The LINNEAN SOCIETY of London BIOLOGICAL Journal of the Linnean Society

Biological Journal of the Linnean Society, 2011, **103**, 397–408. With 5 figures

Late quaternary environmental changes in Patagonia as inferred from lacustrine fossil and extant ostracods

GABRIELA CUSMINSKY[1]*, ANTJE SCHWALB[2], ALEJANDRA P. PÉREZ[3], DANIELA PINEDA[4], FINN VIEHBERG[5], ROBIN WHATLEY[6], VERA MARKGRAF[7], ANDREA GILLI[8], DANIEL ARIZTEGUI[9] and FLAVIO S. ANSELMETTI[10]

[1]*Departamento de Ecología CRUB UNC-INIBIOMA CONICET Quintral 1250, 8400 S. C. Bariloche, Argentina*
[2]*Institut für Umweltgeologie, Technische Universität Braunschweig, Langer Kamp 19c, D-38106 Braunschweig, Germany*
[3]*Laboratorio de Fotobiología CRUB UNC-INIBIOMA CONICET Quintral 1250, 8400 S. C. Bariloche, Argentina*
[4]*Department of Biology Lund University Sölvegatan 37, 223 62 Lund, Sweden*
[5]*Institut für Geologie und Mineralogie, Universität zu Köln, Zülpicherstrasse 49a, D-50674 Köln, Germany*
[6]*Department of Geology, Institute of Earth Studies, University of Wales, Aberystwyth, Cardiganshire SY23 3DB, UK*
[7]*INSTAAR, University of Colorado, Boulder, CO 80309-0450, and Northern Arizona University, Flagstaff, AZ 86001, USA*
[8]*Geological Institute, ETH Zurich, Sonneggstrasse 5, CH-8092, Zurich, Switzerland*
[9]*Section of Earth & Environmental Sciences, University of Geneva, Rue des Maraichers 13, 1205, Geneva, Switzerland*
[10]*Eawag, Swiss Federal Institute of Aquatic Science & Technology, Department of Surface Waters, Überlandstrasse 133, CH-8600 Dübendorf, Switzerland*

Received 18 February 2011; accepted for publication 18 February 2011

In the present study, we compare modern and Quaternary ostracods from two lacustrine basins: Laguna Cari-Laufquen (41°S) and Lago Cardiel (49°S) in Patagonia. Taxonomic and quantitative analyses along with isotopic and chemical studies of the extant ostracod fauna indicate that distinct ostracod associations can be identified as a function of conductivity. Three ostracod associations can be distinguished: (1) springs, ponds and small creeks, characterized by low conductivity (e.g. 1015 µs cm^{-1}); (2) lakes and permanent ponds, characterized by medium conductivity (e.g. 1625 µs cm^{-1}) and (3) ephemeral lacustrine environments, generally characterized by higher conductivity (e.g. 16 480 µs cm^{-1}) These modern ostracod associations were also identified in older sequences from sediments outcropping in the Laguna Cari-Laufquen current shoreline, as well as in sediment cores from Lago Cardiel. The predominance of *Limnocythere rionegroensis* Cusminsky & Whatley in the Cari-Laufquen sections suggests the development of a saline and turbid lake during the Late Pleistocene and Early Holocene, and thus higher precipitation at these latitudes. Changes in ostracod abundance and associations have been observed in Lago Cardiel during the last approximately 16 000 calibrated years BP. Conductivity is known to change as a function of the ratio of precipitation to evaporation and a decrease in conductivity from the Late Pleistocene to the Middle Holocene suggests substantial hydrological variations (i.e. increase of the precipitation/evaporation ratio suggests minor conductivity). These two examples show that ostracods provide an excellent proxy for interpreting palaeoclimatic and palaeoenvironmental changes in Patagonia. © 2011 The Linnean Society of London, *Biological Journal of the Linnean Society*, 2011, **103**, 397–408.

ADDITIONAL KEYWORDS: autoecology – non-marine ostracods – ostracods – Pleistocene to Recent sequences – Southern South America.

*Corresponding author. E-mail: gcusminsky@gmail.com

Se comparan ostrácodos modernos y cuaternarios de dos cuencas lacustres, la Laguna Cari-laufquen (41 °S) y el Lago Cardiel (49 °S) localizadas en Patagonia. Análisis taxonómicos, cualitativos junto con estudios isotópicos y químicos de la fauna actual indican que las asociaciones de ostrácodos pueden ser reconocidas a partir de la conductividad. De esta manera, tres asociaciones de ostrácodos pueden distinguirse: 1) manantiales, ojos de agua o arroyuelos caracterizados por una baja conductividad (p.ej., 1.015 μs cm^{-1}); 2) lagos y lagunas permanentes representados por una conductividad media (e.g. 1.625 μs cm^{-1}) y 3) ambientes lacustres efímeros en donde la conductividad es mayor (por ej., 16480 μs cm^{-1}). Estas asociaciones de ostrácodos fueron reconocidas en secuencias antiguas como ser en afloramientos de líneas costa de la Laguna Cari-Laufquen o en testigos sedimentarios del Lago Cardiel. La dominancia de *Limnocythere rionegroensis* Cusminsky y Whatley en las secciones de la Laguna Cari-Laufquen sugieren la presencia de un lago salino y turbio durante el Pleistoceno tardío-Holoceno temprano el cual estaría relacionado con un incremento de las precipitaciones en esas latitudes. Por otro parte, en el Lago Cardiel durante los últimos 16.000 años calibrados AP se observaron variaciones tanto en la abundancia como en la asociación de ostrácodos. Dichos cambios se han debido a las variaciones hidrológicas sustanciales acaecidas durante el Pleistoceno tardío-Holoceno medio en donde hubo una disminución de la conductividad como consecuencia de los cambios en la relación precipitación/evaporación (por ej., un incremento de la relación P/E indicaría una menor conductividad). Estos dos ejemplos muestran la utilidad de los ostrácodos como indicadores para la interpretación de cambios palaeoclimáticos y palaeoambientales en Patagonia.

PALABRAS CLAVE: Ostrácodos lacustres – autoecología – Cuaternario – Patagonia.

INTRODUCTION

Modern lakes and lacustrine sediments are ideal sites for the study of environmental change (Ariztegui *et al*., 2008). Lakes respond quickly to environmental change and their sediments provide a wealth of multiproxy information (Schwalb, 2003) that can be used for the reconstruction of past climate patterns. Non-marine ostracods (microscopic crustaceans often exhibiting a calcareous shell of calcium carbonate) are benthic organisms found in almost every aquatic environment (Horne *et al*., 2002; Frenzel and Boomer, 2005 and Laprida and Ballent, 2008). Their shells, which are used for taxonomic identification, function as archives for information on the geochemistry of trace elements, as well as carbon and oxygen isotope ratios, all of which can inform on environmental conditions at the time of deposition.

