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Holocene palaeoclimates of southern Patagonia: limnological and environmental history of Lago Cardiel, Argentina

Vera Markgraf,[1]* J. Platt Bradbury,[2] Antje Schwalb,[3] Stephen J. Burns,[4] Charles Stern,[5] Daniel Ariztegui,[6]** Adrian Gilli,[6] Flavio S. Anselmetti,[6] Scott Stine[7] and Nora Maidana[8]

([1]Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado 80309–0450, USA; [2]5784 Horseradish Gulch, Golden Colorado 80403, USA; [3]Institut für Umwelt-Geochemie, Universität Heidelberg, Im Neuenheimer Feld 236, D-69120 Heidelberg, Germany; [4]Department of Geosciences, University of Massachusetts, Amherst, Massachusetts 01003–5820, USA; [5]Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309–0399, USA; [6]Geological Institute, Swiss Federal Institute of Technology ETHZ, Sonneggstrasse 5, CH-8092 Zürich, Switzerland; [7]Department of Geography and Environmental Studies, California State University, Hayward, California 94542, USA; [8]Departamento de Ciencias Biologicas, Laboratorio de Morfologia Vegetal, Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, 1428 Buenos Aires, Argentina)

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Abstract: Multiproxy palaeoenvironmental and palaeolimnological analyses of two Holocene-age sediment cores from the margin of Lago Cardiel, a 76 m deep, closed-basin lake in southern Patagonia (latitude 49°S), provide information on lake-level changes that can be related to regional palaeoclimate scenarios. Sedimentologic (magnetic susceptibility, organic and inorganic carbon content) and environmental indicators (pollen, diatoms, ostracodes and stable isotopes on ostracodes) show lake levels markedly higher than today during the early Holocene, following a rapid lake-level rise after a desiccation phase prior to 11 000 BP. After about 6000 BP, lake levels were generally lower, but underwent repeated fluctuations. These inferred changes support the previously proposed view that the southern westerly stormtracks were focused (zonal) north of latitude 50°S during the early Holocene, allowing for Antarctic cold fronts to bring easterly moisture to southern Patagonia, whereas during the late Holocene the stormtracks shifted seasonally, with an overall more meridional behaviour, resulting in less and more variable moisture at these latitudes.

Key words: Environmental history, multiproxy approach, palaeolimnology, palaeoclimates, lake levels, stormtracks, Patagonia, Lago Cardiel, Argentina, South America, Holocene.

Introduction

Lago Cardiel, located in the Patagonian region of Santa Cruz province in Argentina (Figure 1), lies at an elevation of 276 m a.s.l., beyond the reach of past and present Andean glaciers and their meltwaters. The heart-shaped lake of about 370 km^2 and a lake drainage area of about 4500 km^2 has a present maximum water depth of 76 m. Cretaceous sediments and Tertiary basalts outcrop in the watershed (Feruglio, 1950; Hensheimer, 1959). Rio Cardiel is the principal, perennial inflowing river. Several smaller, permanent and ephemeral streams originate within the perimeter

*Author for correspondence (e-mail: markgraf@spot.colorado.edu)
**Present address: Institut Forel and Department of Geology and Paleontology, University of Geneva, Rue des Maraichers 13, 1211 Geneva 4, Switzerland

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of the basin. Present-day mean annual precipitation, falling primarily during the winter months (May to August), ranges from about 160 mm near the lake to a maximum of 500 mm in the western and northwestern mountainous area (1300 to 1700 m elevation) where the Rio Cardiel originates (Heinsheimer, 1959). Mean annual air temperature is about 8°C and prevailing winds, especially strong and persistent during summer, are from the west. Like many closed lakes in Patagonia, Lago Cardiel has been receding since 1940 (Stine and Stine, 1990). Present-day vegetation is Patagonian steppe-scrub, with patches of tall shrubs in the valley bottoms (*Schinus patagonicus, Berberis empetrifolia, Lycium chilense* and *Verbena tridens*). Exposed mudflats around the lake margin are covered by dense growth of Chenopodiaceae and other weedy taxa, some of European origin. Subantarctic *Nothofagus antarctica* woodland and *Nothofagus pumilio* forest grow on the higher-elevation mountains about 50 km to the northwest of the lake catchment.

In studying fossil shoreline tufas and sediments, dissected by Rio Cardiel and other streams, Galloway *et al*. (1988) and subsequently, in far greater detail, Stine and Stine (1990) identified and radiocarbon dated former Lago Cardiel highstands. Stine and Stine (1990) measured and dated lake-transgressive and lake-regressive deposits exposed in the walls of stream cuts, as well as numerous strandlines that encircle the lake. The highest strandline at +75 m above the 1990 lake surface (273 m) is deeply dissected by numerous arroyos, and is characterized by a subdued morphology and by wind-polished stone pavements. Its age is beyond radiocarbon dating. At +55 m is a littoral embankment (beachridge) that has been dissected by only the largest of the lake's inflowing streams, and whose surface clasts lack notable polish. In cross-sections exposed in stream cuts, this embankment can be seen to conformably overlie a lake-transgressive sequence of upwardly fining littoral gravels and sands intercalated with thin plates of cemented tufa near the base. Fossil oogonia and stems of *Chara* near the top of the deposits represent a lagoon that subsequently developed behind the embankmant. Radiocarbon dates on calcareous plates of tufa and *Chara* yield ages of 9780 and 9480 BP, respectively, demonstrating an early-Holocene age for this high stand (Stine and Stine 1990). Thoroughly tufa-cemented littoral gravel at the +43 m level forms a beachrock that dates at 8620 BP, indicating that the lake had fallen at least 12 m from its early-Holocene highstand by that time. A sequence of five radiocarbon dates on thin plates of tufa that lie within a stratigraphic section of deltaic bottomset beds at the +28 m level indicate that the lake remained above that elevation until 7690 BP, after which it declined to an undefined lowstand. Since then the lake has undergone at least five transgressions and regressions, all of which have been dated by radiocarbon analyses of buried soils and peats and rooted stumps. Only the first of these five trangressions, which peaked at 5130 BP, exceeded a level of +20 m. The four other late-Holocene lake-level highstands of +3 to +10 m were dated between 4540 and 3070 BP, around 2000, 1450 and 800 BP. At least two of the late-Holocene regressions took the lake to levels below that of 1990, though the precise elevations of these lowstands could not be determined. In 1990 the lake stood, by Holocene standards, at a very low level.

In 1998 a renewed interdisciplinary effort was undertaken, with funding from the US and Swiss National Science foundations, to provide a more complete history of palaeoenvironmental and palaeolimnological changes for this basin. The co-operative international project included present-day limnological data collection (Schwalb *et al*., 2002), analysis of data based on seismic mapping of the basin sediment fill (Gilli *et al*., 2001), collection of sediment cores, analysis of sediment stratigraphy and palaeoenvironmental indicators in sediment cores. Here we report on the multiproxy study of two Holocene-age cores taken at the present-day shoreline in the Bahía Pescaderia on the north coast of Lago Cardiel. The analyses included radiocarbon dating of the sediments, chemical fingerprinting of distinct tephra layers, using trace element analysis, diatom, pollen and stable isotope analyses on ostracodes, and total organic (TOC) and inorganic (TIC) carbon.

