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Lateglacial and Holocene wet–dry cycles in southern Patagonia: chronology, sedimentology and geochemistry of a lacustrine record from Laguna Potrok Aike, Argentina

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Abstract: A high-resolution multiproxy geochemical approach was applied to the sediments of Laguna Potrok Aike in an attempt to reconstruct moist and dry periods during the past 16 000 years in southeastern Patagonia. The age–depth model is inferred from AMS ^{14}C dates and tephrochronology, and suggests moist conditions during the Lateglacial and early Holocene (16 000–8700 cal. BP) interrupted by drier conditions before the beginning of the Holocene (13 200–11 400 cal. BP). Data also imply that this period was a major warm phase in southeastern Patagonia and was approximately contemporaneous with the Younger Dryas chronozone in the Northern Hemisphere (12 700–11 500 cal. BP). After 8650 cal. BP a major drought may have caused the lowest lake level of the record. Since 7300 cal. BP, the lake level rose and was variable until the 'Little Ice Age', which was the dominant humid period after 8650 cal. BP.

Key words: Holocene, Younger Dryas, Lateglacial, 'Little Ice Age', lacustrine sediments, geochemistry, tephrochronology, multiproxy approach, Patagonia, Argentina.

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Introduction

High-resolution palaeoenvironmental information from southern South America, the only continental landmass between 38°S and the Antarctic Circle, is urgently needed in order to compare the Southern Hemisphere climate history with better known tropical and Northern Hemisphere palaeoclimate reconstructions. These data allow assessment for a possible synchrony of global climate events in the past, and to validate global climate models. However, available terrestrial climate records from southern South America are restricted to pollen and charcoal studies of peat bogs and mires from the Andes and the forest-steppe ecotone with relatively low temporal resolution (Schäbitz, 1991; Markgraf, 1993a; Heusser, 1998; McCulloch and Davies, 2001). In the extremely windy and semi-arid region of southeastern Patagonia, lake sediments provide an opportunity to reconstruct continuous records of late Quaternary environmental changes (Zolitschka *et al.*, 2006). Despite their potential, to date only one such record has been reported from Lago Cardiel (Figure 1). However, at 13120 cal. BP, there is a gap in the record, as this lake dried completely (Gilli *et al.*, 2001). Other studies are either based on events such as dating of glacier fluctuations in the Northern and Southern Patagonian Ice Field (Wenzens, 1999; Glasser *et al.*, 2004) or dating of lake (Stine and Stine, 1990) and marine (Aguirre, 2003) terraces. Owing to the limited data coverage, many questions about regional climate evolution are still a matter of debate. For example, the existence of a Younger Dryas

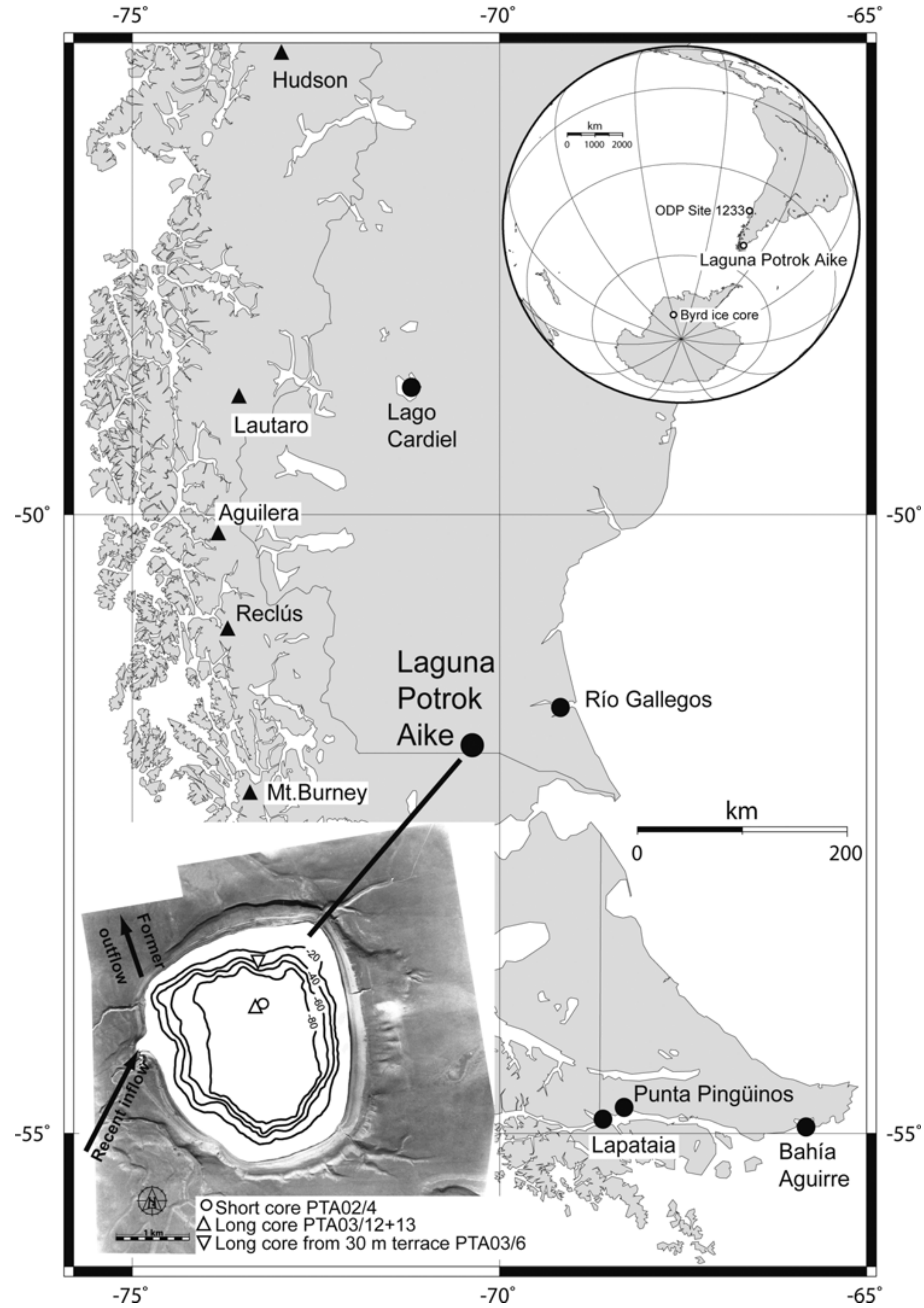

Figure 1 Study area and locations discussed in the text. Maps were created with OMC (Weinelt, 1996–2004). Bathymetry of Laguna Potrok Aike and locations of analysed cores are shown on the inset map

