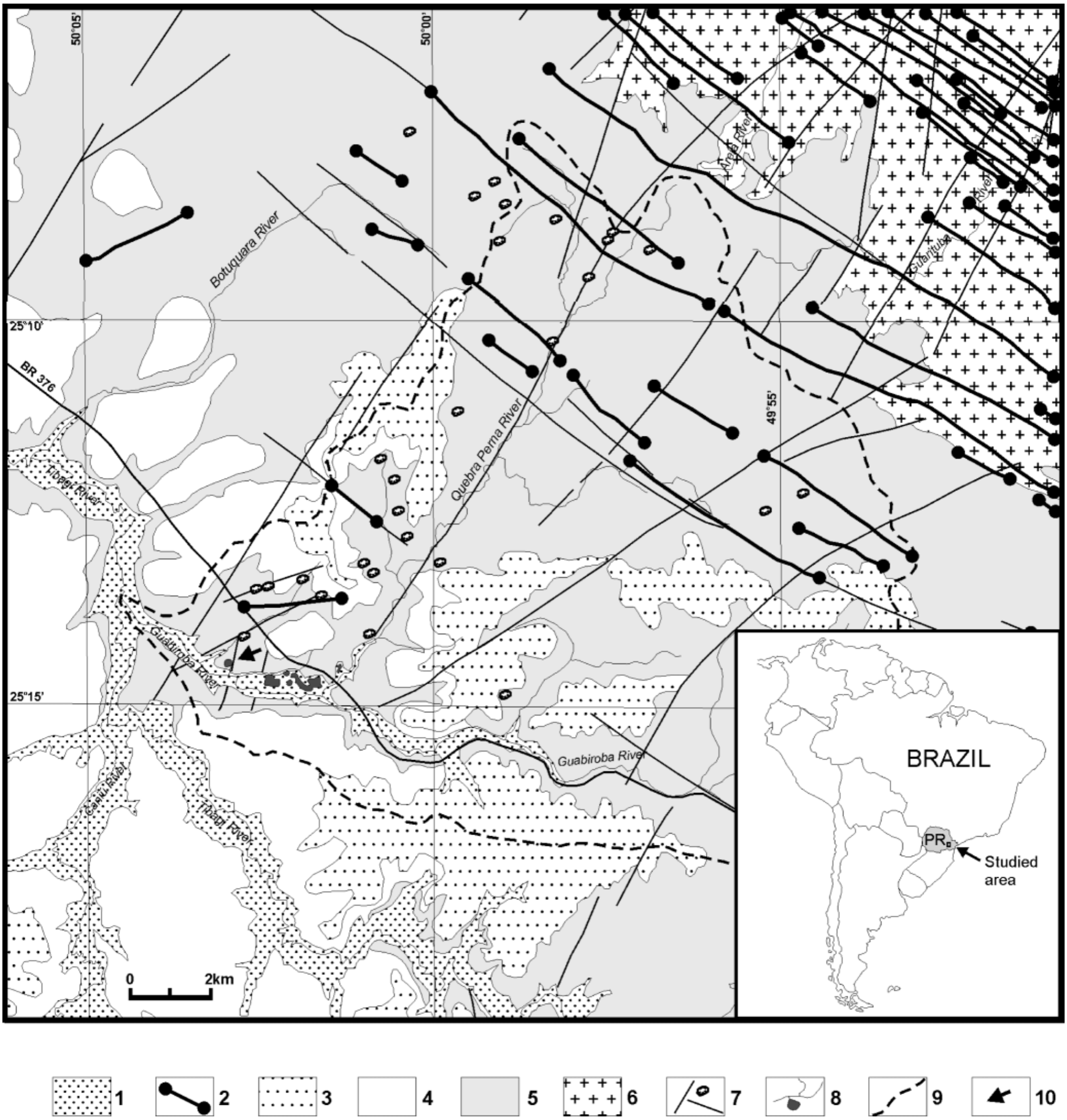

FIGURE 1 **Geographical situation and geological map of the Lagoa Dourada and the hydrographic basin of the Guabiroba River; 1: Quaternary alluvium; 2: diabase dyke; 3: Itararé Group; 4: Ponta Grossa Formation; 5: Furnas Formation; 6: Proterozoic basement; 7: main geological structures (faults, fractures and *furnas*); 8: rivers and ponds; 9: limits of hydrographic basin of the Guabiroba River; 10: Lagoa Dourada. Compiled from Fuck et al. (1965), Trein et al. (1967), Maia and Soares (1971), Aguiar Neto (1977) and Soares (1989).**