Methods

Two sediment sections were cored with a square-rod Livingstone piston corer in 1998 and 1999. Magnetic susceptibility (10^{-5} SI) was measured prior to opening the cores using a multisensor core logger at the Paleolimnology Laboratory, ETH, Zürich, Switzerland. Subsequently the cores were photographed and subsampled for different analyses. Total inorganic carbon (TIC) and total carbon (TC) were measured on the <2 mm sediment fraction ground to <500 μm, using a coulometer in the Sedimentologic Laboratory of INSTAAR. Ostracodes were separated according to a modified version of Forester (1988). One to 12 g of wet sediment were placed in wide-mouth plastic bottles and shaken with 250 mL of 90°C deionized water and one teaspoon of baking soda. To promote full dispersal, the sample sat for several more hours. The sample was then frozen, allowed to thaw and sit for several hours. The disaggregated sediment was slowly sieved by hand through a 63 μm sieve, rinsed with deionized water and air-dried. Well-preserved valves of *Eucypris* sp. aff. *E. fontana*, the most abundant ostracode species in the lake, were selected for stable isotopic analyses ($\delta^{18}O$ and $\delta^{13}C$). Two samples from the lowermost levels were analysed on valves from *Ilyocypris ramirezi*. One to four valves per sample were analysed for oxygen and carbon isotopes on a VG Prism ratio mass spectrometer (Universität Bern) using an online, automated carbonate preparation. Analytical reproducibility for standards is 0.08‰ for $\delta^{18}O$ and 0.04‰ for $\delta^{13}C$. All analyses are reported relative to the VPDB standard, and were corrected using the phosphoric acid fractionation factor for calcite at the appropriate temperature. Pretreatment for pollen analysis consisted of hydrofluoric acid, to eliminate inorganic matter, followed by acetolysis, to reduce dispersed organic matter. Pollen was counted on a Leitz Ortholux microscope with ×400 to ×1000 magnification. Pretreatment for diatom analysis consisted of digesting the sample in concentrated HNO_3 at 100°C for 30 minutes in a hot water bath to eliminate carbonates and labile organic compounds. Diatom concentration was determined by mounting similar volumes of diatom residue and determining the number of frustules per mm^2 on the microscopic coverslip. Tephra samples were washed with distilled water and dilute HCl, ground to a powder, and analysed for trace elements (Rb, Sr, Zr, Y and Nb; Table 3) concentrations by energy-dispersive X-ray fluorescence.

Results

Core lithology and chronology

The 1062 cm long sediment core CAR-98–2L was retrieved in January 1998 on the north side of Lago Cardiel (48°48.5′S, 71°13′W) at the present-day shoreline in Bahía Pescaderia at 276 m elevation (Figure 1). The core site lies at the mouth of an incised drainage channel, which carries water and sediment at times of heavy rainfall. In the upper 520 cm the sediment is composed of fine grey, light and dark banded clay, interbedded with fine black sand bands, especially between 100 and 300 cm. Plant detritus (probably *Ruppia)* is abundant at 175–190 cm, 257–300 cm, 380–400 cm and 500–520 cm. Below 520 cm the sediment is more uniform, compact clay with increasing amounts of sand below 950 cm. One major black sandy layer at 838–839 cm was identified by petrochemical analysis as volcanic tephra derived from a mid-Holocene (~6700 BP) eruption of the Hudson volcano. The base at 1062 cm is composed of bluish, dry clay with reworked clay granules.

A second, 704 cm long sediment core (CAR-99–2L) was retrieved in March 1999 *c*. 1 km west of core CAR-98–2L (Figure 1), also at the present-day shoreline, but distant from any inflowing stream channel. The stratigraphy resembles core CAR-98–2L, showing a higher frequency of sandy layers in the upper 260 cm, more compact clays between 260 and 480 cm, sandy clays between 480 and 620 cm, and compact clays below 620 cm. Plant remains (probably *Ruppia*) are abundant at 210–216 cm and 620–645 cm. At 100 cm, 550 cm and between 620 and 638 cm the sediment contains snails. Wood pieces are found at 626 cm, and *Chara* detritus at 627–632 cm. At 683 cm there is a sharp transition to mottled red and green, dry, reworked clay granules.

AMS radiocarbon dates were obtained for both cores on wood, snails, *Ruppia* plant remains and *Chara* detritus (Table 1). To test for potential dating problems caused by hard-water effects originating from occasional Cretaceous-age oyster shells in deposits surrounding the lake, three samples of living green algae and *Ruppia* were also dated. All three samples were reported as postmodern (108% to 117% of modern), suggesting that the fossil aquatic organic materials should yield reasonable ages.

Both cores CAR-98–2L and CAR-99–2L represent a fairly complete record of near-shore Holocene sedimentation. Although the base of core CAR-98–2L could not be dated, it was correlated with core CAR-99–2L based on the characteristic stratigraphy of the diatom *Epithemia argus* and the calcareous green alga *Phacotus*. Presence of *Phacotus* at 1050 cm in CAR-98–2L can be related to the level of 645 cm in CAR-99–2L. The initial increase of *Epithemia argus,* occurring at 645 cm depth in core CAR-99–2L and dated to 9880 ± 85 BP correlates to the depth of 1020 cm in CAR-98–2L. The end of the *Epithemia argus* interval at 627 to 632 cm depth in CAR-99–2L, dating 9590 ± 65, correlates to the depth of 1000 cm in core CAR-98–2L.

Chronologic evaluation of the cores was aided by identification of distinct volcanic ashes. Geochemical fingerprinting of ash deposits from cores and outcrops in southern Patagonia and Tierra del Fuego indicate that just five eruptions of four different volcanos are responsible for the most important and regionally widespread volcanic tephra deposits in this region (Stern, 1991; 1992; 2000). Only two of these eruptions are known to have deposited ash in the area of Lago Cardiel; one produced by the Hudson volcano (46°S latitude), and another from one of three volcanos (Aguilera, Viedma or Lautaro, located between 49 and 50°S latitude) in the Northern Austral Volcanic Zone (NAVZ). For the Hudson H1 tephra, found both north and south of Lago Cardiel (Stern, 1991; Naranjo and Stern, 1998), an age of ~6700 BP was determined, and for the ash derived from one of the NAVZ volcanos the age is ~3345 BP (Tables 2 and 3). A tephra layer with the same petrochemical characteristics as the NAVZ standards, found in a peat outcrop within the Lago Cardiel drainage, has been dated to 3010 ± 45 BP. We use this latter age rather than the ~3345 BP age proposed by Stern (1991; 1992; 2000). Other widespread tephra in southernmost Patagonia, produced by explosive eruptions of Reclus (51°S) and Mt Burney (52°S) volcanos, are found only south of Lago Cardiel.

All Hudson tephra samples are characterized by olive-green glass with relatively high amounts of zirconium (Zr > 200 ppm) (Figure 2) and other high-field-strength elements such as titanium, hafnium, yttrium and niobium. Green Hudson-derived tephra found at Lago Cardiel, both in cores and in one outcrop, are compositionally similar to tephra formed by explosive eruption H1 of the Hudson volcano at 6700 BP. In contrast, all tephra from the three NAVZ volcanos are characterised by clear glass, the presence of biotite and relatively low zirconium (Zr <150 ppm) and other high-field-strength elements. Mt Burney and Reclus tephra are also characterized by clear glass, but lack biotite and have relatively low rubidium (Rb 5–15 ppm for Mt. Burney and 25–40 ppm for Reclus) compared to tephra derived from the NAVZ volcanos (Rb 55–90 ppm) (Figure 2). White, biotite-bearing tephra found at Lago Cardiel, both in cores and outcrops, are compositionally similar to the tephra formed by the ~3345 BP eruption from one of the three NAVZ volcanos.

Whereas both volcanic ashes are well distinguished in the open-water cores (Gilli *et al*., 2001), the correlation of the volcanic ashes in the shore cores is problematic. The 6700 BP Hudson H1 ash is found as a distinct tephra layer at 838 cm depth in core CAR-98–2L, but in core CAR-99–2L volcanic glass shards characteristic of Hudson H1 ash are found in variable concentrations between 615 and 460 cm depth. Extrapolating from the dates of 9590 BP at 627–632 cm depth, directly underlying the first occurrence of Hudson H1 volcanic shards, and 8610 BP at 550 cm depth suggests the 6700 BP Hudson H1 ash should occur

Table 1 Radiocarbon and tephra dates from Lago Cardiel cores CAR-98–2L and CAR-98–2L

Sample	Depth (cm)	Age (BP)	Laboratory no.	Dated material
Ruppia		117% modern	NSRL-10767	Living *Ruppia* leaves
Green algae in Rio Cardiel		108% modern	LDGO-1714Y	Living green algae
Green algae in Lago Cardiel		108% modern	LDGO-1714Z	Living green algae
CAR-98–2L	257–258	1630 ± 40	CAMS-59501	*Ruppia* stems/leaves
CAR-98–2L	383–384	3100 ± 40	CAMS-59592	*Ruppia* stems/leaves
CAR-98–2L	518.5–519.5	4460 ± 30	CAMS-59593	*Ruppia* stems/leaves
CAR-98–2L	837–838	6700		Hudson H1 tephra
CAR-99–2L	460–615	6700		Hudson H1 tephra
CAR-99–2L	550–551	8610 ± 75	NSRL-11432	snail
CAR-99–2L	626	10 230 ± 65	NSRL-11433	wood
CAR-99–2L	627–632	9590 ± 65	NSRL-12507	*Chara* hash, carbonate
CAR-99–2L	645	9880 ± 85	NSRL-12508	*Ruppia* (?), rootlets (?)