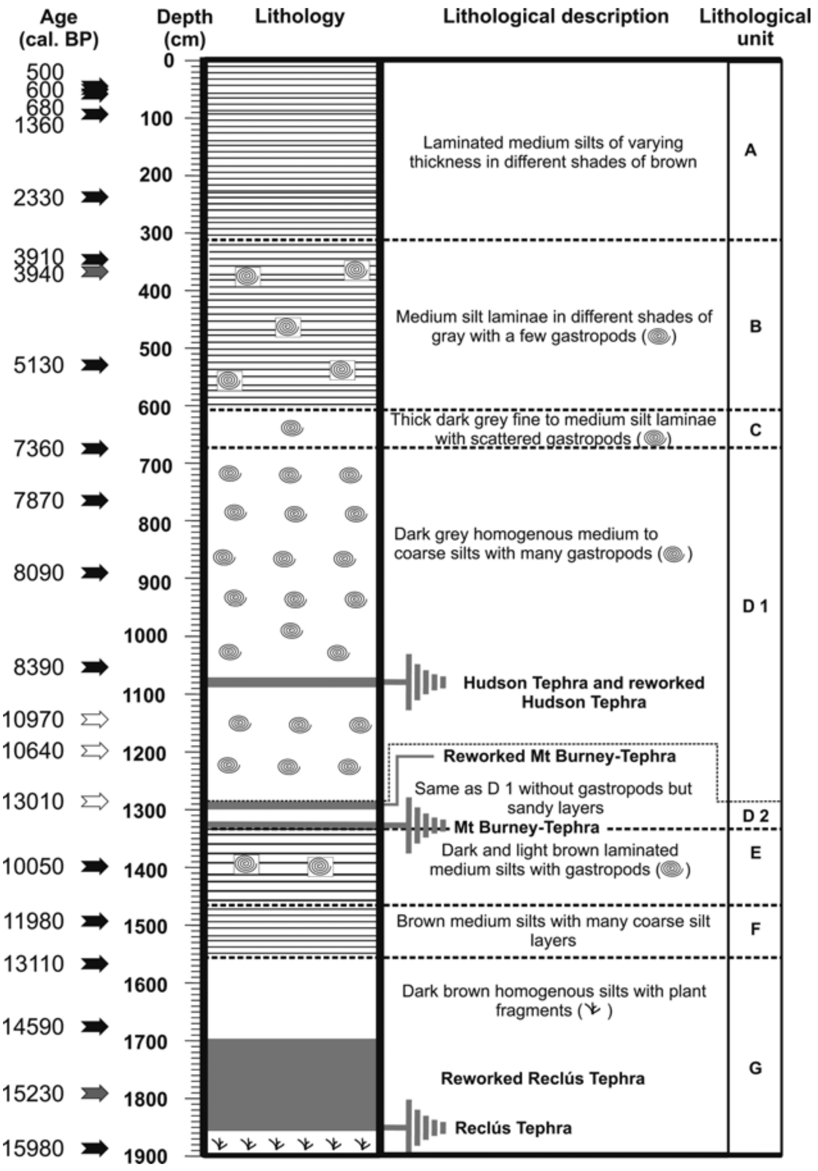

Figure 2 Lithology of composite core PTA02/4, PTA03/12 and PTA03/13 from Laguna Potrok Aike including medians of calibrated radiocarbon dates (black arrows, dates used for age model; white arrows, rejected dates; grey arrows, validation dates)

cold phase (12 700–11 500 cal. BP) has been discussed extensively, particularly on the basis of pollen records (Heusser and Rabassa, 1987; Heusser, 1989, 1998; Markgraf, 1991, 1993b; Rabassa *et al.*, 2000; Heusser *et al.*, 2000), chironomids (Massaferro *et al.*, 2005), glacial moraines (Wenzens, 1999, 2003; Glasser *et al.*, 2004) and marine sediments (Andres *et al.*, 2003; Kim *et al.*, 2002).

Here a continuous high-resolution terrestrial record from Laguna Potrok Aike (51°58'S, 70°23'W, Figures 1 and 2), which was recovered within the project SALSA (South Argentinean Lake Sediment Archives and modelling) and spans the last 16 000 cal. BP, is presented.

The aim of this study is to present the lithology, the chronology and the sedimentology together with geochemical data obtained from two overlapping sediment cores from the deepest part of Laguna Potrok Aike. Based on these data the palaeoenvironmental conditions and the hydrological history will be reconstructed.

Site description and modern climate

Laguna Potrok Aike (Figure 1) is located in southern Santa Cruz, Patagonia, Argentina, approximately 90 km west of the city of Río Gallegos (51°37'S, 69°10'W, Figure 1) and 80 km north of the Strait of Magellan. With the exception of Laguna Azul (52°05'S, 69°35'W, Figure 1; Mayr *et al.*, 2005), this maar lake is the only investigated permanently water-filled lacustrine system in the Patagonian steppe south of 49°S. A permanent water body is important as most closed lakes in southern Patagonia have been receding since 1940 (Stine and Stine, 1990; Gilli *et al.*, 2001) and hence tend to desiccate during dry summers, which causes discontinuous deposition or even erosion. With a current water depth of *c*. 100 m this is unlikely to happen to Laguna Potrok Aike. Only minor intra-annual lake level variations of ⩽1 m have occurred since March 2003. However, the lake level has been rising by more than 1 m since then. The dominating climatic element is the westerly wind, constituting more than 50% of all wind directions and reaching mean monthly wind speeds of 9 m/s during early summer (Endlicher, 1993). Precipitation is almost equally distributed around the wind rose, with maxima from southwestern and northern directions (Haberzettl, 2006). Owing to the strong winds that enforce polymictic conditions today, there is almost no stratification of the waterbody (Zolitschka *et al*., 2006) in summer and freezing in winter is inhibited. Temperatures during summer time reach 10–12°C. The rain shadow effect of the Andes causes only about 200 mm/yr of precipitation, which is the reason for the steppe vegetation around the lake. Therefore, despite a catchment area larger than 200 km^2, surface inflow only happens episodically through gullies and canyons. Currently, the 3470 m wide circular (shoreline development 1.1) lake has no surface outflow. As such, Laguna Potrok Aike responds very sensitively to changes in the precipitation/evaporation ratio, with rising lake levels in times of wetter climatic conditions and falling lake levels during drier periods (Haberzettl *et al.*, 2005). This is documented by numerous well-preserved subaerial as well as subaquatic lake level terraces around the lake (Haberzettl *et al.*, 2005, 2007). Further details about Laguna Potrok Aike, the catchment area and climatic conditions have been published elsewhere (Haberzettl *et al*., 2005; Haberzettl, 2006; Zolitschka *et al.*, 2006).

Field and laboratory methods

Two overlapping sediment cores (PTA03/12: 1988 cm and PTA03/13: 1003 cm, 51°57'39"S, 70°22'46"W) were recovered with a 5-m coring chamber of a hand-driven UWITEC piston coring system (http://www.uwitec.at; acrylic glass tubes, I.D. 60 mm) from the 100 m deep central basin of Laguna Potrok Aike (Figure 1) during 2003. Core sites were selected on the basis of a dense seismic survey grid consisting of ~70 km of high-resolution single-channel seismic data which was acquired in February 2003 with a 3.5 kHz pinger system characterized by a vertical resolution of ~10 cm. The survey was performed with a steel-hulled catamaran with a conventional GPS-based navigation. Seismic data were stored digitally in SEG-Y format, allowing further processing and interpretation. A 2–6.5 kHz bandpass filter was applied to the data (Haberzettl *et al*., 2007). In the laboratory sediment cores were stored dark and cool at +4°C. Core sections 1 m long were split, photographed and described lithologically. Magnetic susceptibility (κ) measurements were performed on split cores with a Bartington MS2F point sensor at 1 cm resolution. An XRF-scanner provided analyses of K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Sr and Pb (Jansen *et al.*, 1998) at 1 cm depth intervals. Ca data graphs plotted on photographs of the cores were used for correlation and to establish a composite profile in which PTA03/13 was used to close gaps in PTA03/12. The top 95 cm of the sedimentary record are covered by the already studied short core PTA02/4 (1380 cal. BP, 51°57'24"S, 70°22'38"W, Haberzettl *et al.*, 2005). After correlation the total length of the composite record was 1892 cm.