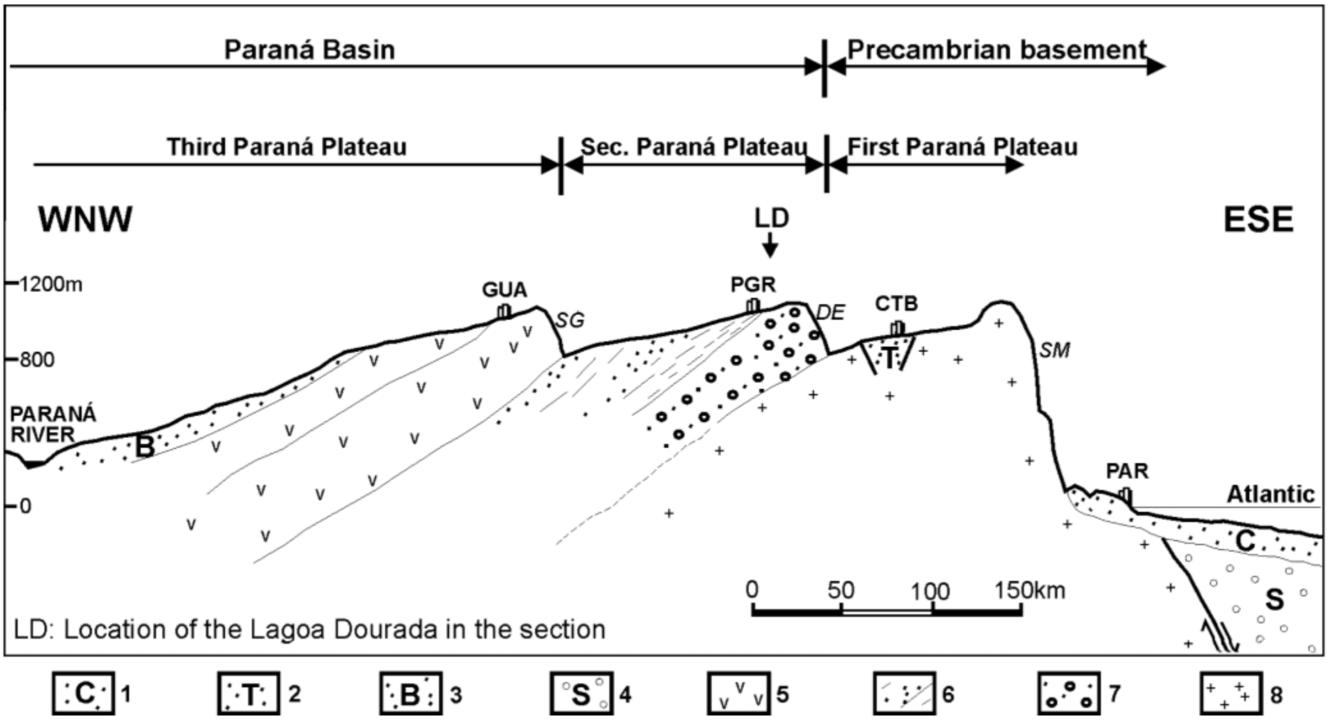

FIGURE 2 **Schematic section of the Paraná State showing the geological structure of the relief. PAR, CTB, PGR and GUA: cities of Paranaguá, Curitiba, Ponta Grossa and Guarapuava; *SM*, *DE* and *SG*: Serra do Mar, Devonian Escarpment and Serra Geral, respectively. 1: Cenozoic sediments; 2: Tertiary sediments of the Curitiba Basin; 3: Mesozoic sedimentary rocks of the Bauru Group; 4: Mesozoic sedimentary rocks of the Santos Basin; 5: Mesozoic lava flows; 6: Permian-Carboniferous sedimentary rocks of the Paraná Basin; 7: Devonian sedimentary rocks of the Furnas Formation; 8: Proterozoic basement.**

age of organic material. They noted that the biological parameters (variations in the diatoms community) should not be analysed alone in paleoclimatic interpretations. They interpreted four zones in the sediments of the Lagoa Dourada:

1) 12.1-11.5 m (about 11000 years B.P.): phases of relative aridity followed by short warm and wet phase.

2) 11.3-10.0 m (about 8700 years B.P.): maximum aridity.

3) 9.9-1.9 m (after 8700 years B.P.): wet conditions with fluctuations.

4) 1.8-0.05 m (recent): tendency to warmer and dryer than preceding.

Ages and sedimentation rates

Two standard radiometric dates are reported in plant remains coming from the Lagoa Dourada sediments (Lorscheitter and Takeda, 1995; Moro, 1998), carried out at Beta Analytic Inc. (Florida, USA), as follows: 11170±110 years B.P. at the depth of 11.9 m and 8720±150 at the depth of 10.6 m (Fig. 4).

Based on these two dates, the following sedimentation rates can be obtained for the Lagoa Dourada: 0.52 mm yr^{-1} for the interval between 11.9 and 10.6 m, and 1.22 mm yr^{-1} for the interval between 10.6 m and the sediment/water interface. The apparent slower rates in the deeper sediments are probably due to the stronger effect of compaction.

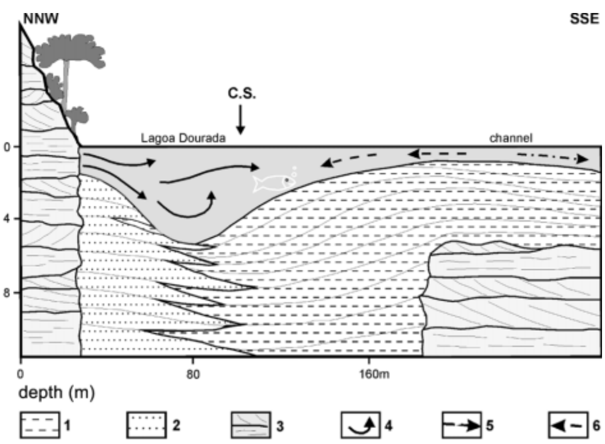

FIGURE 3 **Hypothetical geological section through the Lagoa Dourada. 1: silty-clayey sediments; 2: fine sandy sediments; 3: Furnas Formation; 4: course of underground springs; 5: normal course of water; 6: reflux during floods of the Guabiroba River; C.S.: position of core sampling.**