Table 2 Petrographic data from regionally widespread tephra in southern Patagonia (Stern, 1990; 1991; 1992; 2000; Stern and Kilian, 1996; Naranjo and Stern, 1998)

Standards	Number of samples	Rb	Sr	Zr	Y	Identity
Hudson <6720 >6625, green tephra						
Average	10	50	374	360	40	H1
Range	10	44–54	351–412	324–393	36–43	H1
Hudson <3670 >3495, green tephra						
Average	10	75	243	424	49	H2
Range	10	68–80	218–328	396–466	46–51	H2
Aguilera/Lautaro volcanos <3345, white tephra with biotite						
Average	6	60	390	137	12	NAVZ
Range	6	52–67	301–450	121–150	9–15	
Reclus volcano <12,060 >12,010, white tephra, no biotite						
Average	9	28	400	123	9	
Range	9	22–35	303–544	84–158	7–11	

Table 3 Petrographic data from Lago Cardiel samples, cores and outcrops

Sample/core/outcrop	Rb	Sr	Zr	Y	Identity
CAR-98–2L core, 838 cm, green tephra	51	360	320	42	H1
Duplicate	48	357	342	41	H1
CAR-98–11 core, 124 cm, green tephra	56	368	328	40	H1
Duplicate	59	382	319	37	H1
Duplicate	64	346	341	41	H1
CAR-99–2L core, 463–464 cm, green tephra	55	399	363	38	H1
Duplicate	62	409	330	43	H1
PCAR-99–7–4 core, 59–60.5 cm, green tephra	46	391	330	45	H1
Duplicate	48	378	350	41	H1
PCAR-99–9–11 core, 365.5–375.5 cm, green tephra	60	410	349	45	H1
Arroyo Cerro Bajo outcrop, green tephra	48	377	344	40	H1
Duplicate	53	358	359	43	H1
CAR-98–8 core, 121 cm, white tephra w. biotite	101	280	111	16	NAVZ
Duplicate	98	282	121	14	NAVZ
Duplicate	99	279	105	15	NAVZ
CAR-98–11 core, 124 cm, white tephra w. biotite	102	297	110	13	NAVZ
Duplicate	95	318	120	15	NAVZ
Duplicate	110	309	111	12	NAVZ
PCAR-99–7–0B core, 16–17 cm, white tephra with biotite	79	373	135	13	NAVZ
PCAR-99–9–6 core, 32–33 cm, white tephra with biotite	88	304	127	15	NAVZ
Bahía Puntudo outcrop, white tephra with biotite	80	295	128	13	NAVZ
Ea. La Colorada, Meseta Strobel, white tephra with biotite; dated 3010 ± 45 (Table 1)	68	307	147	12	NAVZ
Ruta 40 excavation, LC40, white tephra with biotite	70	364	117	10	NAVZ

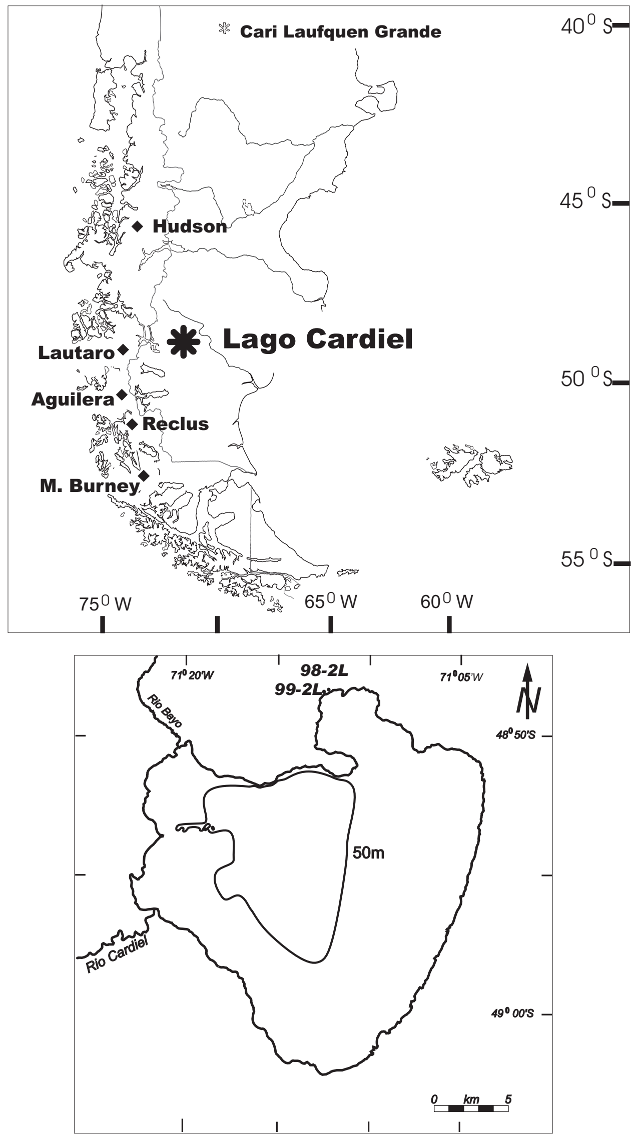

Figure 1 Map of southern South America with location of Lago Cardiel and volcanos mentioned in text (upper panel). Map of Lago Cardiel with location of shore cores CAR-98–2L and CAR-99–2L (lower panel). Water depth in area within dotted line is between 50 m and 76 m.

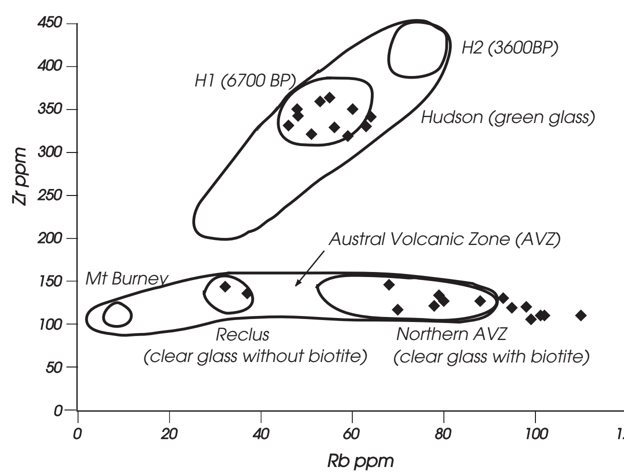

Figure 2 Rubidium (Rb) versus zirconium (Zr) concentrations, in parts per million (ppm), for samples of tephra from Lago Cardiel cores (solid diamonds) compared to fields for the compositions of Patagonian tephra derived from the Hudson (Stern, 1991; Naranjo and Stern, 1998) and Austral Volcanic Zone (AVZ) volcanos (Stern, 1990; 1992; 2000; Stern and Kilian, 1996) in the southern Andes.

in core CAR-99–2L around 460 cm depth. The presence of Hudson H1 ash over 155 cm depth in core CAR-99–2L might be explained by reworking of ash into desiccation cracks or by post-depositional intrusion of the ash into the deeper, soft clay levels (e.g., Anderson *et al*., 1984; Beierle and Bond, 2002). In either case, the well-defined diatom stratigraphy suggests that there was no sediment mixing.

Volcanic glass shards of the younger light-coloured ash, ascribed petrochemically to a volcanic eruption in the Northern Austral Volcanic Zone (NAVZ), are found in very small amounts in core CAR-99–2L at 370 cm depth. Absence of this tephra layer at the levels in core CAR-98–2L dated 3100 BP (383 cm) is due either to the dilution of the sediments by sand or to erosion during a lacustrine lowstand, although discrete layers of this ash are found in outcrops of littoral, bedded sand at several locations around Lago Cardiel at about 1 m above the 1998/1999 shoreline level (276 m).