Temporal changes in species composition and trace element ratios can be used for estimating past climate variations. Hence, ostracods recovered from lake sediments provide information on the physical and chemical properties (e.g. salinity, solute composition, temperature, and flow conditions) of the environment in which they flourished, which then allow inferences on lake level changes (Palacios-Fest *et al*., 1994; Belis *et al*., 1999; Schwalb, 2003; Mezquita *et al*., 2005) and hence climate. Although there are a substantial number of studies that deal with ostracods from Argentina, only a small part of this work is devoted to Quaternary non-marine deposits. Daday (1902) was the first to describe a number of non-marine taxa from Patagonia, whereas Ramirez (1967) analyzed the soft and calcareous parts of the ostracod fauna from Lake Chascomús in Buenos Aires province. Other studies have examined systematic, palaeoecological, and palaeoenvironmental issues from outcrops and sediment cores from central and northern provinces in Argentina (Chaco, Entre Ríos, and Buenos Aires; Zabert, 1981; Zabert & Herbst, 1986; Bertels & Martínez, 1990; Ferrero, 1996; Laprida, 2006; Laprida & Valero-Garcés, 2009) but not from Patagonia. More recently, ostracod studies in Patagonia focused on the analysis of Quaternary outcrops and sediment cores from the Cari-Laufquen area (41°S) by identifying new species and inferring their palaeoecological and palaeoclimatological signals (Cusminsky & Whatley 1996, 2008; Whatley & Cusminsky 1995, 1999, 2000).

The Patagonian Lake Drilling Project (PATO-PALATRA) was a multi-disciplinary, international collaborative initiative, with the objective of reconstructing latitudinal palaeoenvironmental changes during the Late Quaternary using two closed basins in Argentina: Laguna Cari-Laufquen in northern Patagonia (41°S) and Lago Cardiel in southern Patagonia (49°S) (Fig. 1A) (Ariztegui *et al*., 2001, 2008; Gilli *et al*., 2001, 2005a, b; Markgraf *et al*., 2003; Beres *et al*., 2008). Modern limnological data were collected as part of this collaborative effort from a wide range of lacustrine environments in the surrounding regions in both basins (Schwalb *et al*., 2002; Cusminsky *et al*., 2005). In the present study, we summarize our findings focusing on the relationship between the abundance, diversity, and distribution of ostracods with climatically-induced environmental changes.

Figure 1. A, location map of Patagonia in South America. B, Laguna Cari-Laufquen. C, Lago Cardiel.

REGIONAL SETTINGS

At present, the closed-basin (endorheic) Laguna Cari-Laufquen (41°S, 69°W) encompasses two water bodies: Cari-Laufquen Grande at 800 m a.s.l and Cari-Laufquen Chica at 820 m a.s.l. The mean annual precipitation in the area is approximately 160 mm, primarily occurring between May and August with prevailing westerly winds; mean annual temperature is 4 °C. (Coria, 1979). Laguna Cari-Laufquen Chica is a permanent water body, with pH 8.7 (Schwalb *et al.*, 2002) and a sodium bicarbonate concentration of 230 p.p.m. (Galloway, Markgraf & Bradbury, 1988). Occasionally, excess water overflows through the Maquinchao River into Cari-Laufquen Grande, which is an ephemeral body of brackish water with pH 8.8 (Schwalb *et al.*, 2002) and solute concentration of 4000 p.p.m. (Galloway *et al.*, 1988) (Fig. 1B). The Pleistocene sequence of the Cari-Laufquen lake system can be seen on outcrops along the shore of the present lakes. Two high stages have been recognized in shorelines at 55 and 35 m above modern lake level. These have been radiocarbon dated at 19 000 years BP and between 14 000 years BP and 10 000–8000 years BP, respectively (Galloway *et al.*, 1988; Bradbury *et al.*, 2001). The two lakes merged during those high stands forming a larger palaeolake (Ariztegui *et al.*, 2008). Lago Cardiel (49°S, 71°W) is also a closed (endorheic) lake basin situated on the Patagonian Plateau (Argentina) at 276 m a.s.l. (Fig. 1C). This heart-shaped lake has a diameter of 20 km covering an area of 370 km^2. The maximum modern water depth is approximately 76 m with a catchment area of approximately 4500 km^2. Río Cardiel is the principal perennial inflowing river. The mean annual precipitation varies from approximately 500 mm in the mountain area west and north-west of the lake to 160 mm near the lake. The mean annual temperature is approximately 8 °C, and strong westerly winds prevail during summer months (December to March) (Gilli *et al.*, 2001, 2005a, b; Markgraf *et al.*, 2003; Ariztegui *et al.*, 2008, 2010). Galloway *et al.* (1988) and Stine & Stine (1990) recognized and dated several palaeoshorelines indicative of former lake level high stands. A deeply dissected highstand at +75 m a.s.l. was beyond radiocarbon dating. A highstand at +55 m above the actual lake level was dated to 9780 ^{14}C years BP (approximately 10 800 calibrated years BP). An intermediate highstand at +21 m a.s.l was dated at 5130 ^{14}C years BP and four minor lake level fluctuations between +3 and +10 m were dated, respectively, between 4530 and 3070 ^{14}C years BP, approximately 2000, 1450 and 800 ^{14}C years BP (Markgraf *et al.*, 2003). Seismic surveys of Lago Cardiel allowed the classification of the sedimentary succession into six major seismic sequences that correspond to different lake levels. Thus, these geophysical data show very low lake levels and even complete evaporation during glacial times before the dramatic increase in water level that characterizes the beginning of the present interglacial (Holocene). It further shows that the lake level during the Holocene has never been lower than today (Gilli *et al.*, 2001, 2005a, b; Beres *et al.*, 2008).

Late Pleistocene–Holocene sediment sequences and ostracod assemblages

Cari-Laufquen lake system (Fig. 2A) Cari-Laufquen Grande outcrop: (Fig. 2B). This 6 m thick section is located on the southern coast of Lago Cari-Laufquen Grande and was sampled in 1998 from the shore towards the surrounding dunes (41°10′26″S, 69°28′41″W). The outcrop comprises from the base upwards a sequence of ash and clay layers with ostracods, overlain by banded yellow clays and silt with chippy carbonate, clays, and a thick carbonate layer with ostracods, banded yellowish silty-clays and chocolate-coloured clays (Pineda *et al.*, 2010). Two ^{14}C ages were obtained for this sequence (Table 1). Ostracod assemblages (Fig. 3) are dominated by *Limnocythere rionegroensis* Cusminsky and Whatley, which are especially abundant in the lower levels. *Eucypris virgata* Cusminsky and Whatley and *Eucypris fontana* (Graf) are also present. The upper levels are characterized by an abrupt decrease in abundance of all species, including *Limnocythere patagonica* Cusminsky and Whatley. The population of each ostracod species, including *Limnocythere rionegroensis* along the outcrop, comprises adults and juveniles, and male and female individuals (Pineda *et al.*, 2010).