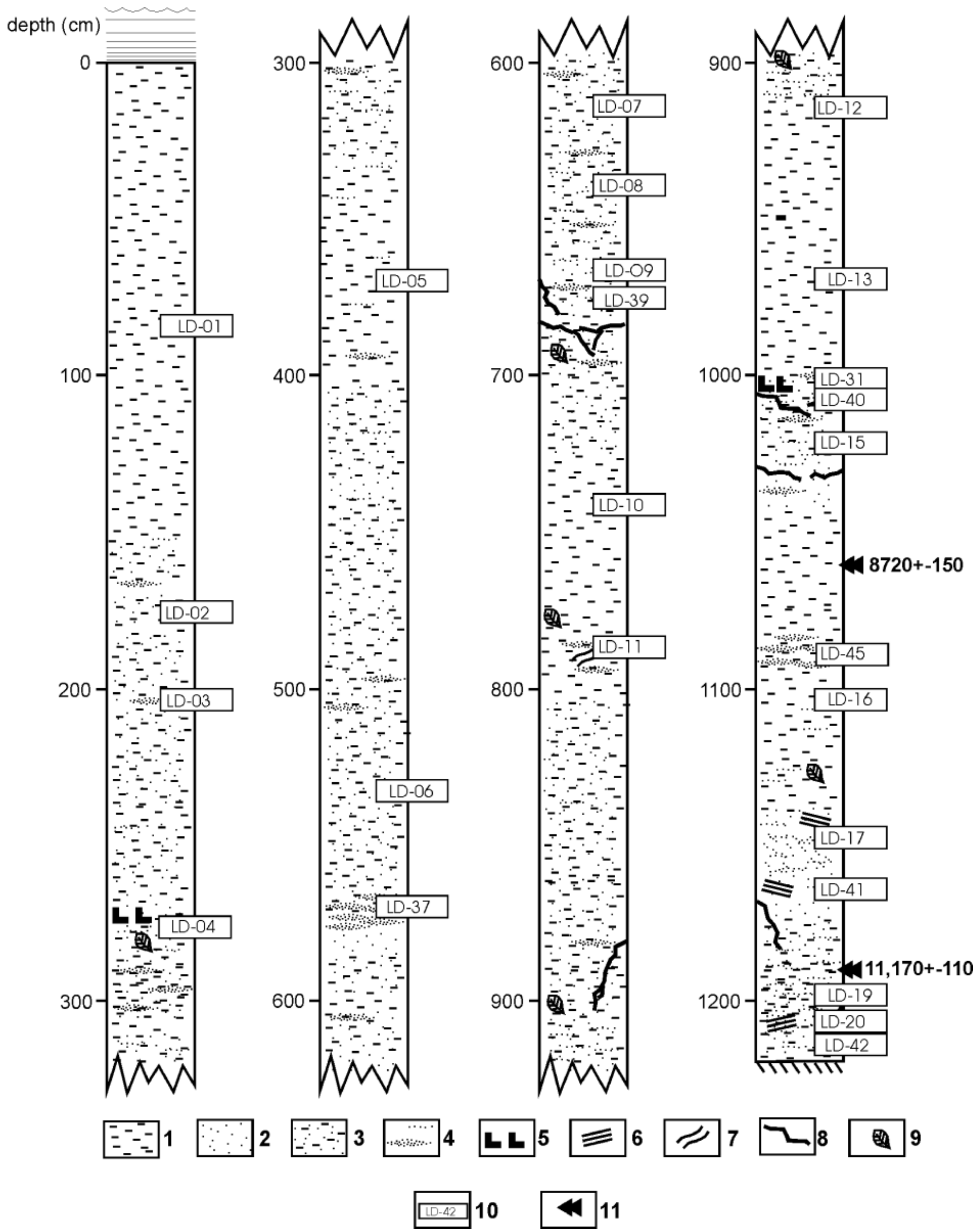

FIGURE 4 **Core of the Lagoa Dourada sediments. 1: clay; 2: very fine sand; 3: clay with a little very fine sand; 4: millimetric layers and centimetric lenses of very fine sand; 5: pyrite and/or gypsum; 6: layer tilting; 7: deformation of layers; 8: ruptures; 9: plant remains; 10: samples on Tables 2 and 4; 11: radiometric ages.**

These relatively high sedimentation rates in the Lagoa Dourada, even for the deeper sediments, suggests that the invasion by the muddy floodwaters of the Guabiroba River has being a determinant process in the silting-up of the pond during the period represented by the samples collected. Such an assumption is reinforced by the comparison of these sedimentation rates with those of the Lagoa do Infernão (Lobo, 1997; 1.16 mm yr^{-1}), another example of a Holocene floodplain pond in southeastern Brazil.

METHODS AND TECHNIQUES

The sedimentological studies were based on the analysis of 10 samples of sedimentary rocks and soils collected from the source areas of the Lagoa Dourada; one sample from the bottom of the pond and 36 samples from the core representing 12.2 m of sedimentary infill. This core was collected in 1991 using a Livingstone-type sampler (Livingstone, 1955). The study of the geological and geomorphological context of the Lagoa Dourada, including source rocks, and the interpretation for landforms and brittle structures from LANDSAT and radar images, complemented these.

The core was submitted to an initial visual-tactile description, for such aspects as colour, sedimentary structures, plant remains and grain size evaluation. X-ray radiographs of the core sample taken at the time of sampling aided the interpretation of textures and structures of sediments. Then the samples were collected for mineralogical, carbon content and isotope analyses. The sedimentological analyses were based on the granulometry of the sand grains and clay minerals obtained from the sediments of the pond as well as from the weathered rocks of the source areas. The carbon content of the pond sediments was also analysed. The rocks of the source area were submitted to petrographic analysis.

The grain size analyses followed the usual procedures (v.g. Müller, 1967). However, this procedure was found to inefficient in the case of the sediments obtained from the core due to the high content of colloidal matter (organic substances and clay), which flocculated the fine particles (silt and clay), leading to distorted results. Qualitative estimation of grain size of these sediments was obtained by tactile evaluation of the material of the core and by observation of the X-ray radiographs.

The mineralogical analyses were based on the use of the petrographic microscope (after Folk, 1980), X-ray diffractometry (XRD) and the scanning electron microscopy (SEM).

X-ray diffractometry on oriented clay samples helped in the identification of minerals present in the sedimentary rocks of the source areas as well as in the sediments collected from the pond.

Scanning electron microscopy (SEM) was done to obtain images of the shape and fabric of the micro-constituents of the sediments of the pond and of the sedimentary rocks of the source areas, as well as to make semi-quantitative chemical microanalysis, by means of energy dispersive X-ray analysis (EDX). The habit of the clay minerals aided the interpretation of their terrigenous or authigenic origin (after Welton, 1984).

Analyses of the carbon content (% in weight of total plant C) and carbon isotope ratios ($^{13}C/^{12}C$) of the sediments of the core were carried out at the Laboratory of Environment Isotopes of the University of Waterloo, Canada. The samples were first subjected to chemical attack to eliminate carbonate and fulvic/humic acids. Thereafter, the sediments were burnt in a vacuum to obtain the CO_2, directly introduced in the mass spectrometer. The isotope ratio $^{13}C/^{12}C$ is expressed in delta (δ) per thousand ($^{o}/_{oo}$) relative

TABLE 1 **Heavy minerals (d>2.85g cm^{-3}) from sedimentary rock samples from the source areas of the Lagoa Dourada.**