Sedimentology

Sedimentologic changes are based on macroscopic sediment characteristics, trends and shifts in magnetic susceptibility and total inorganic carbon (TIC) and total organic carbon (TOC, calculated as the difference between TIC and TC). Palaeoenvironmental changes are interpreted from changes in ostracode assemblages, stable carbon and oxygen isotope ratios on ostracodes, diatoms, green algae and pollen.

Magnetic susceptibility and TIC/TOC (Figure 3) show more stable conditions below 520 cm (*c*. 4500 BP) and 560 cm (*c*. 4700 BP), respectively, and more variable changes above those depths. The peak in magnetic susceptibility at 832 cm represents the Hudson H1 ash. Throughout core CAR-98–2L, TIC and TOC fluctuate inversely. TIC shows relatively higher levels between 1040 and 1000 cm (9500–9000 BP), followed by a decreasing trend to 620 cm depth. At the same time, TOC shows an increasing trend. Above 620 cm primarily TIC, but also TOC to a minor degree, show five fluctuations of relatively higher and lower values. The high TIC values often correspond to high values in magnetic susceptibility, represented by sandy layers in the sediment, including ostracode and mollusc remains. The high TOC values correspond to levels with high amounts of macroscopic plant detritus, primarily *Ruppia*.

Ostracodes and stable isotopes

The ostracode species assemblages of core CAR-98–2L consist of only four species; *Eucypris* sp. aff. *E. fontana, Limnocythere patagonica, L. rionegroensis* and *Ilyocypris ramirezi*. Changes in the assemblage composition divide the core into five ostracode zones (Figure 3). The lowermost zone 1 (below 1055 cm, > *c*. 9500 BP) is characterized by *Ilyocypris ramirezi*, a species characteristic of seeps, spring pools and small streams. It suggests that there was significant input of stream water at the core location and/or that the core site was close to the site where the stream entered. Between 1055 and 1005 cm (zone 2), *Eucypris* sp. aff. *E. fontana* and *Limnocythere rionegroensis* are dominant, and *L. patagonica* is present at most levels. This suggests moderate salinity and shallow lake conditions. Zone 3 (1005 to 765 cm, *c*. 9000 to 6000 BP) is characterized by *Eucypris* sp. aff. *E. fontana* and *Limnocythere patagonica*. This is the only zone in the core where *L. rionegroensis* is absent, attesting to fresher water and high lake levels. Between 765 and 485 cm (*c*. 6000 to 4000 BP zone 4), E*ucypris* sp. aff. *E. fontana* is again the dominant species, accompanied by variable occurrences *of Limnocythere patagonica. Limnocythere rionegroensis* is present in most samples. This suggests a return to more concentrated lake chemical conditions and lower lake levels. The uppermost 485 cm of sediment (zone 5) contain fluctuating abundances of *Eucypris* sp. aff. *E. fontana* and variable numbers of *Limnocythere patagonica. Limnocythere rionegroensis* is present in 50% of the sample horizons, indicating repeated changes between more saline and fresher phases.

A present-day ostracode calibration set helps interpret palaeolimnological conditions for data derived from core studies (Schwalb *et al*., 2002). Modern ostracode species assemblages, and ostracode and water isotope compositions from sites in the Lago Cardiel area at 48° to 49°S and 70° to 71°W, as well as in the Laguna Cari Laufquen area at 41°S and 68° to 69°W can be assigned to three groups: (I) springs, spring-fed pools and streams; (II) permanent ponds and lakes fed by a combination of surface water and runoff; and (III) ephemeral ponds and lakes. Group I is characterized by *Ilyocypris ramirezi, Amphycypris nobilis, Heterocypris incongruens* and *Eucypris* sp. aff. *E. fontana,* with oxygen isotope (δ^{18}O) values between –11 and –5‰, and carbon isotope (δ^{13}C) values between –13 and –7‰. Ostracodes from permanent ponds and lakes (group II) are characterized by *Limnocythere patagonica, Eucypris labyrinthica, Limnocythere* sp. and *Eucypris* sp. aff. *E. fontana,* with δ^{18}O values between –8 and +2‰ and δ^{13}C values between –6 and +4‰. Ostracodes of ephemeral ponds (group III) are dominated by *Limnocythere rionegroensis* with values between –1 and +3‰ for δ^{18}O and –5 and +2‰ for δ^{13}C.

The δ^{18}O values of Lago Cardiel waters show small seasonal variation of about 0.3‰; between –3.8‰ (January) and –4.1‰ (October) (VSMOW). These values are approximately 8 to 9‰ enriched compared to the primary source waters of the lake, Rio Cardiel (–12.3‰: January, –11.9‰: March, –14.1‰: October) and Rio Bayo (–13.4‰: January, –12.4‰: March, –13.2‰: October). Both input rivers are fed by snowmelt with a similar isotopic composition of –12.6‰.

Modern ostracode δ^{18}O values from surface sediments in Lago Cardiel show no clear trend with water depth, varying by

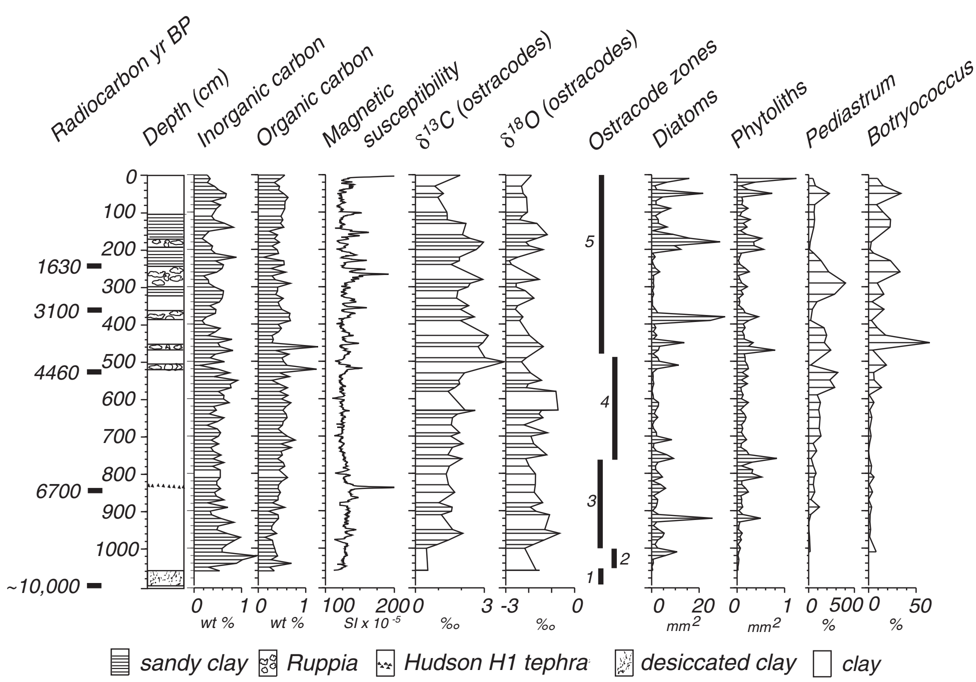

Figure 3 Selected sedimentologic and palaeoenvironmental records from core CAR-98–2L. See text for discussion of ostracode zones.

0.9‰ (of the mean values between 7 m and 35 m water depth), and show a positive offset from equilibrium (at measured temperatures) of up to 2‰. This difference is consistent with the observations by Xia *et al*. (1997), von Grafenstein *et al*. (1999) and Keatings (2000). The δ^{18}O values from *Eucypris* sp. aff. *E. fontana* do not show any marked differences between dead and living animals, consistent with the small seasonal difference in lake-water δ^{18}O. Thus, the isotopic signatures from *Eucypris* sp. aff. *E. fontana* specimens record annual averages of lake water δ^{18}O composition.