Maquinchao outcrop: (Fig. 2C). This outcrop is located in the lower valley of the Maquinchao River. The lithology of the section exhibits different facies (Whatley & Cusminsky, 1999). Facies A (5 m thick) comprises levels with gravel, sand, and mud (facies A1) overlain by lacustrine rhythmites and carbonate-rich levels (facies A2). The facies A1 represents environments of high energy, which were interrupted periodically by lacustrine episodes of deeper water (facies A2). Facies B1, composed of 6 m of laminated clays with silty marls and sporadic gypsum layers, represents deep-water lacustrine sedimentation. Facies C1 (1 m thick) comprises coarse-grained sediments with irregular stratifications and stromatolites, representing a regressive sequence of the palaeolake. A tephra layer (a distinctive level of pyroclastic material associated with a volcanic eruption) divides facies B1 from facies C1 (Fig. 2C). Three samples from this section have been radiocarbon dated and an additional sample was dated by thermoluminiscence (Table 2). Radiocarbon dating of two samples from the bottom and the top of the sequence (samples 2 and 3 in Table 2, respectively) show reversal values (i.e. the base older than the top). The latter suggests that radiocarbon dates do not reflect the true age of the sediments most probably as a result of the contribution of older carbonates from the watershed (i.e. 'hard water effect') and, thus, the present chronological model relies preferentially on the thermoluminiscence age (Whatley & Cusminsky, 1999, 2000). At the bottom (facies A1 and A2), the Maquinchao section (Fig. 4) is characterized by a low diversity and low abundance of ostracods; only four species were detected: *L. rionegroensis*, *E. virgata*, *Candonopsis brasiliensis*

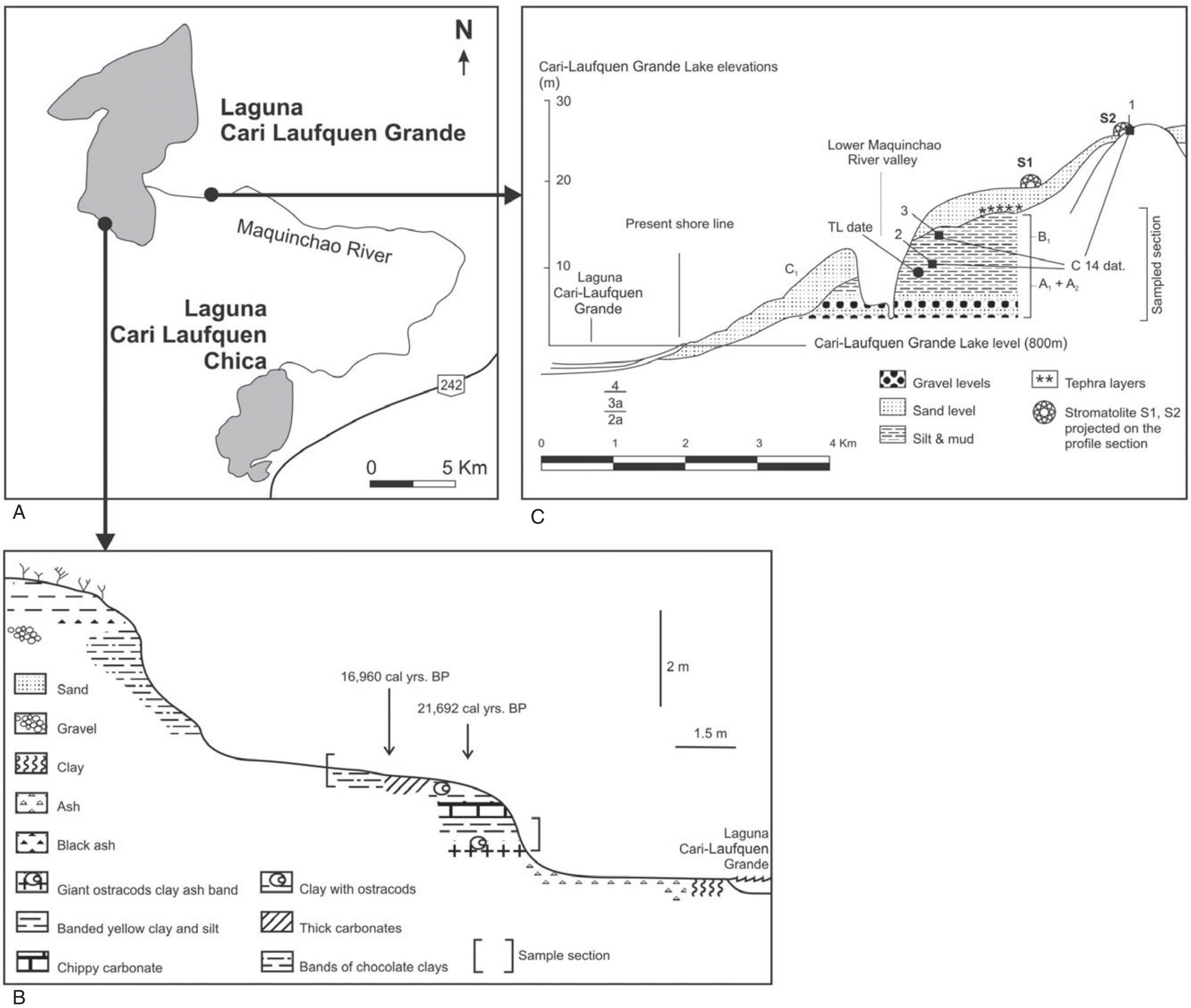

Figure 2. A, location map of the Cari-Laufquen Basin showing Laguna Cari-Laufquen Grande (CLG) and Laguna Cari-Laufquen Chica (CLC). B, lithology and sampled section of CLG outcrops. C, lithology and facies distribution of the Maquinchao outcrop.

Table 1. Radiocarbon and calibrated ages from the Cari-Laufquen Grande outcrop

Sample	Laboratory number	^{14}C age (years BP)	Calibrated age (calibrated years BP)
1.36	NSRL-10775	15 630 ± 110	16 960 ± 239
1.28	NSRL-10774	19 750 ± 128	21 692 ± 288

Sars and *L. patagonica*. In the immediately overlying levels (facies B1), the number of individuals of *L. rionegroensis* greatly increases along with the appearance of two extra species, *E. fontana* and *E. virgata*. The overlying level (facies C1), however, exhibits a dramatic drop in diversity (only two species detected: *E. fontana* and *L. rionegroensis*) and abundance, with the number of individuals of these two species greatly reduced. Both adults and juveniles of all species are present and their population structure does not suggest any evidence of transport or reworking. *Limnocythere rionegroensis*