Sample	Unit	Lithotype	%	%	% of non-micaceous transparent grains															Maturity index		
			OPQ	TRA	zrn	tur	rt	ant	st	ep	mnz	ttn	sil	ky	crn	hbl	ens	alt	X	iZTR	iMET	iINS
LD-06A f	Furnas	sandstone	18	82	2,7	74,1	21,4	0	0	0,9	0	0	0	0	0	0	0	0,9	0	98,2	0,9	0,9
LD-06A vf			12	88	18,1	38,1	40,0	0	0	1,0	0	0	0	1,0	1,0	1,0	0	0	0	96,2	2,9	1,0
LD-06B f			41	59	2,0	81,4	12,7	0	2,0	0	0	0	0	0	0	1,0	0	1,0	0	96,1	2,0	2,0
LD-06B vf			30	70	24,5	48,0	19,6	2,9	2,0	1,0	0	0	1,0	0	0	1,0	0	0	0	94,9	4,0	1,0
LD-09B f	Itararé		12	88	27,6	60,0	11,4	0	0	0	0	0	0	0	0	0	0	1,0	0	99,0	0	1,0
LD-09B vf			30	70	66,7	17,9	12,0	0,9	0	0	0,9	0	0	0	0	0,9	0	0,9	0	97,4	0,9	1,7
LD-10B f		diamictite	87	13	14,3	68,3	1,6	0	1,6	0	0	0	0	0	0	0	0	4,8	9,5	84,1	11,1	4,8
LD-10B vf			86	14	43,0	40,2	5,6	0	0	0,9	0	0	0	0	0	0	0	0	10,3	88,8	11,2	0
LD-12A f	P. Grossa	shale	only ferriferous aggregates																			
LD-12A vf																						

Fractions studied: fine sand = f (2-3 phi) and very fine sand = vf (3-4 phi). Total counting of non-micaceous transparent grains greater or equal to 100, except in sample LD-06B f (64 grains). OPQ: opaques; TRA: transparent; zrn: zircon; tur: tourmaline; rt: rutile; ant: anatase; st: staurolite; ep: epidote; mnz: monazite; ttn: titanite; sil: sillimanite; kya: kyanite; crn: corundum; hbl: hornblende; ens: Ferroan enstatite; alt: alterites (weathered heavy minerals); X: indeterminate isotropic mineral; iZTR: sum total of ultrastable minerals; iMET: sum total of metastable minerals; iINS: sum total of unstable minerals.

TABLE 2 **Heavy minerals (d>2.85 g cm^{-3}) from sediments from the interior of the Lagoa Dourada (see abbreviations legend on Table 1).**

Sample	Local	Depth	%	%	% of non-micaceous transparent grains															Maturity index		
		cm	OPQ	TRA	zrn	tur	rt	ant	st	ep	mnz	ttn	sil	ky	crn	hbl	ens	alt	X	iZTR	iMET	iINS
LD-01C f	spring	surface	10	90	17,7	51,0	17,7	4,2	0	8,3	0	0	1,0	0	0	0	0	0	0	90,2	9,8	0
LD-01C vf			5	95	62,4	13,8	10,1	3,7	0	8,3	0	0	0	0	1,8	0	0	0	0	89,5	10,5	0
LD-37T f	core	560	14	86	10,7	70,7	8,0	0	2,7	1,3	0	0	0	0	5,3	0	0	1,3	0	89,3	9,3	1,3
LD-37T vf			7	93	40,9	39,1	14,8	1,7	0	0,9	0	0	0	0	1,7	0	0	0,9	0	96,5	2,7	0,9
LD-39T f	core	675	16	84	9,6	68,4	8,8	0,9	0,9	6,1	0	0	0	0	3,5	0	0	0,9	0	87,6	10,6	1,8
LD-39T vf			8	92	36,4	36,4	12,7	7,3	0	4,5	0	0	0	0	1,8	0	0	0,9	0	92,2	6,9	1,0
LD-40T f	core	1015	9	91	7,7	78,0	7,7	1,1	0	1,1	0	0	0	0	4,4	0	0	0	0	94,4	5,6	0
LD-40T vf			8	92	36,6	44,6	6,9	5,0	0	3,0	0	0	0	0	4,0	0	0	0	0	92,7	7,3	0
LD-45T f	core	1090	13	87	4,0	91,0	4,0	0	0	0	0	0	0	0	0	0	0	1,0	0	99,0	0	1,0
LD-45T vf			2	98	40,0	36,0	17,0	3,0	0	4,0	0	0	0	0	0	0	0	0	0	95,9	4,1	1,0
LD-41T f	core	1165	22	78	10,9	88,1	1,0	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0
LD-41T vf			8	92	49,1	29,1	11,8	1,8	0	5,5	0	0,9	0	0	0	0,9	0	0,9	0	91,7	6,5	1,9
LD-42T f	core	1210	4	96	5,8	82,7	5,8	0	0	0	0	0	0	0	3,8	0	1,0	1,0	0	94,2	3,8	1,9
LD-42T vf			8	92	37,0	45,0	7,0	5,0	0	3,0	0	0	0	0	3,0	0	0	0	0	93,7	6,3	0

to the standard PDB (belemnite of the PeeDee Formation of North America, *cf.* Craig, 1957).

RESULTS OF THE SEDIMENTOLOGICAL AND ISOTOPE ANALYSIS

In the study of the source rocks and the core from Lagoa Dourada (Fig. 4), there was an attempt made to define the main characteristics of the sediments and their source materials, in terms of their significant mineralogical variations, texture and structure, with a view to interpreting the possible relationships between the nature of sediments, deposition and deformation processes, paleoenvironmental changes and hydrological regimen of the pond and its watershed.

TABLE 3 **Mineralogical composition of sedimentary rocks from the Lagoa Dourada source areas.**

Sample	Unit	Lithotype	Method and Lab	Minerals
LD-01B	Furnas	sandstone	SEM (IGUSP)	qtz eu, ill aut, kao aut, fs, mic
LD-06A		K sandstone	rX (IGUSP)	qtz, kao, ill
LD-06A			SEM, EDX (IGUSP)	ill aut, ill detr, kao aut
LD-06B		sandstone	rX (IGUSP)	qtz, kao
LD-06B			SEM (IGUSP)	qtz eu, kao aut
LD-09A	Itararé	intraclast*	rX (IGUSP)	qtz, kao, ill
LD-09A			SEM, EDX (IGUSP)	ill detr, ill aut, kao aut
LD-09B		rX (IGUSP)	qtz	
LD-09D		intraclast		qtz, kao, ill
LD-09E		sandstone	sandstone	qtz
LD-10A				qtz
LD-10A			EDX (IGUSP)	ill detr, ill aut
LD-12A	Ponta Grossa	shale	rX (IGUSP)	chl, ill
LD-12A			SEM, EDX (IGUSP)	ill detr, kao aut
LD-12B	soil	soil		kao aut, ill detr

* mud clasts in resedimented deposits

qtz: quartz; ill: illite; kao: kaolinite; chl: chlorite; fs: feldspar; mic: mica; eu: euhedral; aut: authigenic; detr: detrital.