In contrast to the δ^{18}O values, the δ^{13}C values for *Eucypris* sp. aff. *E. fontana* show a clear trend in the transect samples from Lago Cardiel, ranging from +1.8‰ (7 m) to +2‰ (14.5 m), +2.9‰ (18 m), +3.0‰ (19 m) and +1.7‰ (35 m). This increasing and subsequently decreasing trend appears to relate to productivity which for diatoms and green algae increases from near-shore sediments to a maximum between 10 and 20 m water depth. The isotopic values are comparable to the range documented in the core.

Overall, neither carbon nor oxygen isotope ratios vary greatly over the length of the core. δ^{13}C values range from +1 to + 3‰ and δ^{18}O values from –3 to –1‰. Downcore changes for oxygen and carbon ratios analysed on *Eucypris* sp. aff. *E. fontana* in the Lago Cardiel shore core do not co-vary (Figure 3). Below 520 cm (*c*. 4500 BP), the δ^{18}O record is overall less negative (–1 to –2‰), whereas δ^{13}C values are less positive (+1 to +2‰); above 520 cm the reverse is true with more negative values of δ^{18}O (–2 to –3‰) and more positive values for δ^{13}C (+2 to +3‰). If Lago Cardiel remained a closed lake over the entire period of deposition recorded in our cores, then the fraction of water lost to evaporation was always 100%. For such a system, changes in lake-water δ^{18}O values are driven solely by changes in humidity, which determine the kinetic fractionation factor (Gonfiantini *et al*., 1986). In terms of regional climate, humidity changes probably correlate to changes in the evaporation to precipitation ratio (E/P). If interpreted in terms of changing E/P, then the shift upcore at 520 cm depth from less negative to more negative oxygen isotope values would suggest a shift from higher to lower evaporation, which should be accompanied by a shift from initially shallower to relatively deeper water levels. This scenario is, however, inconsistent with the results from the ostracode species assemblages that indicate higher water levels below 485 cm and shallower levels above that depth. Another way to interpret the isotopic and ostracode species assemblage data sets would suggest a change in temperatures instead. Below 520 cm bottom-water temperatures would have been lower, related to higher lake levels, while above 520 cm water temperatures would have been higher as lake levels fell, bringing the littoral zone where the ostracodes were living closer to the core site. A relatively small average increase in temperature of 4°C at the lake bottom would decrease ostracode calcite δ^{18}O values by about 1‰, as observed.

Carbon isotopes are controlled by the isotopic composition of the lake-water DIC which can be affected by external sources that include groundwater, dissolved old carbonates and soil DIC. The latter is influenced by the vegetation in the catchment, and depends strongly on the ratio of plants with C3 or C4 photosynthetic pathways. In Lago Cardiel, however, these external sources for DIC remained relatively unchanged (according to the pollen record) over the time period under consideration, and changes in δ^{13}C are thus probably affected by photosynthetic activity in the lake. Plankton preferentially take up the lighter carbon isotope ^{12}C leading to an enrichment of ^{13}C in the residual dissolved inorganic carbon (DIC) pool of the epilimnion (Stuiver, 1975: McKenzie, 1985). Organic matter depleted in ^{13}C may be oxidized during decay to release ^{13}C depleted CO_2 that is taken up by benthic ostracodes. More positive δ^{13}C values of ostracodes could therefore suggest a decrease in surface water productivity. However, the more positive δ^{13}C values above 520 cm in the Lago Cardiel record might indicate shallower-water littoral environments, where photosynthetic activity was high and ^{12}C enriched macrophyte and algal organic matter were buried. This interpretation seems supported by the modern data. In this scenario, overlying waters would have become enriched in ^{13}C that subsequently would be taken up by ostracodes growing in the littoral zone.

Pollen record

The pollen record (Figure 4) is dominated (60 to 70%) by non-arboreal taxa, including Poaceae (oscillating around 20%), Asteraceae subfamily Asteroideae (between 5 and 10%), Chenopodiaceae (20 to 40%) and a great diversity of other herbaceous taxa (10 to 20%). Arboreal taxa are represented by *Nothofagus dombeyi*-type (10 to 20%), *Podocarpus* (1 to 8%), and traces of *Drimys, Maytenus* and Cupressaceae (probably *Pilgerodendron*), all of which most likely represent long-distance transport from the west. Also, *Dryopteris*-type fern spores probably reflect long-distance sources. Shrub taxa include *Ephedra* (5 to 15%), *Schinus* (1 to 10%), *Berberis* (1 to 2%), Rhamnaceae (1 to 2%), Asteraceae subfamily Mutisieae (10% throughout) and traces of *Verbena. Botryococcus* and *Pediastrum*, both green algae, are abundant in the record, with values up to 60% (*Botryococcus*) and over 400% (*Pediastrum*) (calculated relative to the sum of pollen).

Modern pollen spectra from surface sediment samples from Río Cardiel and Lago Cardiel are generally similar to the fossil spectra in terms of taxa composition and proportions, reflecting the regional vegetation. Some differences are evident in the modern pollen proportions, however. For instance, Chenopodiaceae are more abundant near shore (100 to 300 m), in shallow-water (2 to 10 m) surface sediments, where they range from 20 to 30%, than at greater distance from shore (>400 m) and in greater water depths (>20 m), where the percentages decrease to less than 10%. Similarily, the green algae, *Botryococcus* and *Pediastrum*, show different relative proportions in surface samples from Lago Cardiel depending on water depths. Percentages are lowest (*Pediastrum*: 10 to 30%; *Botryococcus:* 3 to 10%) in samples near shore (<100 m) and at shallow depth (<5 m), percentages increase to 100 to 300% (*Pediastrum*) and 20 to 30% (*Botryococcus*) at intermediate distances from shore (100 to 400 m) and intermediate depths (6 to 15 m), and percentages decrease again to 50 to 80% (*Pediastrum*) and 10 to 20% (*Botrycoccus*) at distances >400 m and water depths >20 m. The intermediate zone of high green algae abundance is also the zone where *Ruppia* grows.

Whereas the fossil pollen spectra of CAR-98–2L show only minor proportional changes in the regional pollen input, major proportional changes characterize the input of local taxa, primarily Chenopodiaceae and green algae spectra (Figure 4). From 1020 cm to about 900 cm (*c*. 9500 to 7500 BP) regional pollen spectra are dominated by Poaceae, followed by Asteraceae and steppe herbs and scrub taxa. *Nothofagus* is present with only 10% and *Podocarpus* with less than 5%, reflecting low levels of pollen input from long distance. Among the herbaceous taxa, *Calandrinia* is present with 10% and among the steppe scrub taxa especially *Ephedra* is abundant with percentages of 15 to 18%. The abundance of C*alandrinia* and *Ephedra*, both found today on rocky and gravelly substrates, especially along shorelines or exposed deltas, suggests proximity to an active shoreline at that time. Between 900 and 750 cm (7500 to 6000 BP), *Ephedra* decreases, but continues with proportions above present-day values. Chenopodiaceae and other herbs increase slightly to 20% each (with almost 10% of the herbs represented by Caryophyllaceae replacing *Calandrinia*), and the green alga *Pediastrum* increases to over 50%. The Chenopodiaceae increase might suggest seasonal drying of many of the small lakes within the Cardiel basin and seasonally fluctuating lake levels. The *Pediastrum*