Smear slides were prepared from pooled subsamples of consecutive 5 cm intervals. SEM pictures were taken with a LEO 1530 electron microscope. Bulk mineralogy was determined for selected samples using x-ray diffraction (XRD) techniques (Philips X'Pert Pro MD equipped with an X'Celerator Detector-Array). Gastropods and plant macroremains were picked out prior to analyses. Age determinations were carried out at the Poznań Radiocarbon Laboratory, Poland. Four radiocarbon dates had already been obtained from the short core (Haberzettl *et al.*, 2005). Additionally, remains of aquatic macrophytes located close to a calcite date were measured in order to test the reliability of dates obtained from the carbonate fraction (Table 1). All ^{14}C ages were calibrated with the Northern Hemisphere calibration curve (Reimer *et al.*, 2004) using the software CALIB 5.0.2 (Stuiver and Reimer, 1993; Stuiver *et al.*, 2005). Uncalibrated dates from other studies used for comparison were calibrated in the same manner.

All core sections were sampled continuously and volumetrically (6 cm^3) at 1 cm intervals. A total of 1892 samples were freeze-dried for determination of water content (WC). The number of freshwater gastropods (Lymnaeidae) found in equal sample volumes was used as gastropod-index (GI). Total nitrogen (TN), total carbon (TC) and total sulfur (TS) were determined with a CNS-analyser (Euro EA). For determination of total organic carbon (TOC) subsamples were subsequently treated with 3% and 20% HCl at 80°C to remove any carbonates and then measured with the CNS analyser again. Total inorganic carbon (TIC) was calculated as the difference between TC and TOC. A depth-constrained cluster analysis of analysed data was performed using MVSP (Multi-Variate Statistical Package, Kovach Computing Services, 2005).

Possible tephra layers were characterized geochemically and microscopically in order to define their volcanic sources. For comparison, tephra samples from the volcanoes Hudson, Reclús and Aguilera/Lautaro (Gilli, 2003; Markgraf *et al.*, 2003) obtained from the sediment record from Lago Cardiel (Figure 1) were also analysed. Samples were cleaned with 30% H_2O_2 to remove organics and surface coatings, and dried with ethanol. Major-element chemistry of single glass shards was determined on polished thin sections by electron probe micro analyses (EPMA) using a CAMECA SX100 (WDS) instrument at GFZ Potsdam. The operating conditions for measurements were 15 kV accelerating voltage, 20 nA beam current, a defocused beam of 15 μm diameter and peak counting times of 20 s except for Na (10 s). For instrumental calibration, Lipari obsidian was used as reference material (Hunt and Hill, 1996). Individual analyses of glass shards with total oxide sums $\leqslant$95 wt.% were excluded.

Results

Lithology and sediment analyses

The composite profile is divided into seven lithological units (A to G, Figure 2) and unit D into two subunits (D1 and D2, Figure 2). This classification is based on unambiguous lithological characteristics such as colour variations, the distinction between laminated and homogenous sections, as well as the presence of organic macroremains and gastropods. A depth-constrained cluster analysis including all analysed data revealed the same classification. In general, the major part of the record consists of clayey and sandy silts becoming coarser with depth (Figure 2). Only tephra layers and reworked volcanic ashes comprise fine to medium sand. Reworked layers were identified by the combination of their lithological characteristics (colour, coarser grain size), their high content of reworked tephra material, which was detected either macroscopically or on smear slides, and the characteristic incorporation of macrophyte layers. The elements V, K and Fe are significantly correlated with Ti ($R^2 = 0.73, 0.67, 0.66$) for the whole record. Hence, Ti was chosen as a representative for these elements in Figure 3.

Table 1 AMS radiocarbon dates from Laguna Potrok Aike

Sediment depth (cm)	^{14}C age (BP)	Error	Sample description	Median cal. age (cal. BP)	Min. cal. age (cal. BP)	Max. cal. age (cal. BP)	Lab. no and/or reference
43.5	440	30	Stems of aquatic moss	500	340	535	Poz-834 (Haberzettl *et al.*, 2005)
50.0	655	25	Bulk sediment	600	560	670	Poz-897 (Haberzettl *et al.*, 2005)
57.5	735	25	Calcite fraction of bulk sample	680	660	720	Poz-3570 (Haberzettl *et al.*, 2005)
92.5	1470	40	Stems of aquatic moss	1360	1295	1485	Poz-896 (Haberzettl *et al.*, 2005)
237.5	2300	35	Twig of *Berberis*	2330	2160	2360	Poz-5182
345.5	3600	35	Calcite fraction of bulk sample	3910	3785	4065	Poz-8549
368.5*	3625	35	Stems of aquatic moss	3940	3840	4080	Poz-8390
529.5	4465	50	Stems of aquatic moss	5130	4890	5300	Poz-8398
673.5	6440	70	Calcite fraction of bulk sample	7360	7185	7485	Poz-8550
763.0	7025	50	Stems of aquatic moss	7870	7740	7955	Poz-8391
890.5	7260	50	Calcite fraction of bulk sample	8090	7980	8175	Poz-8546
1052.5	7580	50	Stems of aquatic moss	8390	8220	8515	Poz-8392
1074.5***	6915 7635	40 40	Hudson	8100	7670	8535	(Kilian *et al.*, 2003)
1142.5**	9640	50	Stems of aquatic moss	10 970	10 780	11 190	Poz-8393
1198.5**	9410	50	Calcite fraction of bulk sample	10 640	10 510	10 755	Poz-8547
1286**	11 090	60	Stems of aquatic moss	13 010	12 895	13 115	Poz-8394
1320***	7635 7890	40 40	Mt Burney	8680	8380	8975	(Kilian *et al.*, 2003)
1398.5	8930	50	Bone of *Ctenomys* sp.	10 050	9905	10 215	Poz-5985
1493.5	10 240	60	Calcite fraction of bulk sample	11 980	11 715	12 345	Poz-8548
1578.5	11 200	60	Stems of aquatic moss	13 110	12 960	13 220	Poz-8396
1676.5	12 490	70	Stems of aquatic moss	14 590	14 205	14 960	Poz-8397
1790.5*	12 850	70	Stems of aquatic moss	15 230	14 440	15 820	Poz-5072
1861***	12 638	60	Reclús	14 900	14 605	15 190	(McCulloch *et al.*, 2005)
1888.5	13 450	70	Stems of aquatic moss	15 980	15 605	16 410	Poz-5073

Median, minimum and maximum of calibrated ages refer to the 2σ ranges. If two dates are given for one tephra sample, they refer to above and below the respective ash layer.
* Validation date.
** Date excluded from age model.
*** Tephra dates from literature (re-)calibrated with CALIB 5.0.2.

Lithology

Lithological unit G (1892–1557 cm) consists of dark brown homogenous silts (Figure 2). It is subdivided by the Reclús tephra and 166 cm of reworked volcanic ashes from the same volcano. In the silts below the tephra many plant fragments were found (Figure 2). Unit F (1556–1465 cm) is composed of brown medium silts with many coarse silt layers in between, which are covered by dark and light brown laminated medium silts containing gastropods in unit E (1464–1320 cm). The transition between units E and D (1319–669 cm) comprises the Mt Burney tephra and reworked parts of it directly above (1332–1320 cm). Unit D can be subdivided into two subunits D1 (1319–1298 cm) and D2 (1286–669 cm) subdivided by reworked ashes from Mt Burney (1297–1287 cm, Figure 2). Dark grey homogenous medium to coarse silts are the components of both units but in contrast to D2, unit D1 contains many gastropods. Unit D2 does not hold any gastropods but many coarse silt layers (Figure 2). The number of gastropods decreases in the thick, dark grey fine to medium silt laminae of unit C (668–607 cm). In unit B (606–313 cm) the number of gastropods further decreases. The top of the record, unit A (312–0 cm), is made up of laminated medium silts of varying thickness in different shades of brown (Figure 2).