Mineralogy of the sand grains

Table 1 shows data of the heavy minerals in the sedimentary rocks of the source areas of Lagoa Dourada. Table 2 shows data of the mineralogical composition of the sand grains present in Lagoa Dourada sediments (six samples obtained from the core, and one sample, LD-01C, of sand collected from the surface at the bottom of the pond at its northern edge).

The high ZTR index (sum of the percentages of the ultrastable: zircon, tourmaline and rutile minerals, in relation to transparent non-micaceous components) and the low mineralogical diversity indicate a high chemical maturity of the rocks and sediments studied, which should be attributed to factors linked to the inheritance of the source area rather than to the depositional conditions. Thus the mineralogy of the sand grains was not found to be a useful tool for interpreting weathering and paleoenvironmental changes.

Clay minerals

Table 3 shows the results of the mineralogical analyses, including the clay minerals. The samples were collected from exposures of sedimentary rocks at the source area. The evaluation of authigenic or detrital nature of the clay minerals was based on their habits as seen in the SEM images (Welton, 1984).

TABLE 4 **Mineralogical composition of sediments from the core of the Lagoa Dourada.**

Sample	Depth (cm)	Material	Method and Lab	Minerals
LD-01AT	82	sandy clay	rX (IGUSP)	qtz, kao
LD-01AT	82		SEM (UNESP)	detr kao
LD-02AT	176			
LD-03AT	203			
LD-04AT	278		rX (IGUSP)	qtz, kao
LD-04AT	278		SEM (UNESP)	pyrite, detr kao
LD-04BT	278		EDX (IPT)	gypsum
LD-05AT	371	clay	SEM (UNESP)	detr kao
LD-06AT	530	sandy clay		qtz, detr kao
LD-10AT	741		rX (IGUSP)	qtz, kao
LD-07AT	614		SEM (UNESP)	detr kao
LD-08AT	640			
LD-09AT	665	clay		
LD-10BT	741	sandy clay	rX (IGUSP)	qtz, ms, kao
LD-10AT	741		SEM (UNESP)	detr kao
LD-11AT	788	clay		
LD-12AT	914	sandy clay		
LD-13AT	969	clay		
LD-31AT	1001			
LD-40AT	1010		rX (IGUSP)	qtz, gypsum, kao, ill
LD-15AT	1015	sandy clay	SEM (UNESP)	detr kao
LD-45AT	1089	muddy sand	rX (IGUSP)	qtz, kao
LD-16AT	1101	sandy clay	SEM (UNESP)	detr kao
LD-17AT	1144			
LD-41AT	1163	sand	rX (IGUSP)	qtz, kao
LD-19AT	1195	sandy clay	SEM (UNESP)	detr kao
LD-20AT	1207		rX (IGUSP)	qtz, kao
LD-42T	1212	sand	rX (IGUSP)	qtz

detr kao: detrital kaolinite; qtz: quartz; ill: illite; ms: muscovite; py: pyrite; gp: gypsum.

These results show that kaolinite and illite are the major primary clay minerals of the source areas rocks, and are abundant in the Furnas and Ponta Grossa formations as well as in the sediments of the Itararé Group. Chlorite was observed in weathered shale from the Ponta Grossa Formation (one sample, LD-12A). The presence of kaolinite, illite and chlorite as primary minerals of these sediments was also detected in unweathered rock samples from boreholes studied by Ramos and Formoso (1975).

Table 4 shows results of the mineralogical analysis, including clay minerals, of the sediments from the Lagoa Dourada core. In this case, kaolinite is clearly the dominant clay mineral, illite was only found in two samples, and chlorite was not observed.

Authigenic/diagenetic minerals

The more significant authigenic/diagenetic mineral detected in the analysis was pyrite (sample LD-04AT, Table 4). Small crystals of gypsum occur (samples LD-04BT and LD-40AT, Table 4), associated with pyrite at a point 278 cm from the top of the core and without associated pyrite at 1010 cm. Both minerals appear in microscopic crystals.

The pyrite, identified by its habit (Welton, 1984), appears in the form of microscopic euhedral octahedra, at point 1010 cm. The gypsum, identified by EDX analysis, appears as fibrous (point 278 cm) and prismatic (point 1010 cm) forms.

Carbon content and stable isotopes

The total carbon content (% by weight) and the isotope ratio $\delta^{13}C$ ($^{o}/_{oo}$ relative to PDB standard) were determined in 10 samples from sediments of the Lagoa Dourada (Fig. 5). These studies were directed at the possibility of using the results of the carbon content to support paleoenvironmental interpretations. The results and interpretations below should be considered as preliminary, in view of the small number of samples analysed and the lack of data on

TABLE 5 **Grain size distribution of sediments from the sedimentary rocks of the Lagoa Dourada source areas and of sandy sediments collected from the bottom near the springs at the northern end of the pond.**

Sample	Unit	Material	Grain size fraction (%)							
			G	Svc	Sc	Sm	Sf	Svf	s	c
LD-06A	Furnas	muddy sandstone	0,02	0,27	1,53	7,64	11,94	5,12	45,64	27,84
LD-06B	Furnas	sandstone	0	1,17	30,79	38,86	13,42	6,01	7,57	2,18
LD-09B	Itararé	sandstone	0,04	3,36	27,59	39,02	19,48	1,68	3,22	5,61
LD-10B	Itararé	diamictite	0	1,17	4,59	11,13	16,61	12,54	45,88	8,08
LD-12A	P. Grossa	shale	0	0	1,46	5,87	6,34	5,82	56,44	24,07
LD-01C	bottom surface	sand	0	0,99	20,17	67,16	10,70	0,98	0	0

G: granule; Svc: very coarse sand; Sc: coarse sand; Sm: medium sand; Sf: fine sand; Svf: very fine sand; s: silt; c: clay.