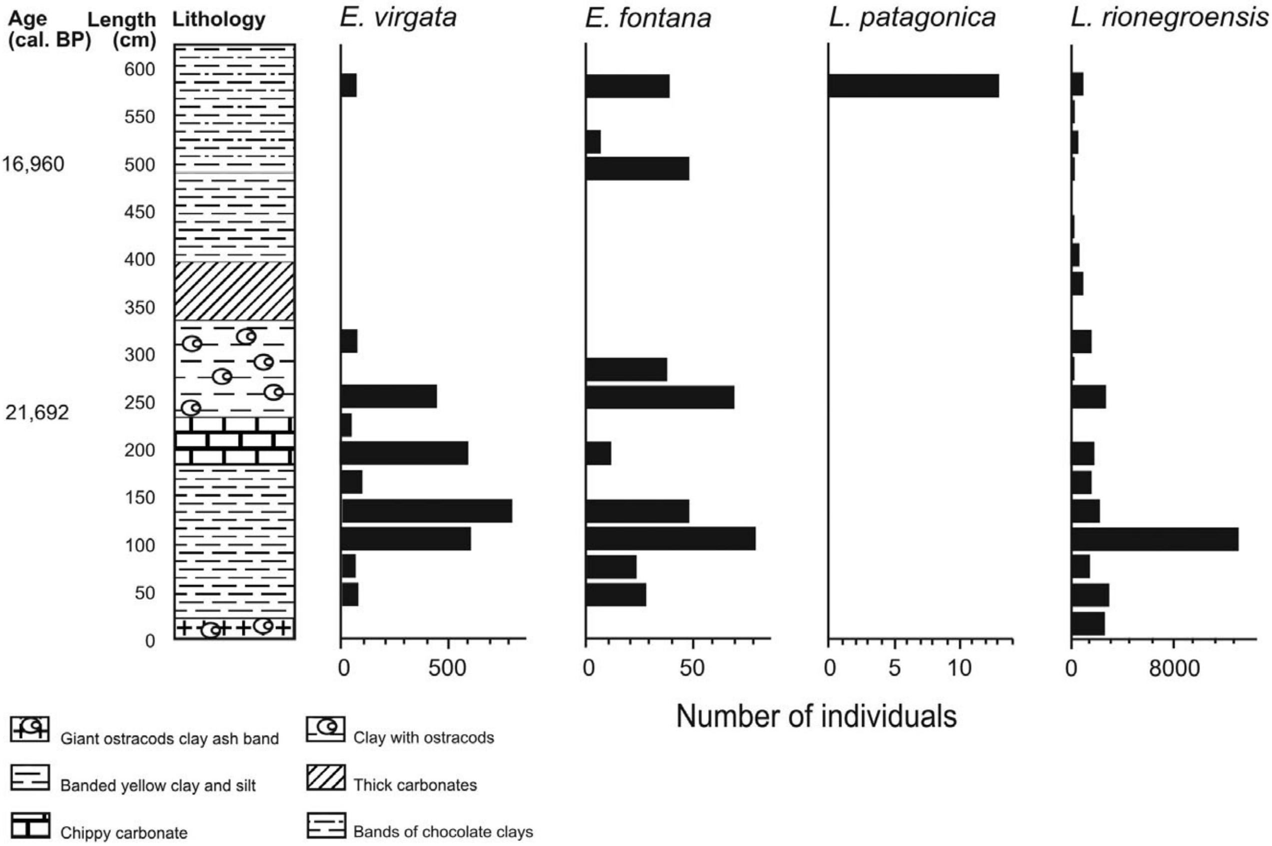

Figure 3. Species distribution of ostracods, age and lithology of the profile at the Cari-Laufquen Grande (CLG) outcrop.

Table 2. Chronological data for the Maquinchao outcrop

Sample	Laboratory number	^{14}C age (years BP)	Calibrated age (calibrated years BP)
Stromatolites (1)	LU 3677	16 520 ± 120	17 880 ± 318
Base of palaeolake (2)	LU 3676	15 220 ± 180	16 406 ± 291
Top of palaeolake (3)	LU 3792	33 200 ± 260	35 732 ± 691
TL (thermoluminiscense dating)		13 200	

presents female and male individuals, especially in facies B1. For more details, see Whatley & Cusminsky (2000: fig. 6) and Whatley & Cusminsky (1999: table 1).

Lago Cardiel Core CAR-99-7P (Fig. 5) was retrieved with an ETH-Kullenberg coring system. The lithology of the core (11.11 m long) is described in detail by Gilli *et al*. (2005b) defining six lithological units. Basal unit 6 consists of silty clays with very fine laminations and plant remains identified as *Ruppia* sp. A tephra layer identified as originated from the Reclús volcano is found at 1055.9 cm depth. Unit 5 consists of black silty clays with sand lenses, gravel, and woody debris towards the top of the unit. Unit 4 is characterized by two meters of silty clay and sandy layers with pebbles and cross bedding at the top of the unit, suggesting a hiatus. Unit 3 consists of finely laminated silty clays with abundant light coloured carbonate layers, alternating with blackish layers. Units 2 and 1 are characterized by laminated silty clays. The chronology of core CAR 99-7P is based on a combination of tephrochronology (Markgraf *et al*., 2003; Stern, 2008) and selected AMS radiocarbon dates (Gilli *et al*., 2005a, b). All radiocarbon ages were calibrated (Table 3) using CALIB 6.0.0 with the IntCal09 and SHCal04 calibration set (Stuiver & Reimer, 1993; McCormac *et al*., 2004; Reimer *et al*., 2009). Five majors units have