Sediment analyses

Lithological unit G (1892–1557 cm): Ti, TN, TOC and WC show a distinct maximum in the lowermost part and high values at the top of unit G. In between, where a tephra and reworked ash were deposited, the lowest values of the record, mostly below the detection limit, are observed. GI, Ca and TIC show minor variations also partly below detection limit. Only TIC and Ca peak at the uppermost part of unit G (Figure 3).

Lithological unit F (1557–1465 cm): according to smear slides and SEM images this is the only unit where the green alga *Phacotus lenticularis* is present (Figure 4). Unit F is characterized by peaks in TIC, Ca, TOC, TN, and WC (Figure 3).

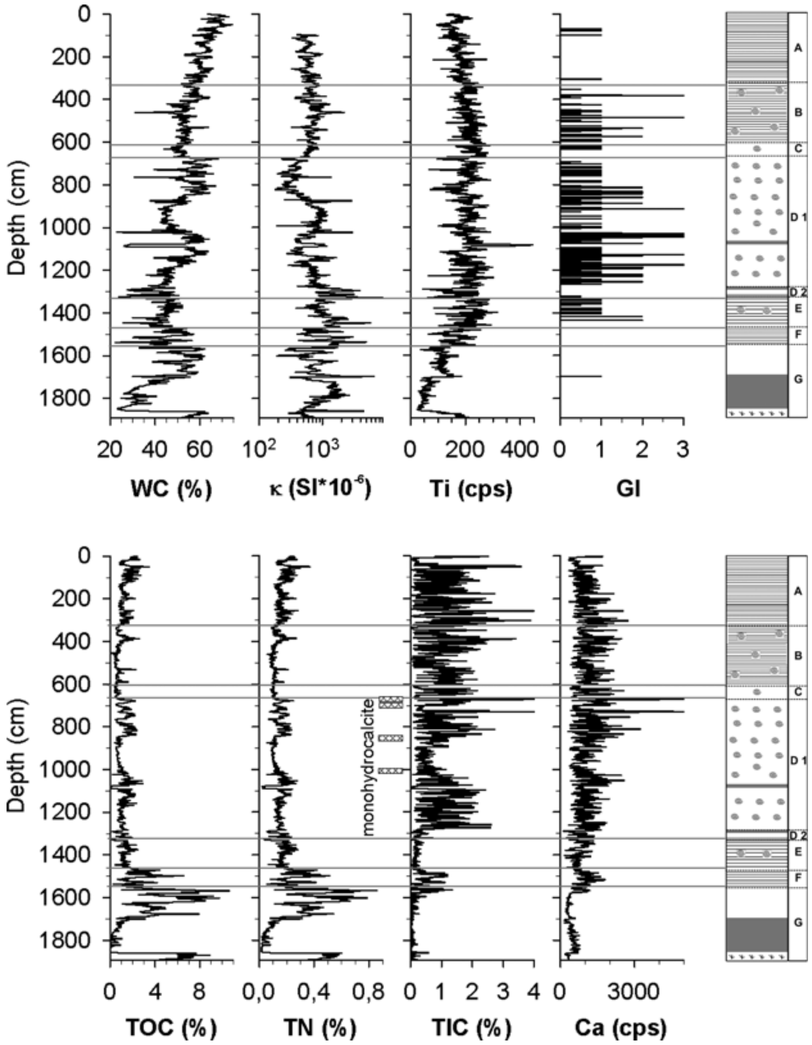

Figure 3 Geochemical and geophysical data versus depth (WC, water content; κ, magnetic susceptibility (logarithmic scale); Ti, titanium; GI, gastropod index; TOC, total organic carbon; TN, total nitrogen; TIC, total inorganic carbon; Ca, calcium). Elemental data are plotted as counts per second (cps)

Lithological unit E (1465–1320 cm): gastropods appear in greater numbers for the first time (Figures 2 and 3). Ti shows distinct high values throughout unit E and κ at the base of this unit. TIC, Ca, TOC and TN are relatively low.

Lithological unit D (1320–669 cm): this unit starts with exceptionally high values of κ (≤15 800 SI*10^{-6} immediately above the boundary of lithological units D and E, note logarithmic scaling) related to a tephra layer and reworked parts of it (Figures 2 and 3). In these sections TIC and Ca show low values and gastropods are not present. However, the highest density of gastropods in the whole core becomes evident above the reworked tephra. In contrast to TOC and TN, the range of variability as well as absolute values of TIC and Ca increase immediately above the reworked tephra (Figure 3). Nevertheless, there is a broad interval between 1036 and 843 cm with lower values of all four parameters as well as WC and a secondary minimum delimited by high TIC and Ca and low Ti values from 729 to 670 cm (Figure 3). Four XRD analyses at 1007, 867, 705 and 682 cm sediment depth showed that monohydrocalcite ($CaCO_3*H_2O$) is only present in this unit. κ shows the lowest values of the record between 856 and 669 cm.

Lithological unit C (669–607 cm): this unit is characterized by low values of TIC and Ca in the upper- and lowermost part and a peak in between (Figure 3). The opposite is the case for Ti and WC. Gastropods are only present in the uppermost part of unit C. All other parameters do not vary significantly (Figure 3).

Lithological unit B (607–313 cm): TIC and Ca show a sequence of two maxima followed by minima (Figure 3). WC, TOC and TN display minor variations with a slight maximum near the top of the unit (~387 cm).

Lithological unit A (313–0 cm): TIC, Ca, TOC and TN show a broader minimum just before values increase again in the uppermost part of the record. The TIC minimum with values below detection limit is the most prominent one observed for TIC and Ca above 12.8 m sediment depth. The opposite pattern is observed for Ti, showing high values before they decrease. Gastropods are almost absent (Figures 2 and 3).

Volcanic ashes

Laguna Potrok Aike, located in a favourable downwind position to the explosive volcanoes of the Austral Volcanic Zone (AVZ, 49–54°S) and the southernmost Southern Volcanic Zone (SSVZ, 46°S), has recorded three major explosive events during the last 16 000 cal. BP. The youngest tephra (1074.5 cm sediment depth) is a fine grained (≤100 μm) brown-greenish vitric ash. The principal mineral assemblage is composed of plagioclase, alkali feldspar and colourless to light greenish clinopyroxene.