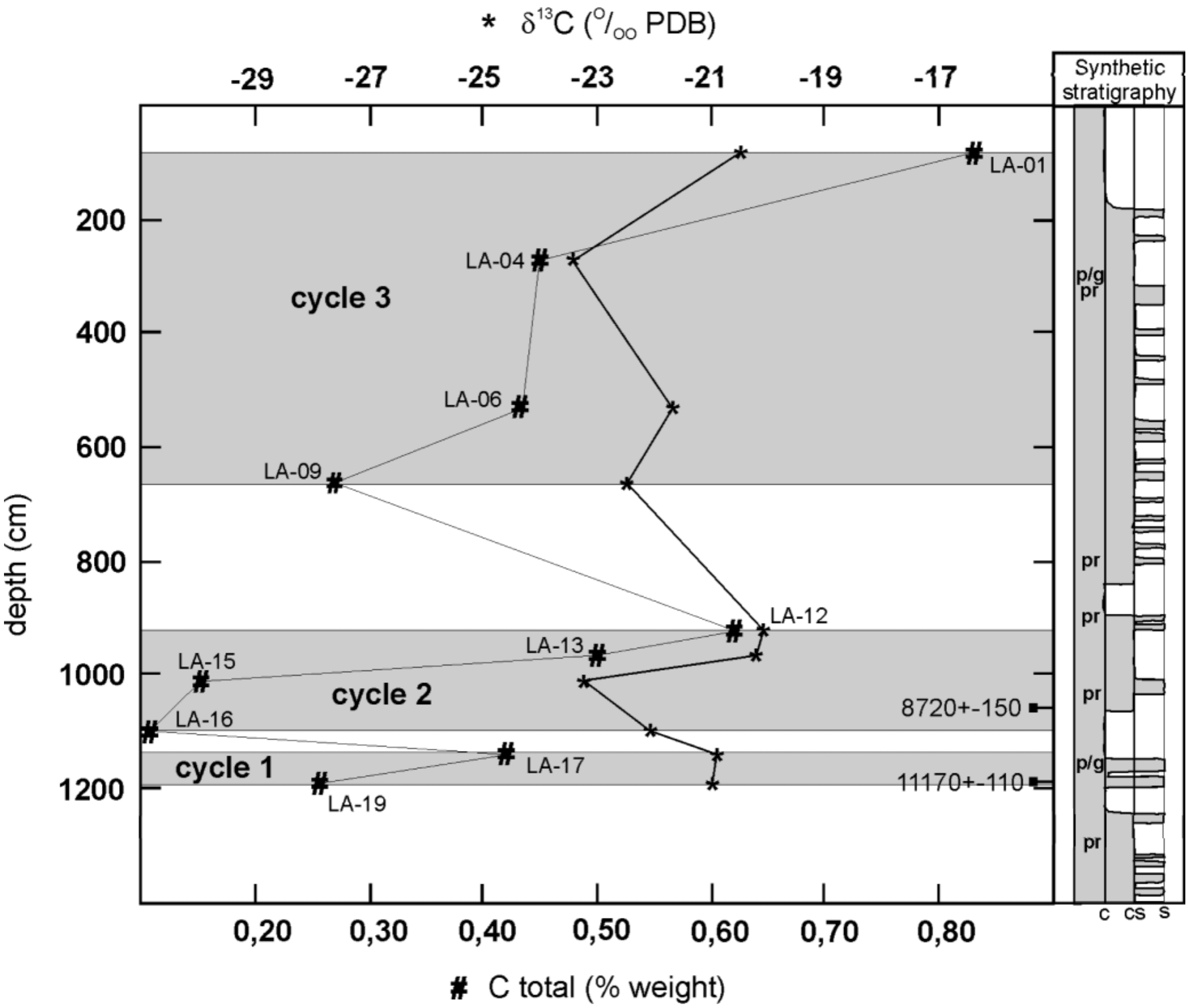

FIGURE 5 **Carbon content of samples of the Lagoa Dourada sediments. Legend of the synthetic stratigraphy column: p/g: pyrite/gypsum; pr: plant remains; c: clay; cs: clay and sand; s: sand.**

the isotope ratios ($^{13}C/^{12}C$) of the plants growing in the region today.

The total carbon values (% by weight) in the Lagoa Dourada showed lower values in the deeper, older and more decomposed sediments. It is possible to distinguish three "cycles" of increased total carbon, from the base to the top of the core that roughly coincide with the increase in $\delta^{13}C$. These "cycles" are (Fig. 5): 1) between 1194.5 (LA-19) and 1143.5 cm (LA-17); 2) between 1100.5 (LA-16) and 923.5 cm (LA-12); 3) between 664.5 (LA-09) and 82.0 cm (LA-01).

The results of the $\delta^{13}C$ for the 10 analysed samples are between -20.1$^{o}/_{oo}$ and -23.4 $^{o}/_{oo}$, (Fig. 5). However, they do not show clear variation trends that might be interpreted as resulting from important changes in the vegetation and consequently in the climate.

Grain size results

Table 5 shows the results of grain size analysis of the sedimentary rocks from the source areas as well as from the bottom surface of the Lagoa Dourada. Because of problems with the flocculation of the fine matter (silt and clay) by colloids (organic substances and clays) the usual grain size analysis of the core sediments led to distorted results. Despite these problems, major sand layers (shown in Figs. 3 and 4) are clearly observed in the core sample, where they are seen as white zones in the visual-tactile examination, and as light coloured levels in the X-ray radiographs.