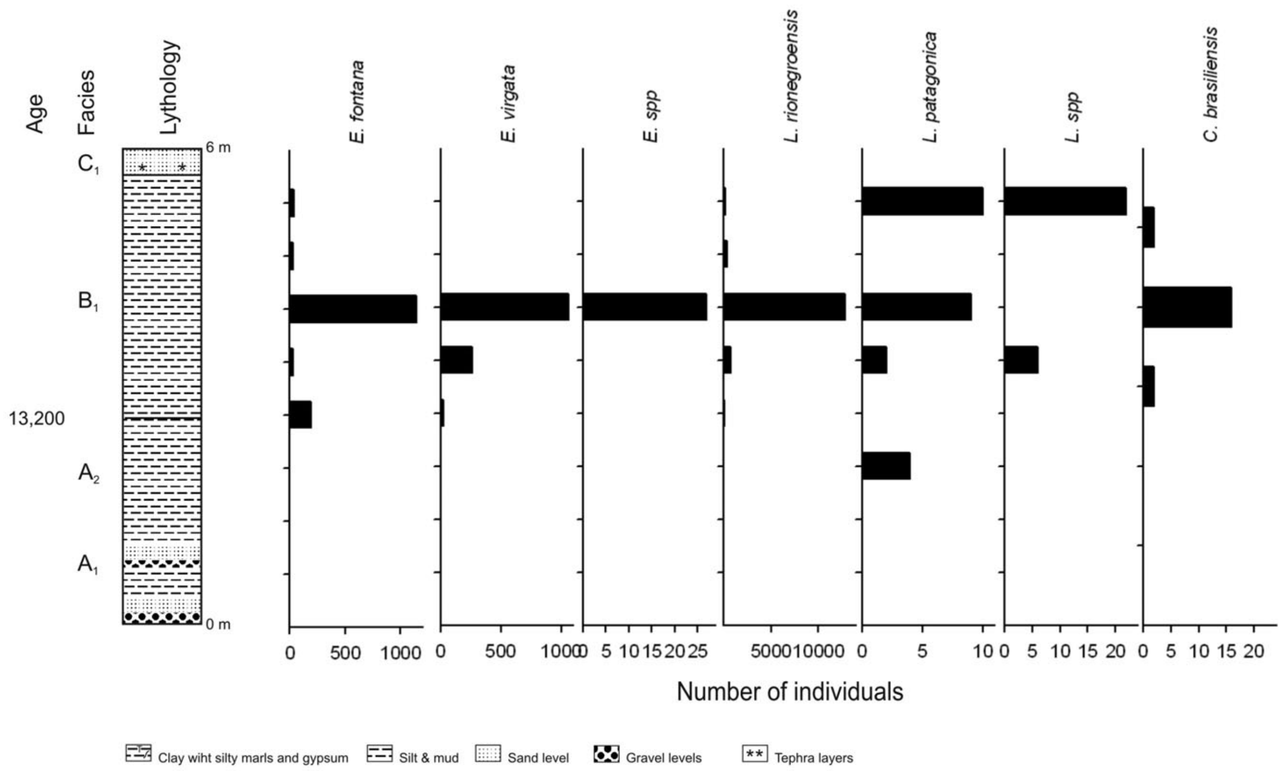

Figure 4. Species distribution of ostracods, age and lithology at the Maquinchao outcrop.

been recognized in core CAR 99-7P on the basis of ostracod stratigraphy. Unit 1 (15 680–15 306 calibrated years BP) displays a low number of ostracod individuals but a relatively high diversity comprising *E. fontana*, *E. virgata*, and *L. rionegroensis* var. 1 with few individuals of *Eucypris* sp. 2. Unit 2 (15 490–12 990 calibrated years BP) contains the highest ostracod abundance of the core and is represented primarily by *L. rionegroensis* var. 1 and few individuals of *E. fontana.* Unit 3 (12 990–12 572 calibrated years BP) shows an increase in ostracod diversity. *Limnocythere rionegroensis* var. 1 is replaced by *L. rionegroensis* var. 2; *E. fontana* is present in higher abundance, whereas L *patagonica* and *Eucypris* sp. 1 appear. Unit 4 (12 572–4100 calibrated years BP) contains primarily *E. fontana and L. patagonica* in equal abundance with few individuals of *E. virgata.* Unit 5 (younger than 4100 calibrated years BP) shows an increase in both number of individuals and diversity. *E. fontana* predominates, *L. patagonica* is less abundant and *L. rionegroensis* var. 2 is also present.

USING MODERN OSTRACOD DISTRIBUTION AS A PALAEOENVIRONMENTAL INDICATOR

According to De Deckker & Forester (1988) and Mezquita *et al*. (1999, 2005), the distribution of modern lacustrine ostracods can be related to water chemistry. With the same rationale, we analyzed modern ostracod assemblages in 38 localities of Cari-Laufquen and Cardiel basins using multivariable statistics such as canonical correspondence analysis (CCA) (Viehberg, 2006). Two main factors were identified as major determinants of the variance in the modern ostracod distribution: (i) Ca : pH ratio and (ii) chloride concentration. The Ca : pH ratio is a valuable measure for the alkalinity of a lake and is closely related to calcite precipitation (Wetzel, 2001). Low values characterize waters with a weak buffer capacity (both low calcium concentrations and pH values). This habitat is preferred by species such as *E. fontana*, *Potamocypris smaragdina (Vavra)*, and *Kapcypridopsis megapodus* Cusminsky and Whatley. By contrast, *L. rionegroensis* dominates in waters with higher buffer capacities. Chloride concentration covaries with conductivity. Low values occur in waters with constant freshwater supply that are preferred by *Penthesilenula incae* (Delachaux) and *P. smaragdina*. Together with *Heterocypris incongruens* (Ramdohr), *E. fontana*, *Amphicypris nobilis* Sars and *Ilyocypris ramirezi* Cusminsky and Whatley, they are characteristic of springs, seeps, and streams (Schwalb *et al*., 2002) with low and rather stable ionic concentrations (Cusminsky *et al*., 2005). *Limnocythere rionegroensis*