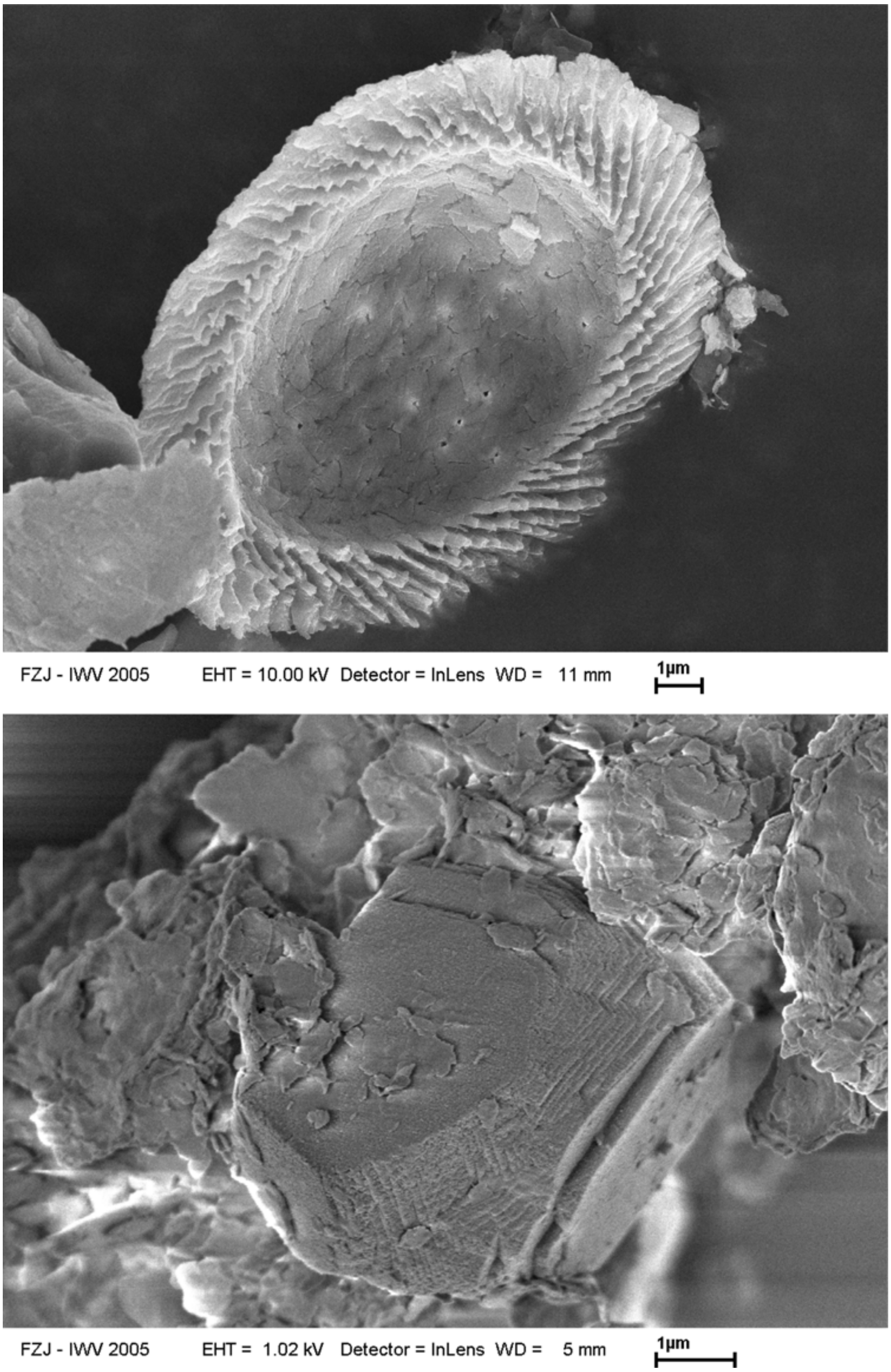

Figure 4 SEM images of *Phacotus lenticularis* (top) and autochthonously precipitated calcite crystal (bottom)

Lithics are represented by limestone fragments and vitric (palagonite) tuffs. Volcanic glass shards are blocky shaped and trachydacitic to dacitic in chemical composition (Table 2). The major-element glass chemistry corresponds to the plinian eruption *H1* of the Hudson volcano (Figure 5). Another tephra layer (1320 cm) represents a relatively coarse grained (≤1 μm) whitish pumice fallout. Its mineral assemblage is made up of zoned plagioclase, clinopyroxene, orthopyroxene and amphibole phenocrysts. Aggregates of olivine and clinopyroxene microcrysts are common. Volcanic glasses are homogeneously rhyolitic in composition, providing a major element chemistry identical to Mt Burney volcanic ejecta (Table 2, Figure 5). Owing to its stratigraphic position in the Laguna Potrok Aike profile – below the *H1* tephra – this tephra correlates with a plinian eruption of Mt Burney. The oldest tephra (1861 cm) is a fine-grained (≤150 μm), beige vitric ash layer that is composed of abundant phenocrysts of clinopyroxene, orthopyroxene, zoned plagioclase and rare amphibole. Corroded quartz xenocrysts and clasts of plagioclase crystals are common. The chemical composition of micropumices and glass shards is heterogeneously rhyolitic and dacitic (Table 2). It most likely corresponds with a late Pleistocene distal tephra layer from Reclús volcano.

Table 2 Mean values of major-element EPMA data of glass shards from tephras occurring in the Potrok Aike profile PTA03/12 + 13.

Tephra source	1090 cm Hudson	1334–1332 cm Mt. Burney	1855–1854 cm Reclús	
			Glass type a	Glass type b
SiO_2	65.30 (0.97)	75.70 (0.92)	75.38 (0.53)	66.38 (0.00)
TiO_2	1.23 (0.06)	0.14 (0.01)	0.13 (0.02)	0.42 (0.00)
Al_2O_3	16.16 (0.09)	12.88 (0.32)	12.71 (0.28)	16.33 (0.00)
FeO	4.93 (0.37)	1.05 (0.06)	1.21 (0.08)	3.71 (0.00)
MnO	0.16 (0.04)	0.03 (0.03)	0.05 (0.02)	0.11 (0.00)
MgO	1.50 (0.26)	0.24 (0.01)	0.23 (0.02)	1.81 (0.00)
CaO	2.97 (0.43)	1.18 (0.09)	1.59 (0.15)	4.20 (0.00)
Na_2O	4.47 (0.29)	3.64 (0.31)	3.00 (0.25)	3.48 (0.00)
K_2O	2.80 (0.12)	1.76 (0.07)	2.27 (0.13)	1.45 (0.00)
P_2O_5	0.35 (0.06)	0.05 (0.05)	0.03 (0.03)	0.17 (0.00)
Cl	0.13 (0.02)	0.19 (0.02)	0.17 (0.03)	0.10 (0.00)
Total	100.01 $n = 19$	96.87 $n = 7$	96.78 $n = 15$	98.16 $n = 1$

Numbers in parentheses: 1σ standard deviation; *n*, number of glass shards analysed. Glass shards from Reclús reveal to types of glasses (a and b).

Though a number of age determinations for the tephra layers detected in the sediment record of Laguna Potrok Aike exists, a composite of those ages would have resulted in errors larger than 2000 years, minimizing the value of such isochronous marker horizons. Thus, data from the latest publications (Kilian *et al.*, 2003; McCulloch *et al.*, 2005) calibrated with the Northern Hemisphere calibration curve (Reimer *et al.*, 2004) of CALIB 5.0.2 (Stuiver and Reimer, 1993; Stuiver *et al.*, 2005) were assumed to provide most accurate results (Table 1).

Age–depth model

The age–depth model is based on 16 radiocarbon dates performed on different materials (Table 1, Figure 6) and on the Mt Burney tephra (Kilian *et al.*, 2003). It was necessary to include the tephra because three radiocarbon dates above that volcanic ash were too old, probably because they contain reworked old carbon (Figure 6). A hard water effect in the sediments of Laguna Potrok Aike has been demonstrated to be absent (Haberzettl *et al.*, 2005). The sediment/water interface serves as time marker for the year of coring (2002) for the uppermost section of the record (PTA02/4, Haberzettl *et al.*, 2005). The medians of the 2σ-probability distributions of all age determinations were connected linearly (Figure 6). Events such as tephra layers or reworked tephra were marked with grey bars in the lithology and show the same age with increasing depth in Figure 6 (only visible for unit G). These events were excluded in Figure 7.