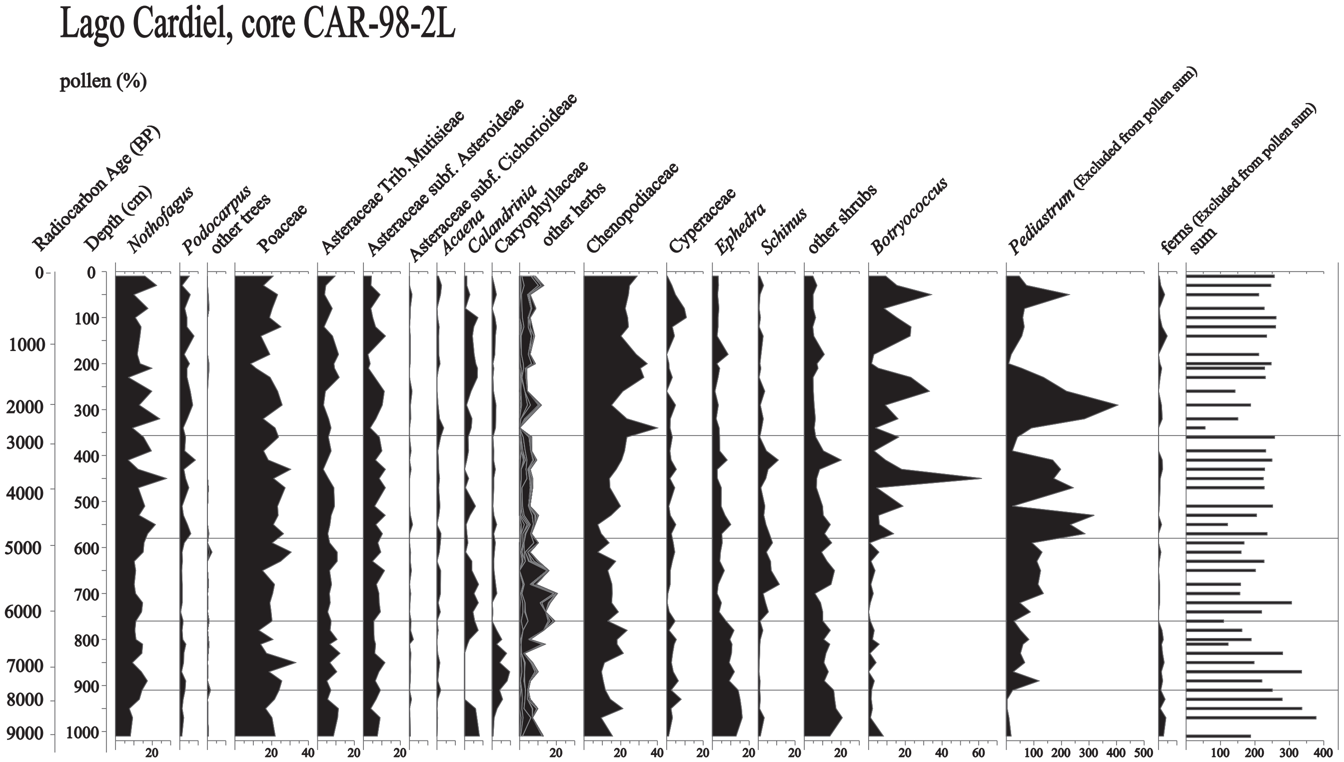

Figure 4 Pollen diagram of core CAR-98–2L (in %), showing major taxa, including ferns and green algae (*Pediastrum* and *Botryococcus*, in % of total pollen sum).

increase might imply increased turbulence, characteristic of conditions closer to the shore, with shallower water than before. At 750 cm (*c.* 6000 BP), *Ephedra* declines to less than 5%, *Schinus* increases up to 10%, and herbaceous taxa, the major component among them again *Calandrinia*, increase to near 30%. Poaceae decrease only slightly. However, pollen preservation during this interval, especially of herbaceous taxa, is poor. Simultaneously, *Pediastrum* increases from about 50% to over 100%. Higher amounts of pollen of *Schinus*, which today grows primarily along the watercourses, together with higher proportions of other shrubs, and lesser proportions of herbs, may indicate overall drier conditions. The higher values of *Pediastrum*, suggesting further increase in turbulence and thus further lowering of lake levels, would support this interpretation. Above 580 cm (*c.* 5000 BP) long-distance components *Nothofagus* and *Podocarpus* increase to 20% and 10%, respectively, both showing high variability. This suggests either that both taxa increased in abundance, growing closer to Lago Cardiel than before, or possibly that increased winds enhanced pollen transport. The increase in forest density at higher latitudes related to a decrease in fire frequency (Huber, 2001) supports the first explanation. The green alga, *Botryococcus* (maximum 40%) and *Pediastrum* (maximum 400%) increase markedly and show repeated fluctuations during the remainder of the record. All this suggests fluctuating environmental conditions in terms of turbulence and lake levels. At 350 cm (*c.* 3000 BP) *Schinus* decreases and remains at 2% for the remainder of the record, whereas shrubs as well as Chenopodiaceae increase, suggesting further increased regional dryness and lower lake levels.

Changes in pollen spectra probably reflect regional climatic variability, specifically changing moisture conditions, although the concomitant changes of Chenopodiaceae and green algae indicate that changing lacustrine conditions in part influenced shifts in pollen proportions.

Diatom record

Littoral benthic diatom taxa dominate cores CAR-98–2L and CAR-99–2L. Today, in Bahía Pescaderia, the productive littoral habitat lies about 200 m offshore in water 7 to 10 m deep, where aquatic macrophytes (e.g., *Ruppia cirrhosa*) grow within the photic zone (Lucchini, 1975). Diatoms, other algae, snails, ostracodes, amphipods and fish inhabit this zone and oxidation of the organic production here causes underlying sediments to become anoxic. The distribution of submerged macrophytes elsewhere in the lake is not known and the comparatively protected water of Bahía Pescaderia may represent a special case. Although planktic diatoms (*Cyclostephanos* sp. and *Thalassiosira patagonica*) are present and may dominate in surface sediment samples at greater depths, these small diatoms do not appear to contribute substantially to the overall productivity of Lago Cardiel because of the generally low numbers of all diatoms in deep-water sediments. Large quantities of suspended clay, and occasionally $CaCO_3$ whitings, give the lake a turquoise blue colour, and may curtail phytoplankton production through nutrient (P) removal by sorption or by co-precipitation with calcite (Otsuki and Wetzel, 1972).

Low, fluctuating diatom abundance and poor preservation characterize the shoreline cores CAR-98–2L and CAR-99–2L (Figures 5 and 6). This probably reflects dilution by clay-rich sediment entering Bahía Pescaderia from Cretaceous outcrops in the basin along with breakage and diatom dissolution in the turbulent and high pH water (~9) of the lake. Such fluctuations may not have large-scale limnologic significance. The greatest concentration and best preservation of diatoms coincides approximately with sandy or silty intervals identified by magnetic susceptibility and often with higher concentrations of phytoliths. Phytoliths are silt-sized silica deposits in terrestrial plant cells. Both the phytoliths and detrital silt and sand are concentrated in the shallow, high-energy depositional environments in the littoral zone of Lago Cardiel which also supports beds of subaquatic macrophytes and their epiphytic and benthic diatom communities within the photic zone. This productive zone, coupled with higher sedimentation rates, linked to sediment trapping by aquatic macrophytes, helps account for the preservation of diatoms in this lacustrine setting.

The diatom stratigraphy of both lake margin cores begins about 10 000 BP with high percentages of *Epithemia argus*, a benthic