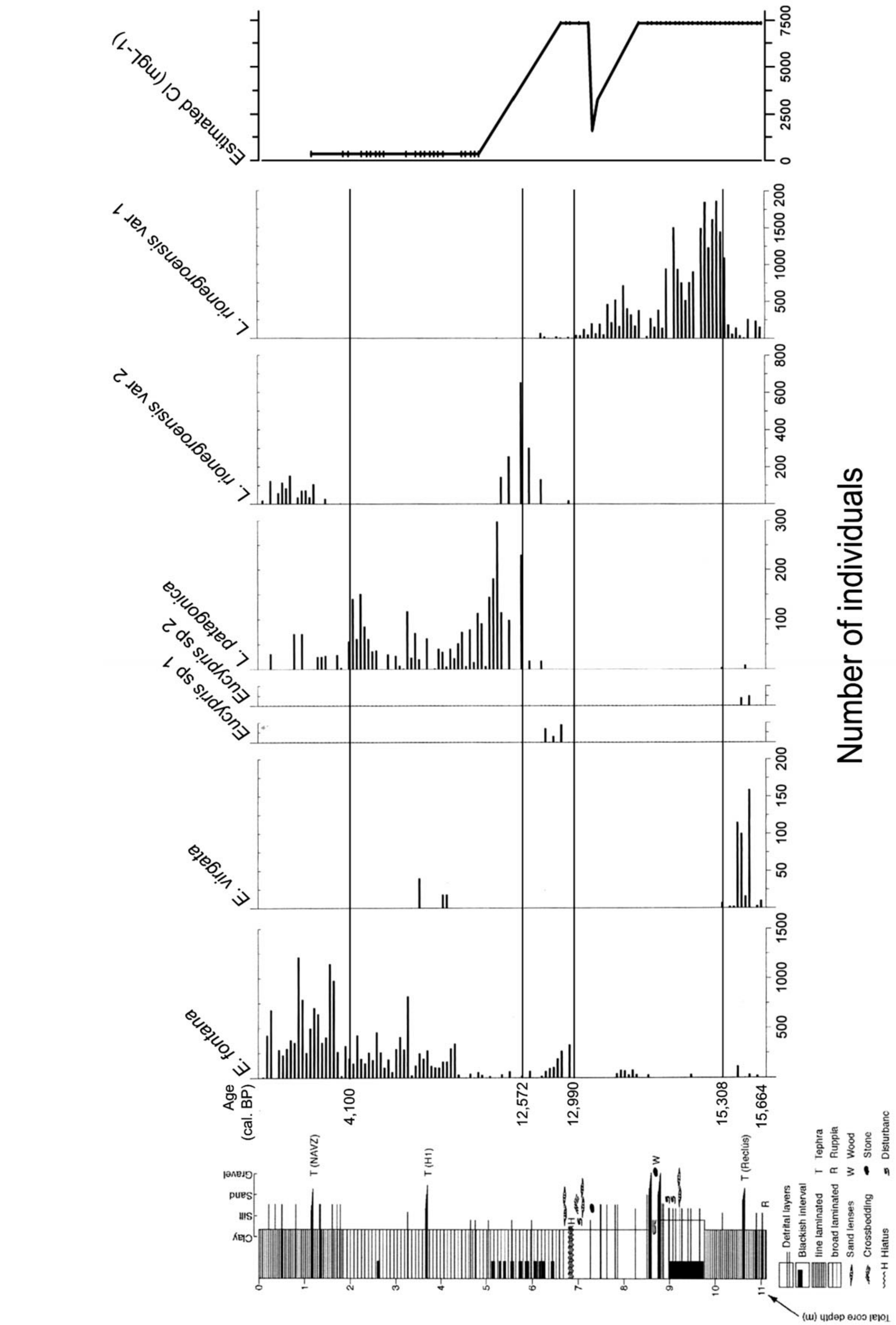

Figure 5. Lithology, age, species distribution of ostracods, and estimated Cl (mg^{-1}) along core CAR 99-7P.

Table 3. Lago Cardiel chronology for core CAR-99-7P

Depth (cm)	^{14}C age (years BP)	2-range calibrated years BP	Calibrated age (calibrated years BP)	Calibration set	Material	Reference/laboratory number
114.5	3 000 ± 100	2 857–3 361	3 109	ShCal04	A1 tephra	Stern (2008)
366.1	6 850 ± 160	7 343–7 962	7 652	ShCal04	H1 tephra	Stern (2008)
648.6	10 370 ± 75	11 981–12 528	12 254	IntCal09	Carbonate	ETH-28325/26
665.9			12 536		Estimation: start of lake level rise	
865.9	11 220 ± 85	12 865–13 305	13 087	IntCal09	Wood	ETH-22124
986.6	12 390 ± 85	14 054–14 979	14 516	IntCal09	Carbonate	ETH-28327
1055.9	12 685 ± 260	14 034–16 298	15 166	IntCal09	Reclús tephra	Stern (2008)

is the dominant species in waters with the relatively highest ionic concentration such as ephemeral ponds and lakes (Schwalb *et al.*, 2002), whereas *I. ramirezi*, *E. fontana*, and *E. virgata* live in waters with the most variable ionic concentrations, especially Na^+, Cl^- and $SO4^{-2}$ (Cusminsky *et al.*, 2005). Permanent ponds and lakes are characterized by the presence of *L. patagonica* Cusminsky and Whatley, *Limnocythere* sp., *Eucypris labyrinthica* Cusminsky and Whatley, and *E. fontana* (Schwalb *et al.*, 2002). The Pleistocene–Holocene sequences presented here show ostracod associations that resemble the range of studied present-day lacustrine conditions. *Limnocythere rionegroensis* is present in great abundance in recent sediments, as well as in the Late Pleistocene sections of the Lago Cari-Laufquen system. Whatley & Cusminsky (1999, 2000) and Cusminsky *et al.* (2005) considered *L. rionegroensis* as a possible indicator of slightly saline waters and dry climatic conditions. Morphologically, this species resembles *Limnocythere bradburyi* Forester, recorded from the western USA and Mexico (Forester, 1985), and also *Limnocythere sappaensis* Staplin collected from several lakes on the Chilean Altiplano (Schwalb, Burns & Kelts, 1999) that inhabit a somewhat similar environment to those of our study sites.

For the Cari Laufquen lake system, the Cari-Laufquen Grande section contains a high number of individuals especially of *L. rionegroensis.* This is particularly so in the lower levels that are allocated to lacustrine saline environments. The presence of both male and female individuals suggest sexual reproduction what in ostracods is generally associated with environmental instability (Schwalb, 2003) or an increase of the solute concentration (Löffler, 1990). Parthenogenesis reproduction is in general characteristic of stable environments.

The Maquinchao section comprises three types of ostracod assemblages which can be related to the three lithological units described in the outcrop. At the base of the succession, the ostracod assemblage, represented by very few individuals, coincides with facies A1 and A2, which is interpreted as a relatively shallow-water and high energy lake. This interval is followed by a period of quieter-water conditions corresponding to facies B1. It represents a lacustrine environment with deeper-water and lower energy comprising high ostracod abundance especially of the species *L. rionegroensis*. The abrupt change in ostracod associations that follows this unit might be related to increases in volcanic ash at the boundary between Facies B1 and C1, which probably caused an increase of turbidity with diminution of the oxygen and light and/or by a major change on the dominant climatic conditions (Whatley & Cusminsky, 1999).

According to Bradbury *et al*. (2001), Laguna Cari-Laufquen shows several high stand levels during the Late Pleistocene and Early Holocene. The largest and most persistent lake occurred between 18 400 and 13 000 radiocarbon years BP. (i.e. Last Glacial Maximum and Late Glacial, respectively); a second high stand at +35 m above present lake level centered on 10 000 ^{14}C years BP, which is characterized by an unproductive saline and turbid lacustrine system (Bradbury *et al*., 2001). These authors suggest that presumably the Last Glacial Maximum (18 000 radiocarbon years BP), Late Glacial (approximately 13 000 radiocarbon years BP) and Early Holocene (10 000 radiocarbon years BP) highstands at Cari-Laufquen document higher precipitation at this latitude. The sources of the precipitation that generated these high lake levels are still unclear. A south-easterly origin for this moisture has been suggested that would be related to the increasing activity of mobile polar highs or to cold air outbreaks from Antarctica and southernmost South America.

For the Lago Cardiel (Core CAR 99-7P), Mezquita *et al*. (2005) and Viehberg (2006) successfully developed calibration datasets to be applied in palaeoenvironmental research for the study of the responses of modern species assemblages to environmental factors. Using these calibration data sets, they used weighted averaging (WA) regressions to reconstruct past habitat conditions from fossils assemblages that share species with the modern data. Similarly, we used the modern ostracod data sets and applied these techniques (CCA and WA) to derive an ostracod-based transfer function for the reconstruction of the palaeoenvironmental history of Lago Cardiel (Fig. 5). The lower part of the core before 13 000 calibrated years BP is dominated by *L. rionegroensis* var. 1, suggesting high ionic concentrations. This interpretation is consistent with seismic, sedimentological, and limnogeological studies of Lago Cardiel (Gilli *et al*., 2001, 2005a, b; Markgraf *et al*., 2003; Ariztegui *et al*., 2008, 2010). These studies point towards a positive hydrological balance (i.e. abundant precipitation) at the Late Pleistocene–Holocene transition. Before 13 000 calibrated years BP, the lake level was substantially lower and the lake probably even dried out for short time periods (Gilli *et al*., 2005b). Between 13 000 and 12 100 calibrated year BP, *L. rionegroensis* var. 1 is replaced by *L. rionegroensis* var. 2 and *E. fontana*. *Limnocythere patagonica* is present suggesting a decrease of the ionic concentration and thus less evaporation. Between 12 100 and 4100 calibrated years BP, *L. rionegroensis* var. 2 is absent, which could reflect the lowest ionic concentrations in the core, suggesting a permanent, deep lake. For the Early Holocene, Gilli *et al*. (2005b) suggested an increase in moisture showing a positive balance and increasing lake level up to 55 m above modern levels. After 4100 calibrated years BP, the ostracod association is dominated by *E. fontana* with *L. patagonica* and *L. rionegroensis* var. 2. This represents the present-day ostracod association in this lake, suggesting that the lake level decreased after the Early Holocene highstand, bringing the ionic concentration up to present-day values. The accumulation of sediments in the middle of the basins after 6800 calibrated years BP suggests an increase of the southern westerlies strength at latitude 49°S (Gilli *et al*., 2005b; Ariztegui *et al*., 2008). The combined data indicate a sharp change in the Lago Cardiel hydrological balance from a dry Late Pleistocene to substantially more humid conditions for the Early and Middle Holocene. The Late Holocene is in turn characterized by a decreasing trend in the lake level, suggesting diminishing moisture availability in the area.