The age ranges of tephras from Hudson (Kilian *et al.*, 2003) and Reclús (McCulloch *et al.*, 2005) volcanoes (Table 1) serve as a validation for the age–depth model. Further confirmation is given by two other validation dates: one of aquatic mosses

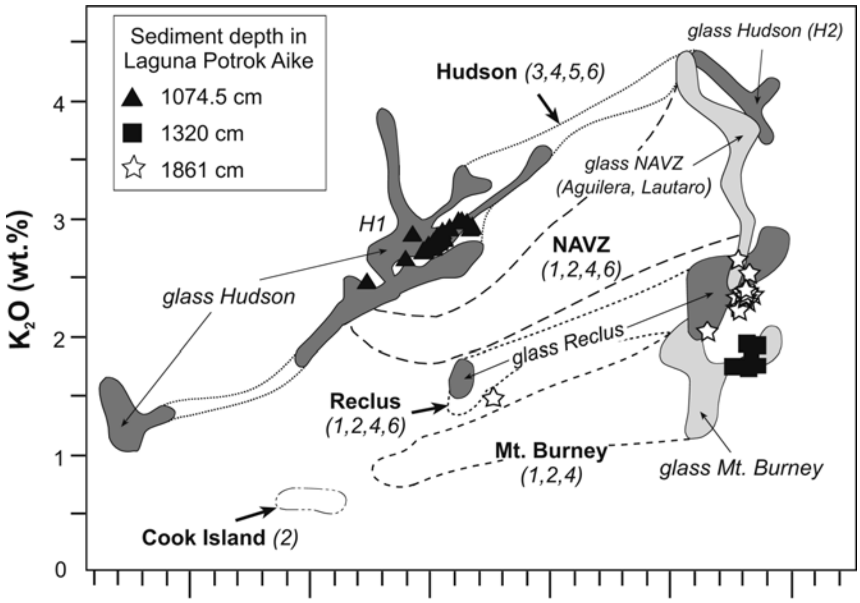

Figure 5 Comparison of SiO_2 and K_2O data of Laguna Potrok Aike tephras with mean oxide concentrations of tephras derived from southern Patagonian volcanoes (geochemical envelopes, EPMA data of juvenile glass; dashed lines, whole rock XRF data). Data from: 1, Stern *et al.* (1990); 2, Stern and Kilian (1996); 3, Naranjo and Stern (1998); 4, Kilian *et al.* (2003); 5, Bitschene and Fernandez (1995); 6, this work

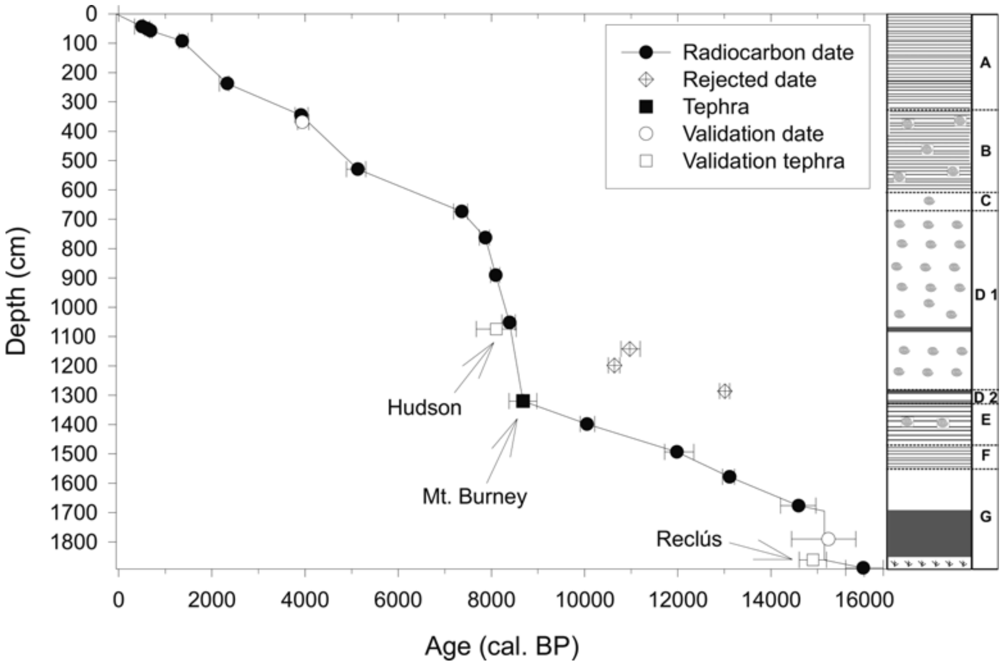

Figure 6 Age–depth model based on calibrated radiocarbon dates and the Mt Burney tephra. Each date is displayed as median of the 2σ-probability distribution with error bars. The sediment–water interface is a time marker for the year of coring (2002). Reclús and Hudson tephras, as well as two radiocarbon dates, were used for validation

found in the reworked Reclús tephra and the other of aquatic macrophytes next to a date based on autochthonously precipitated calcite, which both provided similar results (Figure 6). In addition to confirming the other radiocarbon date, this indicates that the calcite fraction is well suited for dating. All validation dates were excluded from the age–depth model as the age ranges of these dates intersect the linearly interpolated age–depth model (Figure 6).

Discussion

Indicators for lake level changes

The most recent lake level variations of larger magnitude at Laguna Potrok Aike have been demonstrated by dating subaerial shorelines (Haberzettl *et al.*, 2005) and a subaquatic lake level terrace (Haberzettl, 2006). A similar approach was used for Lago Cardiel (Stine and Stine, 1990). However, in all cases the dating of shorelines only provides selective evidence of events. As no single line of sedimentary or geomorphologic evidence defines lake level changes unequivocally (Duck *et al.*, 1998), a multiproxy approach is presented here. The following proxies are related to lake level changes and provide continuous records for hydrological variations.

Calcium carbonates

In an earlier study the presence or absence of autochthonous calcite, represented by TIC and Ca (Figure 4), was identified as a lake level indicator for the last two millennia for Laguna Potrok Aike (Haberzettl *et al.*, 2005). These parameters provide qualitative estimations for past lake level variations with high TIC and Ca values reflecting lower lake levels and *vice versa*.

In lithological unit F, TIC and Ca merely reflect the remains of the calcareous shells of the green alga *Phacotus lenticularis* whereas in all other units calcite crystals are present. *Phacotus* was distinguished from other autochthonous calcites using smear slides and SEM images (Figure 4). It produces $CaCO_3$ in remarkable amounts and massive blooms can influence the $CaCO_3$ budget of lakes (Koschel *et al.*, 1987; Schlegel *et al.*, 1998). In Lake Constance, mass developments of *Phacotus* were assumed to be responsible for serious depletions of calcium (Müller and Oti, 1981; Schlegel *et al.*, 1998). This would probably stop autochthonous calcite precipitation in Laguna Potrok Aike as it was observed in Lake Tollense, Germany (Koschel *et al.*, 1987). Laboratory experiments showed that the occurrence of *Phacotus lenticularis* directly depends on the degree of calcium supersaturation (Hepperle and Krienitz, 1997; Schlegel *et al.*, 2000b). This implies that *Phacotus* in Laguna Potrok Aike, like other autochthonous calcite compounds, is dependent on low lake levels resulting in high calcite saturations (Haberzettl *et al.*, 2005).

The calcite species monohydrocalcite was also recognized in the sediments of Laguna Potrok Aike. Laboratory experiments confirmed that bacteria precipitate monohydrocalcite at high salt concentrations (Rivadeneyra *et al.*, 2000, 2004). In Laguna Potrok Aike such high salt concentrations would point to an enrichment of ions resulting from lower lake levels.