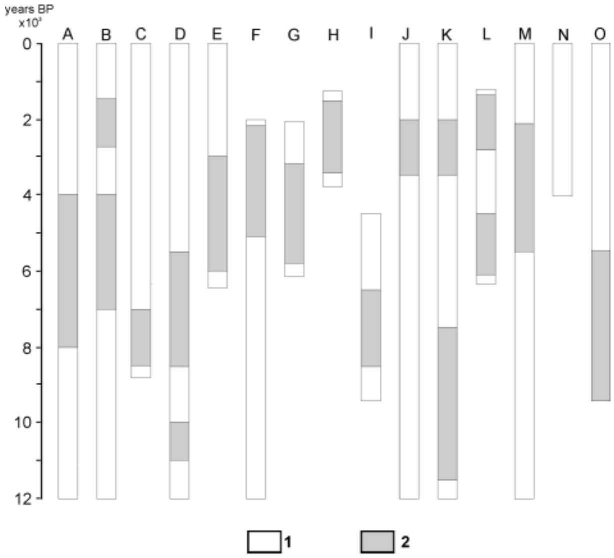

FIGURE 6 **Drier climatic phases interpreted from several studies in Brazil. 1: period covered in the studies; 2: drier climate phases. A) Absy et al. 1991 (Carajás, PA, 6º20'S). B) Siffedine et al., 1994 (Carajás, PA, 6º20'S). C) Servant et al., 1989 (Rio Doce, MG, 18º20'S). D) Ledru, 1993 (Salitre, MG, 19º00'S); E: Vernet et al., 1994 (Salitre, MG, 19º00'S). F) Turcq et al., 1987 (Bonito, MS, 21º12'S). G) Scheel et al., 1995 (São Pedro, SP, 22º06'S). H) Thomaz, 1999 (Porto Rico, PR, 22º25'S); I: Melo, 1995 (Rio Claro, SP, 22º30'S). J) Jabur, 1992 (Porto Rico, PR, 22º45'S). K) Stevaux, 1994 (Porto Rico, PR, 22º45'S). L) Miklos, 1992 (Botucatu, SP, 22º53'S). M) Melo et al., 1987 (São Paulo, SP, 23º30'S). N) Behling, 1997 (Campos Gerais, PR, 24º40'S). O) Pessenda et al., 1996b (Londrina, 23º10'S).**

DISCUSSION OF THE PALEOCLIMATIC EVIDENCES

Based on continental sedimentation and pedogenesis in southern and southeastern Brazil, several authors have demonstrated the existence of Holocene and Pleistocene climatic variations to be indicative of periods of drier climate, or of several short-term dry events (Fig. 6). Despite the dispersion of the results, there are two phases in which the data indicating drier paleoclimates are more consistent: one around 8500 years B.P. and the other about 4000 years B.P.

Figure 7 shows an integration of possible paleoclimatic evidence and interpreted paleoclimatic phases for the Lagoa Dourada. The evidence comprises geological data from this study (mineralogy, grain-size, carbon content), along with palynology (Lorscheitter and Takeda, 1995) and data on diatoms (Moro, 1998). There is no evidence of erosion surfaces or depositional hiatuses in the sediments, the only fractures observed being interpreted as result of shearing of cohesive material during sampling.

Some observations can be made with regard to the clay mineral content in the samples from the core of the Lagoa Dourada sediments. Kaolinite, illite and chlorite are present in the source rocks, but only kaolinite and illite appear in the sediments. Chlorite is an unstable clay mineral that tends to alter to kaolinite and gibbsite in the surface horizons of tropical soils under conditions of well-distributed rainfall (Righi and Meunier, 1995). Thus, the absence of chlorite in the Lagoa Dourada sediments could be interpreted as evidence of paleoclimatic conditions approximating the present-day climate in the region. Although the clay mineral content fails to suggest the occurrence of possible paleoclimatic changes, other indicators suggest these.

The occurrence of pyrite at point 278 cm could be the consequence of the reduction of sulphate by anaerobic bacteria, in the absence of oxygen. This could be due to abundant organic matter and/or high salinity (Friedman et al., 1992; Pierre et al., 1994; Diekmann and Wopfner, 1996). The gypsum may indicate that pyrite had once been present in the sediments.

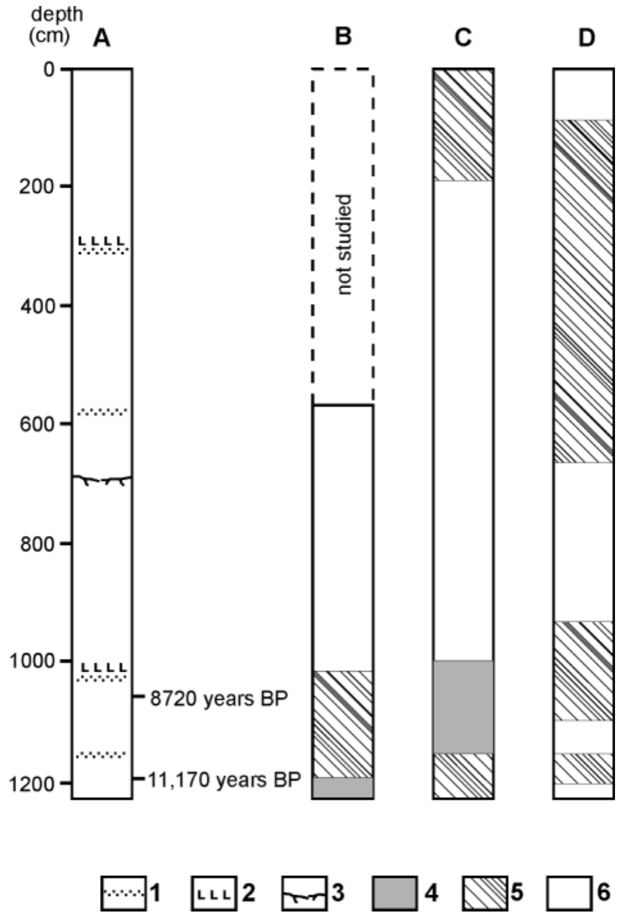

FIGURE 7 **Synthesis of paleoclimatic evidence in the Lagoa Dourada sediments. A) geological data. B) palynological data (Lorscheitter and Takeda, 1995). C) diatoms data (Moro, 1998). D) carbon isotope data. 1: main concentration of sand; 2: pyrite and/or gypsum; 3: fracture; 4: drier climatic phases; 5: intermediary phases; 6: wetter climatic phases.**

Paleoecologic and paleoclimatic studies on the Holocene in South America have shown that savannahs would advance over the forests in the drier periods and retreat during the humid periods (Absy et al., 1991; Ledru, 1993 and others).

The isotope ratio $^{13}C/^{12}C$ (or $\delta^{13}C$) in different plant communities reflect differentiated fractionating during metabolism, which allow for distinguishing plants of type C_3 and of type C_4 (Galimov, 1985). The vegetation communities with predominance of type C_3 plants (especially arboreal) are typical of more humid climates, whilst type C_4 (especially gramineae) is typical of drier climates (Dzurec et al., 1985). Carbon isotope variations in sediments and soils may, therefore, reflect variations in the vegetation paleocommunities from which one may infer the existence of climatic variations (Pessenda et al., 1996a and others).

Type C_3 plants show $\delta^{13}C$ values varying from -32 to -20‰, with average of -27‰, while type C_4 plants show $\delta^{13}C$ values varying from -17 to -9‰, with average of -13‰, existing therefore a difference around 14‰ between the two communities (Boutton, 1991; Pessenda et al., 1996a).