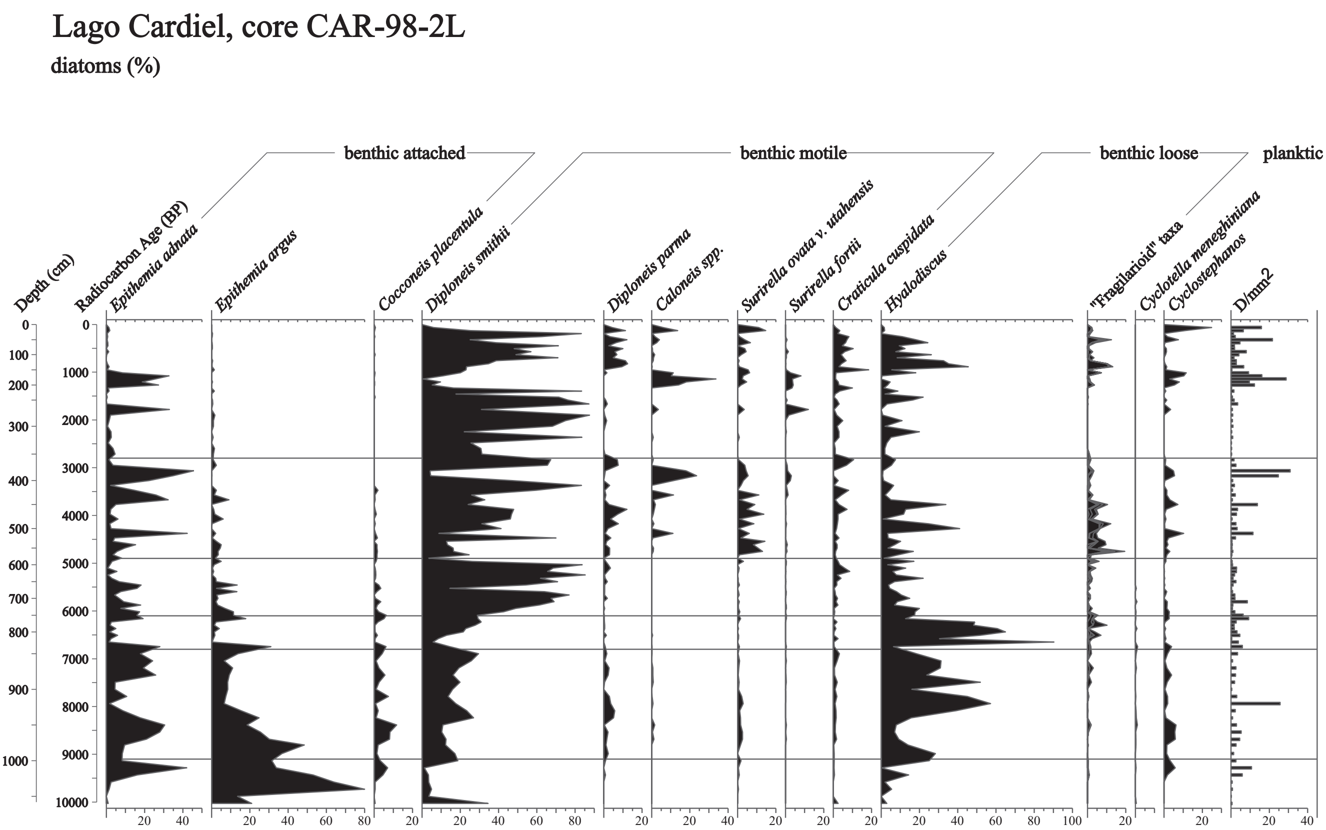

Figure 5 Diatom diagram of core CAR-98–2L (in %), showing major taxa and their limnological affinities.

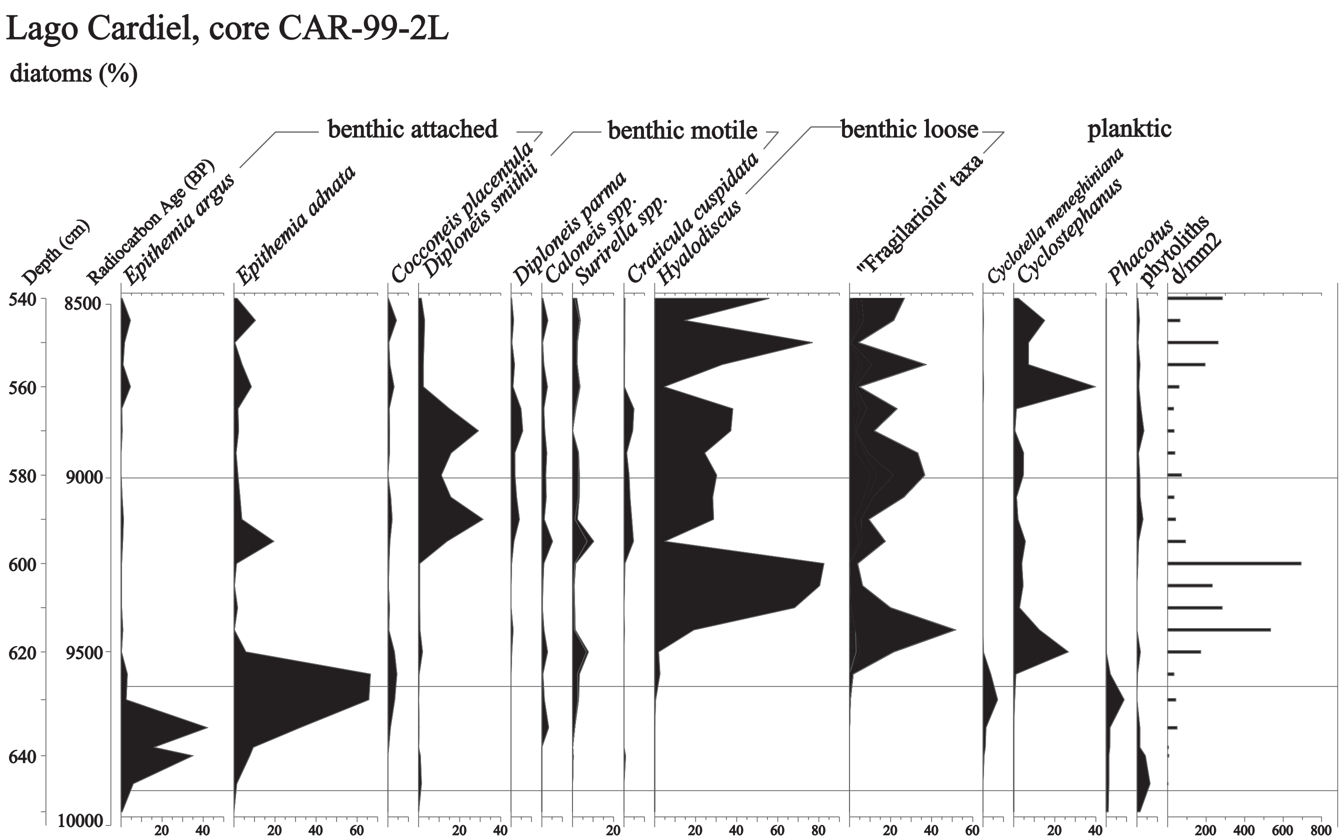

Figure 6 Diatom diagram of core CAR-99–2L (in %), showing major taxa and their limnological affinities.

diatom living attached to aquatic macrophytes and therefore indicative of shallow water within the photic zone of the lake. The age of this interval in core CAR-98–2L is based on correlation of the diatom stratigraphy with core CAR-99–2L, where the first increase of *Epithemia argus* is dated 9880 ± 85 BP and the end of the *E. argus* zone 9590 ± 65 BP (Figure 6). Hence, by the beginning of the Holocene, water level in Lago Cardiel rose to somewhat above the current shoreline elevation of 276 m. The diatom assemblage (*Epithemia argus*) suggests generally fresh (<3 g/L TDS), if alkaline, water with significant magnesium and sulphate concentration.

A small, undescribed species of *Hyalodiscus* characterizes the following interval from 950 cm to 750 cm (9600 to 6800 BP) of core CAR-98–2L. Today, this diatom is found between 15 m and 20 m depth in Lago Cardiel although it is not especially common. It probably lives loosely attached to available substrates within the lower part of the photic zone, but may enter the plankton if turbulence is sufficient. The co-occurrence of small numbers of planktic diatoms (*Cyclostephanos* sp. and *Cyclotella meneghiniana*) between 9600 and 8400 BP could testify to significantly higher water levels above the core site at this time that may relate to highstand deposits (+45 to +55 m) recorded on the margins of the Lago Cardiel basin about 9800 to 9400 BP (Stine and Stine, 1990).

The zone dominated by *Hyalodiscus* sp. encompasses a discrete layer of olive-brown tephra at 838 cm identified as the Hudson H1 ash, dated to 6700 BP. By interpolation between the age of the tephra layer and the overlying radiocarbon date (4460 BP at 520 cm), the end of the *Hyalodiscus* zone and the inferred intermediate lake stage occurred about 6100 BP.