Titanium (Ti) and Ca/Ti ratio

Ti contents were previously used as an indicator for riverine clastic input, eg, to the Cariaco Basin off the Venezuelan coast (Haug *et al.*, 2003). A similar approach was used for Lake Steisslingen, southern Germany (Eusterhues *et al.*, 2005) and Lake Baikal, eastern Siberia (Demory *et al.*, 2005). The presence of Ti in these lakes reflects detrital input since Ti is released from Ti-bearing rocks by physical erosion (Cohen, 2003) through weathering and minerals containing Ti are not sensitive to dissolution (Demory *et al.*, 2005). For Laguna Potrok Aike results of the short core (Haberzettl *et al.*, 2005) and a long core from a subaquatic lake level terrace (Haberzettl *et al.*, 2007) show that Ti was associated with allochthonous input resulting from runoff and hence hydrological variability. Most of the time Laguna Potrok Aike had no surface outflow. Therefore, runoff is assumed to influence lake level variations and, hence, Ti can be used as indicator for lake level fluctuations. Consequently, the Ca/Ti ratio in sediments of Laguna Potrok Aike reflects hydrological variability, with high values

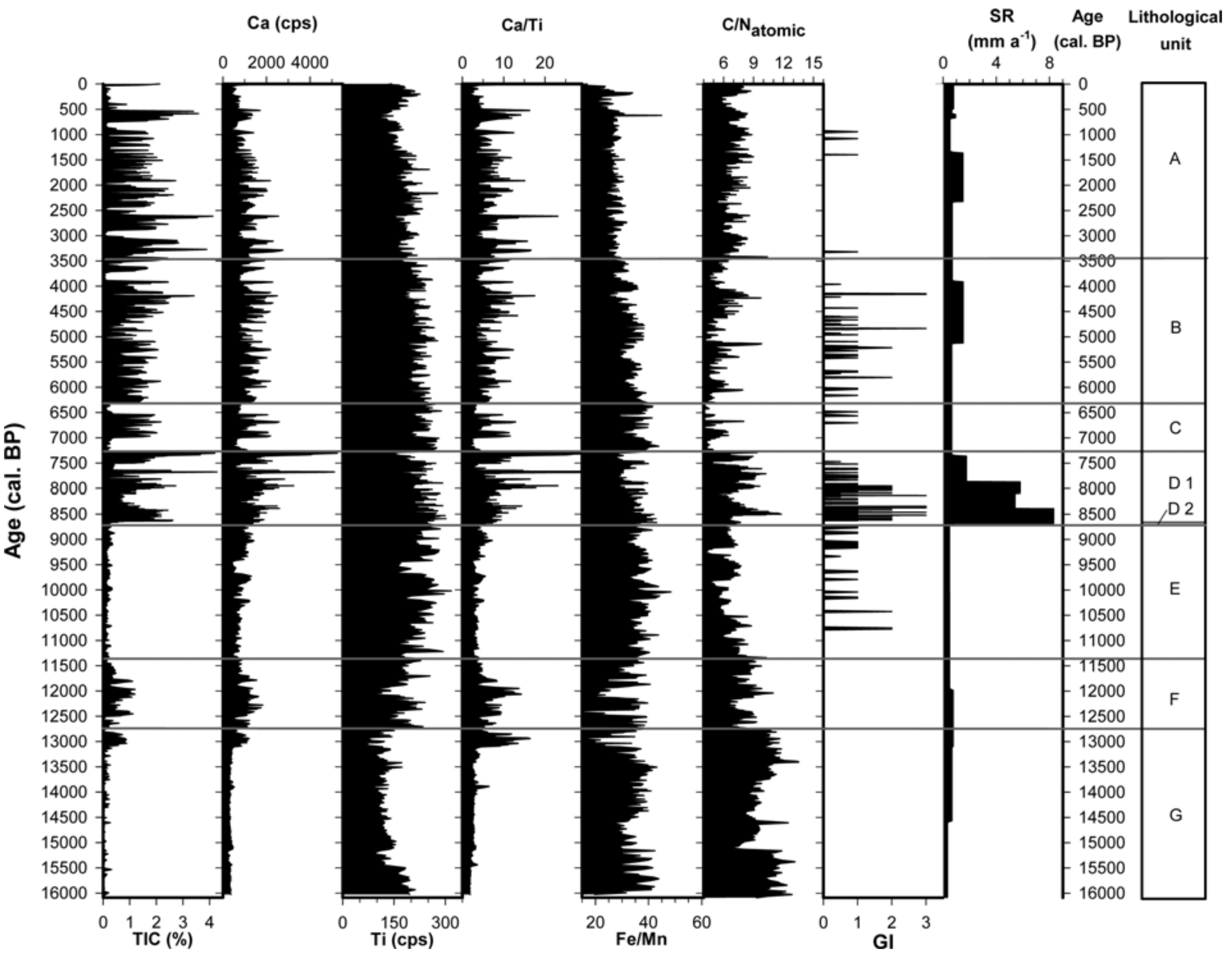

Figure 7 Selected sediment parameters versus time reflecting hydrological variations (lake level changes) at Laguna Potrok Aike (SR, sedimentation rate)

reflecting dry phases and low values responding to moist conditions, and can be used as representative for TIC, Ca and Ti.

Fe/Mn ratio

The higher solubility of Mn versus Fe in the sediment (Wetzel, 1983) has been suggested as a key to the interpretation of the Fe/Mn-ratio (Cohen, 2003). The release of Mn from sediments precedes that of Fe (Wetzel, 1983; Brüchmann and Negendank, 2004). Dissolution of Mn compounds occurs if the redox potential (E_H) decreases below 600 mV because of reduction of Mn^{4+} to Mn^{2+} (Sigg and Stumm, 1996). For iron the critical E_H for reduction of Fe^{3+} compounds to more soluble Fe^{2+} compounds is 100 mV (Sigg and Stumm, 1996). Therefore, if the redox potential drops to values between 100 and 600 mV, Fe/Mn ratios will be increasing. Rising Fe/Mn ratios are hence indicative for the beginning of reducing conditions (Cohen, 2003; Brüchmann and Negendank, 2004) and can be used as a 'palaeo-redox indicator' for lacustrine sediments (Wersin *et al.*, 1991; Granina *et al.*, 2004). Although it cannot be excluded that E_H never dropped below 100 mV in Laguna Potrok Aike, high Fe/Mn ratios are interpreted as being indicative of reducing conditions.

The Fe/Mn ratio will be applied to confirm the interpretation derived from other mentioned parameters. It is assumed that mixing (ie, oxygen supply to the sediment–water interface) and consequently a lower Fe/Mn ratio is easier to achieve if the lake level is lower and/or wind speed is higher.

C/N ratio (TOC/TN ratio$_{atomic}$)

In previous studies the C/N ratio has been used as a palaeoshoreline proximity indicator for Laguna Potrok Aike (Haberzettl *et al.*, 2005, 2007). This is based on the assumption that algal organic matter has molar C/N values commonly between 4 and 10, whereas higher plants produce organic matter with higher C/N ratios (Meyers, 1994, 2003; Cohen, 2003). Submersed aquatic macrophytes collected from Laguna Potrok Aike have C/N values between 24 and 49 and were expected to be the source of organic matter for core sections with elevated C/N ratios (Haberzettl *et al.*, 2005). Therefore, it is assumed that during periods of lake level low stands increased amounts of vascular plants were transported to the coring location, which resulted in increasing C/N ratios (Haberzettl *et al.*, 2005).

Gastropods

Freshwater mollusks are relatively poor indicators of past environmental conditions because of their generally broad environmental tolerance (Ouellet, 1975; Wetzel, 1983). However, they are abundantly preserved in nearshore deposits (Cohen, 2003). Today, freshwater gastropods (Lymnaeidae) in Laguna Potrok Aike are observed alive at the sediment–water interface of short cores in depths up to 12 m. However, sporadic dead specimens were recovered from greater depths (80 m). In sediments that were deposited during a lake level high stand, ie, the 'Little Ice Age' (Haberzettl *et al.*, 2005) and Oxygen Isotope Stage 3 (Haberzettl *et al.*, 2007), no gastropods were observed at all.