In general, the total carbon percentage in the core from the Lagoa Dourada is relatively low (0.11 to 0.83%), corroborating the results for the organic matter content obtained by Moro (1998), who interpreted them as suggestive of sedimentation in shallow water containing an abundant supply of dissolved oxygen resulting in the decomposition of organic matter. The low carbon content may also reflect a strong terrigenous mineral input by the floodwaters of the Guabiroba River.

The $\delta^{13}C$ data (-20.1‰ to -23.4‰) suggest that the deposition of organic matter in the Lagoa Dourada was linked to a plant community very similar to the present-day vegetation of the area, where arboreal plants (average of -27‰) are mixed with gramineae (-13‰). Values of $\delta^{13}C$ near the surface in forest soils at Londrina (51º10'W, 23º18'S, about 230 km to the northwest of Lagoa Dourada) are around -25.8‰ (Pessenda et al., 1996b), more typical of arboreal plants, which reinforces the interpretation that the $\delta^{13}C$ in Lagoa Dourada is really reflecting a mixed vegetation consisting of forests and grasslands.

Three "cycles" of increased total carbon rates are seen in the Lagoa Dourada sediments. They apparently coincide with the increase in the $\delta^{13}C$. Several hypotheses could explain the existence of such "cycles":

a) Alternating conditions of greater or lesser decomposition of the organic matter in the sediments, that due to local conditions; this would promote a variation in isotopic fractionating and the sedimentation of carbon (Martinelli et al., 1996).

b) Variations in the vegetation cover and drier climatic phases would favour the growth of type C_4 plants (gramineae) with a consequent increase in $\delta^{13}C$; the increase in the total carbon rates could result from a greater influx of organic matter during phases of greater environmental imbalance.

c) Variations in the salinity of the pond's water; during drier periods, with consequent increase in the alkalinity due to greater water evaporation; submerged aquatic plants and plankton tend to utilize the bicarbonate and not the CO_2 dissolved in water, resulting in increasing $\delta^{13}C$ values (Stuiver, 1975 *apud* Lobo, 1997).

d) Variations in the productivity of the pond. Higher productivity, with higher dissolved CO_2 content, influenced the selective absorption by biota, with a tendency to increasing $\delta^{13}C$ values (Meyers and Ishiwatari, 1993).

Thick sand layers could be interpreted as reflecting times when the sedimentation in the Lagoa Dourada was due to the influx of spring water, and that this was relatively more important than the contribution of the overflow of the Guabiroba River. These times may indicate dryer climatic phases, with consequent diminution of fluvial overflow, but with maintenance of the influx of groundwater from springs.

The convergence of some of the possible paleoclimatic evidence shown in Fig. 7 (the occurrence of pyrite and gypsum, this resulting from the oxidation of pyrite; major sandy layers; pollen, diatom and carbon content) suggests that a drier paleoclimatic phase may be represented in the Lagoa Dourada sediments at the base of the core (around 1000–1200 cm), dated at 8720±150 years B.P. (point 1060 cm).

Among the studies synthesised in Fig. 6, some make reference to drier phases that could correspond to this period (Servant et al., 1989; Ledru, 1993; Stevaux, 1994; Melo, 1995). Moreover, other studies interpret drier phases around 8500 years B.P., based on the identification of erosive-depositional events (Mello, 1992; Mello et al., 1995).

The signs of another drier phase at the Lagoa Dourada in more recent times, though existing, are less consistent. They are the presence of pyrite (and gypsum from its oxidation) (point 278cm), and a "cycle" of carbon content variation. Most studies synthesised in Fig. 6 indicate the existence of a drier paleoclimatic phase between 5000 and 3000 years B.P. that could correspond to the evidence coming from the upper half of the Lagoa Dourada sediments.

Some statements can be done after these studies in the Lagoa Dourada's sediments: sedimentological data do have useful paleoenvironmental and paleoclimatic information; the reconstructions are coherent with the previous biological (pollens and diatoms) reconstructions; the comparison with other known records of the region support the regional validity of the reconstructions.

CONCLUSIONS

The Lagoa Dourada receives the muddy floodwaters of the Guabiroba River, showing that it is an open rather than a closed system. The sediments that fill the pond originate from the source rocks in its immediate surroundings. These are the rocks along the course of the groundwater system that feeds the springs at the northern margin of the pond and the rocks that underlie the watershed of the Guabiroba River upstream from the pond.

Sediments that fill the Lagoa Dourada are predominantly muddy in the southern and southeastern parts of the pond, changing to sandy in the northern and northwestern parts. The mud comes mainly from the floodwaters of the Guabiroba River, whereas the sand comes from the springs at the northern edge of the pond. The advance of sand layers from northern border suggests dryer climatic phases with diminution of fluvial overflow.

The occurrence of euhedral pyrite in the sediments of the pond indicates the reduction of oxygen, due to abundant organic matter or increased salinity of the water during the sedimentation, which could be related to greater evaporation during dryer climatic phases.

It is possible to distinguish three "cycles" of increase in total carbon content in the pond's sediments, which seemingly coincide with a slight increase in the isotope ratio $^{13}C/^{12}C$ ($\delta^{13}C$). Several hypotheses could explain the existence of such "cycles": a succession of conditions of either a greater or lesser decomposition of organic matter of the sediments; variations in the vegetation cover with greater participation of type C_4 plants (gramineae), possibly related to drier climatic phases and consequent increase in $\delta^{13}C$; and variations in the salinity of the pond's water.

The sedimentological evidence reinforces the interpretation of a drier paleoclimatic phase at the base of the core of the Lagoa Dourada sediments, with radiocarbon dating at 8720±150 years B.P. Indications of a second drier phase in more recent times closer to the top of the core are less consistent. It could correspond to the drier phase in the southern and southeastern Brazil between 5000 and 3000 years B.P. indicated by other paleoclimatic studies.

The carbon content and the mineralogical composition of the clays are more useful tools than the sand mineralogy for the interpretation of paleoclimatic changes in the Lagoa Dourada and other similar geological settings in the region because of the high chemical maturity of the sand grains in the source rocks and sediments.

As the Lagoa Dourada is being regularly invaded by floodwaters of the Guabiroba River, interpretations based on mineralogy, carbon content, palynomorphs and diatoms should consider the influence of the hydrological regimen in the watershed as a whole, and not just that in the immediate environs of the pond itself.

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