CONCLUSIONS

The study of modern lacustrine ostracods in the Cari-Laufquen and Cardiel basins in Patagonia shows distinctive associations that are responding to dominant environmental parameters among which conductivity is the most important. These modern associations were recognized at different intervals within the Late Pleistocene and Holocene sections. In Cari-Laufquen, the predominance of *L. rionegroensis* during the Late Pleistocene and Early Holocene suggest a saline and turbid lake, whereas, in Lago Cardiel, changes in ostracod abundance and association along with results of transfer function analyses show a decrease of conductivity from the Late Pleistocene to the Middle Holocene. These results are coherent with previous studies using independent proxies. Hence, all these observations show the usefulness of lacustrine ostracods as a proxy for changing hydrological conditions. These data indicate the hydrological budgets that differ between latitudes during the Late Glacial–Holocene transition. Although wet conditions characterized the Cari-Laufquen area (northern Patagonia) during this time, the Lago Cardiel region was dry and became dramatically humid during the Early Holocene. Our studies provide information that can be used to improve our understanding of palaeoclimate in Patagonia.

ACKNOWLEDGEMENTS

The core from Lago Cardiel was retrieved by projects funded by the USA and Swiss National Science Foundations (US National Science Foundation grants NSF-EAR-9709145, NSF-ATM-008267, and NSF-ATM-0081279 to Vera Markgraf and Kerry Kelts; and the Swiss National Science Foundation grant No.

21-5086297 to the ETH Limnogeology Group). G. C. thanks CONICET (Project PIP 00819) and Universidad Nacional del Comahue (project B001) for support of this work and SECYT-DAAD project AO731 for a travel grant to Gabriela Cusminsky and Antje Schwalb, as well as their team members. A.S. thanks the German Climate Research Program (DEKLIM E: PROSIMUL III, FKZ 01 LD 003) the DAAD (PROALAR D/07/09565). We thank Jorge Rabassa, Eduardo Tonni, Alfredo Carlini, and Daniel Ruzzante for participation in the Symposium of Palaeogeography and Palaeoclimatology of Patagonia Biodiversity, held in La Plata Museum in Argentina, in May 2009.

REFERENCES

Ariztegui D, Anselmetti FS, Kelts K, Seltzer G, D'Agostino K. 2001. Identifying paleoenvironmental change across South and North America using high-resolution seismic stratigraphy in lakes. In: Markgraf V, ed. *Interhemispheric climate linkages*. San Diego, CA: Academic Press, 227–240.

Ariztegui D, Anselmetti FS, Gilli A, Waldmann N. 2008. Late Pleistocene environmental changes in Patagonia and Tierra del Fuego: a limnogeological approach. In: Rabassa J, ed. *The Late Cenozoic of Patagonia and Tierra del Fuego*. London: Elsevier Science, 241–253.

Ariztegui D, Gilli A, Anselmetti FS, Goñi RA, Belardi JB, Espinosa S. 2010. Lake-level changes in central Patagonia (Argentina): crossing environmental thresholds for Lateglacial and Holocene human occupation. *Journal of Quaternary Science* **25:** 1092–1099.

Belis CA, Lami A, Guilizzoni P, Ariztegui D, Geiger W. 1999. The Late Pleistocene ostracod record of the crater lake sediments of Lago di Albano (central Italy): changes in trophic status, water level and climate. *Journal of Paleolimnology* **21:** 151–169.

Beres M, Gilli A, Ariztegui D, Anselmetti FS. 2008. The Lago Cardiel basin, Argentina (49°S): origin and evolution revealed by high resolution multichannel seismic reflection studies. *Journal of South American Earth Sciences* **25:** 74–85.

Bertels A, Martínez D. 1990. Quaternary ostracodes of continental and transicional litoral shallow marine environments. *Courier Forschungsinstituo. Senckenberg* **123:** 141–159.

Bradbury JP, Grosjean M, Stine S, Sylvestre F. 2001. Full and late glacial records along the PEP1 transect: their role in developing interhemispheric paleoclimate interactions. In: Markgraf V, ed. *Interhemispheric climate linkages*. San Diego, CA: Academic Press, 265–292.

Coria BL. 1979. Descripción Geológica de la hoja 40d Ingeniero Jacobacci. *Boletín Servicio Geológico Nacional* **168:** 101.

Cusminsky GC, Whatley RC. 1996. Quaternary non-marine ostracods from lake beds in northern Patagonia. *Revista Española de Paleontología* **11:** 143–154.

Cusminsky GC, Whatley RC. 2008. Calcareous Microfossils (Foraminifera and Ostracoda) of the Late Cainozoic from Patagonia and Tierra del Fuego: a review. In: Rabassa J, ed. *Late Cenozoic of Patagonia and Tierra del Fuego*. London: Elsevier Science, 327–341.

Cusminsky GC, Pérez PA, Schwalb A, Whatley RC. 2005. Modern lacustrine ostracods from Patagonia, Argentina. *Revista Española de Micropaleontología* **37:** 431–450.

Daday EV. 1902. Mikroskopische-Süsswasserthiere aus Patagonien. *Termeszetranzi Puzetek* **25:** 201–313.

De Deckker P, Forester RM. 1988. The use of ostracods to reconstruct continental palaeoenvironmental records. In: De Deckker P, Colin JP, Peypouquet JP, eds. *Ostracoda in the earth sciences*. Amsterdam: Elsevier, 175–199.

Ferrero L. 1996. Paleoecología de ostrácodos holocenos del estuario del río Quequén Grande (provincia de Buenos Aires). *Ameghiniana* **23:** 202–208.

Forester RM. 1985. *Limnocythere bradbury* n sp., a modern ostracode from central Mexico and possible Quaternary paleoclimatic indicator. *Journal of Paleontology* **59:** 8–20.