The remainder of the core is dominated by large but fluctuating percentages of a motile benthic diatom, *Diploneis smithii*. The motile, benthic diatom community that includes *Diploneis smithii* and several other bilaterally symmetrical raphid diatoms (such as *Craticula cuspidata* and *Caloneis* spp.), typically lives on lake-bottom sediments where light is sufficient for growth. Being motile, these diatoms can move among the sediment grains to position themselves optimally for light and nutrients. Their ability to move to the sediment surface after episodic burial enables them to take advantage of habitats where currents repeatedly alter lake-bottom sediment surfaces. Consequently, in Lago Cardiel this diatom community is most common at shallow water depths, generally less than 15 m. Nevertheless, because of their exposure to high-energy environments, benthic motile diatoms often become short-term members of the plankton when turbulence is high. This is especially true for species of *Surirella,* whose flat, leaf- or disc-like shapes enables these diatoms to remain in the plankton for longer periods so long as wind-generated turbulence can support them.

The fluctuating dominance of *Diploneis smithii* after 6000 BP indicates that water levels of Lago Cardiel fluctuated around 10–15 m above the 1990 level. Strong fluctuations in relative abundance of this and other species may track rapid changes in lake level although similar fluctuations could be caused by diatom destruction or dilution in this high-energy depositional environment. The stratigraphy of *Surirella ovata* var. *utahensis* (*sensu* Sylvestre, 1997), a benthic motile species whose flat shape enables it to easily become planktic, may indicate episodes of somewhat greater water depth. The relative abundance of this diatom along a transect of surficial sediments in Lago Cardiel peaks at water depths between 40 and 45 m, indicating that *Surirella ovata* var. *utahensis* may be able to take advantage of a deep, turbulent water-column.

Discussion and conclusion

The following Holocene palaeoenvironmental history of Lago Cardiel sediments integrates the information from the analysis of sediment characteristics, ostracode assemblages, pollen, green algae, diatoms and stable isotopes on ostracodes (Figure 3). Following the desiccation phase dated 11 200 BP in deep-water core CAR-99–7P at –76 m (Gilli *et al.*, 2001) the lake rose rapidly and reached the present-day shoreline shortly after 10 000 BP. Dominance of benthic diatoms and the green alga *Phacotus*, as well as of the stream ostracode *Ilyocypris ramirezi*, in the basal levels of both lake margin cores represents the initial lake transgression above the present-day shoreline. After about 9500 BP, the lake was relatively deep as suggested by the abundance of benthic, loosely attached diatoms and the presence of planktic diatoms, low proportions of *Pediastrum* and *Botryococcus*, dominance of *Eucypris* sp. aff. *E. fontana* and *Limnocythere patagonica*, and absence of *L. rionegroensis.* This interpretation of an early-Holocene phase of a relatively deep, turbid lake, inferred previously by Stine and Stine (1990) on the basis of shoreline evidence, is also supported by the relatively low, stable magnetic susceptibility during that time. After 6100 BP lake levels fell to less than 15 m above present-day shoreline, judging from the dominance of motile and attached benthic diatoms, increased proportions of Chenopodiaceae, *Pediastrum* and *Botryococcus* and presence of *Limnocythere rionegroensis*. Since that time, the lake did not fall for extensive periods more than a few metres below the 1990 lowstand and, judging from the ostracode and diatom assemblages, water chemistry did not change significantly. As reflected by the pollen record, the regional vegetation experienced no major changes. After 4900 BP all palaeoenvironmental indicators analysed in core CAR-98–2L show generally more variable, almost cyclic changes. This mid- and late-Holocene interval is interpreted to represent changes between more and less turbulent lake conditions related to lake-level fluctuations. Intervals of increased lake turbulence, represented by sandy sediment, higher amounts of inorganic carbon, higher proportions of Chenopodiaceae, *Pediastrum* and *Botryococcus* and of the motile benthic diatom *Diploneis smithii* indicate lower lake levels when the core site was closer to the shoreline. Intervals of relatively more quiet and deeper-water conditions, when the core site was at some greater distance from the shore, are characterized by presence of *Ruppia* layers in the sediment, higher organic carbon content, higher proportions of loosely attached benthic diatoms (e.g., *Fragilaria* spp. and *Hyalodiscus* sp.) and high diatom and phytolith abundances.

With respect to the palaeoenvironmental interpretation of the ostracode stable isotope record, it appears that the $\delta^{18}O$ signal primarily reflects water-temperature changes, related to lake volume. Relatively positive $\delta^{18}O$ values during the early Holocene could relate to lower water temperatures associated with greater lake volume. The shift to more negative $\delta^{18}O$ values after 6100 BP would reflect higher water temperatures associated with the generally lower lake volume. The ostracode $\delta^{13}C$ record shows a comparable history in terms of palaeoproductivity, lower in the early Holocene, when the lake was deep, and higher in the late Holocene, when the water was shallower and the coring site closer to shore.

The earlier reconstruction of lake-level fluctuations (Stine and Stine, 1990), based on dating geomorphic features and lacustrine deposits above the 1990s lowstand level, generally agrees with the lake-level chronology interpreted from the shoreline cores. The +55 m early-Holocene highstand probably relates to the early-Holocene deeper-water phase in core CAR-98–2L, although the core dates suggest that the transgression above the shoreline did not begin until after 9600 BP. Outcrop ages of 8620 BP (+49 m) and of 7690 BP (+28 m) are in keeping with data from the core, pointing to a persistence of high water levels (relative to those of modern time) throughout the early Holocene. A mid-Holocene highstand (+21.5 m), dated 5130 BP, is followed by outcrop records of five lake regressions and four relatively minor (to +10 m) lake transgressions. This lake-level variability may correspond to the repeated fluctuations seen also in the core record, but the low resolution of both the outcrop and core chronologies cannot confirm the contemporaneity of the fluctuations.

The last of Lago Cardiel's regressions began around AD 1940, and culminated about 1990. Since then the lake has risen approximately 4 m (S. Stine, unpublished data), with most of the rise coming in association with El Niño-induced precipitation. This points to a modern climatic pecularity in this portion of Patagonia, which appears to be very dry by Holocene standards.

The multiproxy Holocene palaeoenvironmental history from Lago Cardiel helps to fine-tune the regional palaeoclimate evolution in southern South America. There are numerous records from temperate southern South America between 36 and 55°S, showing different histories for different latitudinal bands (Markgraf, 1991). The differences are related to different timing of maximum moisture, interpreted as reflecting differences in latitudinal position and intensity of the southern westerlies. The early Holocene, between 10 000 BP and 8500 BP, at both the northern (36° to 43°S) and at the southern latitudinal bands (52° to 56°S) are characterized by markedly drier environments (Villagrán, 1991; Markgraf, 1991; Huber and Markgraf, 2003), whereas during that time the intermediate latitudes (43° to 52°S), including Lago Cardiel, show maximum moisture levels (Lumley and Switsur, 1993; Bennett *et al*., 2000; Massaferro and Brooks, 2002). The westerlies must have been focused at the intermediate latitudes, perhaps in response to the small seasonal contrast in insolation at that time (Markgraf *et al*., 1992). Such focusing could allow for higher frequency of Antarctic cold air incursions, which would bring easterly moisture to southern Patagonia (Bradbury *et al*., 2001). After 8500 BP, moisture increased both in the northern and high southern temperate latitudes (Villagrán, 1991; McCulloch and Davies, 2001) whereas intermediate latitudes became drier and warmer (Massaferro and Brooks, 2002; Ashworth *et al*., 1991). The inferred intermediate lake levels of Lago Cardiel would support this scenario. To explain this latitudinal distribution of moisture, the westerly stormtracks probably became more meridional, shifting seasonally across the whole latitudinal band (Markgraf *et al*., 1992). For about 1000 years after 6000 BP, aridity affected the whole temperate region of southern South America, including Lago Cardiel. There is no climatologic explanation for this mid-Holocene widespread aridity that even includes northern South America, Central America and portions of North America (Grimm *et al*., 2001). After *c*. 5000 BP, modern environmental conditions (and climates), characterized by increased variability, became established throughout the southern temperate latitudes. In addition to the establishment of the seasonality shift of the westerly stormtracks, poleward in summer and equatorward in winter, the influence of El Niño/Southern Oscillation (ENSO) was undoubtedly contributing to this variability (McGlone *et al*., 1992). It is not surprising that Lago Cardiel with its repeated lake-level fluctuations illustrates this variability especially well, because ENSO very strongly affects this intermediate latitude east of the Andes (Villalba *et al*., 1997).

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