Frenzel P, Boomer I. 2005. The use from marginal marine, brackish waters as bioindicators of modern and Quaternary environmental change. *Palaeogeography, Palaeoclimatology, Palaeoecology* **225:** 68–92.

Galloway R, Markgraf V, Bradbury P. 1988. Dating shorelines of lakes in Patagonia, Argentina. *Journal of South American Earth Sciences* **1:** 195–198.

Gilli A, Anselmetti F, Ariztegui D, Bradbury J, Kelts K, Markgraf V, McKenzie J. 2001. Tracking abrupt climate change in the Southern Hemisphere: a seismic stratigraphic study of Lago Cardiel, Argentina (49°S). *Terra Nova* **13:** 443–448.

Gilli A, Anselmetti F, Ariztegui D, Beres M, Mc Kenzie JA, Markgraf V. 2005a. Seismic stratigraphy, buried beach ridges and contourite drifts: the Late Quaternary history of the closed Lago Cardiel basin, Argentina (49°S). *Sedimentology* **52:** 1–23.

Gilli A, Ariztegui D, Anselmetti F, Mc Kenzie J, Markgraf V, Hajdas I, Mc Culloch R. 2005b. Mid-Holocen strengthening of the Southern Westerlies in South America- Sedimentological evidences from Lago Cardiel, Argentina (49°S). *Global and Planetary Change* **49:** 75–93.

Horne DJ, Cohen A, Martens K. 2002. Taxonomy, morphology and biology of quarternary and living ostracoda. In: Holmes JA, Chivas AR, eds. *The ostracoda: applications in quaternary research*. Washington, DC: Geophysical Monograph, 5–36.

Laprida C. 2006. Ostrácodos recientes de la llanura pampeana, Buenos Aires, Argentina: ecología e implicancias paleolimnológicas. *Ameghiniana* **43:** 181–204.

Laprida C, Ballent S. 2008. Ostracoda. In: Camacho H, Londobuco M, eds. *Los Invertebrados fósiles*. 599–624. Buenos Aires: Vazquez Mazzini Editorial.

Laprida C, Valero-Garcés B. 2009. Cambios ambientales de épocas históricas en la pampa bonaerense en base a ostrácodos: historia hidrológica de la laguna de Chascomús. *Ameghiniana* **46:** 95–111.

Löffler H. 1990. Palaeolimnology of Neusiedlersee, Austria. I The succession of ostracods. *Hydrobiologia* **214:** 229–238.

McCormac FG, Hogg AG, Blackwell PG, Buck CE, Higham TFG, Reimer PJ. 2004. SHCal04 Southern Hemisphere calibration 0–11.0 cal Kyr BP. *Radiocarbon* **46:** 1087–1092.

Markgraf V, Bradbury P, Schwalb A, Burns S, Stern CH, Ariztegui D, Gilli A, Anselmetti F, Stine S, Maidana N. 2003. Holocene paleoclimates of southern Patagonia: limnological and environmental history of Lago Cardiel, Argentina. *The Holocene* **13:** 581–591.

Mezquita F, Roca J, Wansard G. 1999. Moulting, survival and calcification: the effects of temperature and water chemistry on a ostracods crustacean (*Herpetocypris intermedia*) under experimental conditions. *Arch Hydrobiologie* **146:** 219–238.

Mezquita F, Roca JR, Reed JM, Wansard G. 2005. Quantifying species– environment relationships in non-marine Ostracoda for ecological and palaeoecological studies: examples using Iberian data. *Palaeogeography, Palaeoclimatology, Palaeoecology* **225:** 93–117.

Palacios-Fest MR, Cohen AS, Anadon P. 1994. The use of ostracods as paleoenvironmental tools in the interpretation of ancient lacustrine records. *Revista Española de Paleontología* **9:** 145–164.

Pineda D, Cusminsky G, Schwalb A, Ariztegui D. 2010. Unstable conditions in lake Cari-Laufquen (41°30′08″S; 69°30′28″W), Patagonia, during the late Pleistocene (21 000–16 000 cal yr BP). *VI Southern Connections Congress*. San Carlos de Bariloche, abstract p. 143.

Ramirez RC. 1967. Ostrácodos de lagunas de la provincia de Buenos Aires. *Revista del Museo de La Plata (ns) Sección Zoología* **10:** 5–54.

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Burr GS, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, McCormac FG, Manning SW, Reimer RW, Richards DA, Southon JR, Talamo S, Turney CSM, van der Plicht J, Weyhenmeyer CE. 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50 000 years cal BP. *Radiocarbon* **51:** 1111–1150.

Schwalb A. 2003. Lacustrine ostrácodos as stable isotope recorders of late-glacial and Holocene environmental dynamics and climate. *Journal of Paleolimnology* **29:** 265–351.

Schwalb A, Burns SJ, Kelts K. 1999. Holocene environments from stable isotope stratigraphy of ostracodes and authigenic carbonates in Chilean Altiplano lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* **148:** 153–168.

Schwalb A, Burns S, Cusminsky G, Kelts K, Margraf V. 2002. Assemblage diversity and isotopic signals of modern ostracodes and host waters from Patagonia, Argentina. *Paleogeography. Paleoclimatology, Palaeoecology* **187:** 323–339.

Stern C. 2008. Holocene tephrochronology record of large explosive eruptions in the southernmost Patagonian Andes. *Bulletin of Volcanology* **70:** 435–454.

Stine S, Stine M. 1990. A record from lake cardiel of climate in southern South America. *Nature* **345:** 705–708.

Stuiver M, Reimer PJ. 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. *Radiocarbon* **35:** 215–230.

Viehberg FA. 2006. Freshwater ostracod assemblages and their relationship to environmental variables in waters from northeast Germany. *Hydrobiologia* **571:** 213–224.

Wetzel RG. 2001. *Limnology*. San Diego, CA: Academic Press, 107.

Whatley RC, Cusminsky GC. 1995. Quaternary lacustrine ostracoda from northern patagonia Argentina. In: Riha J, ed. *Ostracoda & bioestratigraphy*. Rotterdam: Balkema, 303–310.

Whatley RC, Cusminsky GC. 1999. Lacustrine ostracoda and late Quaternary palaeoenvironments from the lake Cari-Laufquen region, Rio Negro province, Argentina. *Paleogeography, Paleoclimatology, Paleoecology* **15:** 229–239.

Whatley R, Cusminsky G. 2000. Lacustrine ostracods from Northern Patagonia: a review. In: Kelts K, Gierlowsky-Kordesh E, eds. *Lake basins throught space and time*. Tulsa: American Association of Petroleum Geology Studies in Geology, **45:** 581–590.

Zabert LL. 1981. Ostrácodos cuaternarios de Taco Pozo (provincia de Chaco, Argentina) con algunas consideraciones paleoecológicas. *Facena* **4:** 77–87.

Zabert L, Herbst R. 1986. Ostrácodos pleistocénicos del arroyo Perucho Verma, provincia de Entre Ríos, Argentina. *Ameghiniana* **23:** 224–231.