Therefore, abundant gastropods in this sediment record indicate a rather close palaeoshoreline, facilitating their transport to the coring location.

Sedimentation rate

Increased sedimentation rates have only been observed for lithological unit D. Such sedimentation rates cannot be explained by usual depositional processes. A response of the sedimentation rate to higher amounts of precipitation during entire lithological units spanning at least some centuries, however, is unlikely, as the steppe vegetation responds quickly to increased moisture availability. Denser vegetation probably would reduce erosion. Therefore, increased sedimentation rates may occur either if vegetation in the catchment area was reduced and/or the lake level was relatively low, uncovering vegetation-free lacustrine sediments. In both cases the (enlarged) catchment area was prone to erosion as it was not stabilized by vegetation and/or less resistant lacustrine sediments were exposed and easily eroded by runoff. Furthermore, even if allochthonous input remained constant, a lower lake level would imply an increased sedimentation rate at the coring location, as the area available for deposition decreased. Therefore, increased sedimentation rates in Laguna Potrok Aike point to a low lake level or a regression.

Palaeoenvironmental reconstruction

According to the lake level indicators discussed, a palaeoenvironmental reconstruction with emphasis on hydrological variations is presented for the entire record and compared with other archives of regional and global importance.

High early Lateglacial lake levels

In unit G (16 000–12 800 cal. BP) low Ca/Ti values point to a long period of high lake levels at Laguna Potrok Aike. A low lake level is indicated only during the uppermost 400 years (13 200–12 800 cal. BP) by higher values (Figure 7). This interpretation is supported by more oxic conditions in the lower part of unit G, indicated by high Fe/Mn ratios in the lower and low Fe/Mn ratios in the uppermost part. Only minerogenic input, represented by Ti, is contradictory on first sight because low values would indicate little fluvial input and hence dry conditions. Although Ti variations in this unit are on a lower level, they are positively or negatively correlated with the other proxies, especially towards the top of the unit. One explanation for the low minerogenic input and the variability in this unit might be that the lake level was extremely high, resulting in an outflow of the lake that today is located approximately 25 m above the lake surface. As this outflow of the lake is close to the recent inflow (Figure 1), and as there is geomorphologic evidence for a possible fluvial bypass, large portions of the minerogenic material that normally would have been deposited in the lake centre might have passed the lake. This would also explain why TIC and Ca values are the lowest of the record.

This proposed lake level high stand and the subsequent low stand coincide with the hydrological record of Lago Cardiel (Figure 1), which also points to a high lake level until 13 160 cal. BP (Gilli, 2003) followed by desiccation around 13 120 cal. BP (Gilli *et al.*, 2005).

Dry and warm late Lateglacial

Unit F (12 800–11 400 cal. BP) is the only part of the record in which the calcite fraction of the sediment was produced by *Phacotus.* The ability of *Phacotus* to deplete the calcium budget of lakes (Müller and Oti, 1981; Schlegel *et al.*, 1998) preventing the precipitation of other autochthonous calcite, suggests that high values of Ca/Ti ratio represent a lower lake level. However, Ti shows higher values than in unit G, which would indicate more minerogenic input and hence moister conditions. Nevertheless, compared with the rest of the record values are rather low and follow the pattern of the other proxies (Figure 7). This might be related to a lake level lowering that resulted in an enhanced transport of minerogenic matter to the centre of the lake because there was no longer an outflow or bypass. More oxic conditions inferred from the Fe/Mn ratio support the hypothesis of a lower lake level during that time.

According to temperature studies in European lakes *Phacotus lenticularis* only occurs at temperatures >15.8°C (Müller and Oti, 1981; Schlegel *et al.*, 1998, 2000a). Therefore, the occurrence of *Phacotus lenticularis* in the sediment record from Laguna Potrok Aike suggests much warmer summers. Such high temperatures today occur only at the water surface for a few days during January (Zolitschka *et al.*, 2006). These warm conditions would result in increased evaporation and, in analogy to present-day observations, increased wind speeds, leading to a lower lake level and increased mixing, which would explain the oxidizing conditions.

This period is contemporaneous with the Northern Hemisphere Younger Dryas chronozone (12 700–11 500 cal. BP). The possibility of warmer conditions during the Younger Dryas in the Southern Hemisphere is supported by various other records showing warming and/or peaks in temperature-sensitive parameters on a level never reached again until the present. Such a warming, for example, is recorded in the alkenone-based sea surface temperature reconstruction from ODP Site 1233 off Chile (Figure 1; Lamy *et al.*, 2004), which is similar to the deglacial warming determined for the Byrd ice core, Antarctica (Figure 1, Blunier and Brook, 2001). Both mentioned records suggest a Southern Hemisphere millennial-scale warming pattern (Lamy *et al.*, 2004).

Support for a drought in the steppe area of Patagonia is provided by the sediment record from Lago Cardiel, which shows the lowest lake levels ever recorded in the time span mentioned (Gilli, 2003). Additional evidence for warmer and/or drier conditions on Tierra del Fuego is given by dated basal peat layers evidencing a glacial melting before 11 720 cal. BP at Punta Pingüinos and Lapataia (Figure 1) and at 12 890 cal. BP for tributary glaciers at Bahía Aguirre (Figure 1; Rabassa *et al.*, 2000).

Humid early Holocene

Unit E (11 400–8700 cal. BP) is characterized by consistently moister climate conditions, as evidenced by all proxies from Laguna Potrok Aike. Lower Ti and Ca values around 9500 cal. BP are caused by a rough sediment surface in the liner during XRF-measurements that made it impossible to obtain accurate results in this part of the core (Figure 7).

Analyses of grass cuticles in sloth dung from Tierra del Fuego dated between 10 530 and 9500 cal. BP indicate a mixture of steppe and Magellanic Moorland environment, which points to moister than modern conditions (Markgraf, 1983). Tufa deposits at Lago Cardiel (Stine and Stine, 1990) reveal a high lake level between 11 200 and 10 780 cal. BP. However, the lake level of Lago Cardiel receded during that time (Stine and Stine, 1990). In contrast, no signs for regression were found at Laguna Potrok Aike.

During the early Holocene westerly storm tracks were inferred to have been more tightly focused between 45° and 50°S, leaving Andean regions north and south drier than today (Grimm *et al.*, 2001). As drier conditions west of the Andes will cause wetter conditions east of the Cordillera (Schneider *et al.*, 2003), increased rainfall and runoff are expected for Laguna Potrok Aike, which was probably the cause for the high lake levels.

Early mid-Holocene dry events

Unit D (8700–7300 cal. BP) is the largest section of the record. This is caused by remarkably high sedimentation rates resulting from two primary reasons.

(1) According to the lake level indicators TIC and Ca, the lake level was still high at the very beginning of unit D-2 (8700–8650 cal. BP). This is confirmed by reducing conditions related to high lake levels and increased minerogenic input inferred from Fe/Mn ratio and Ti. Macroscopically, a number of coarse layers can be distinguished, either pointing to increased erosive forces (water, wind) and/or instability of surrounding soils. As D-2 is directly preceded by the Mt Burney tephra and particles of that tephra are found in the coarser layers, the ash layer may have contributed to the high sedimentation rate. A hint for a disturbance of the ecosystem is the absence of gastropods, which might have suffered from an ash cover on submersed littoral plants.

(2) After this rather short unit containing tephra, major changes in most proxies occur around 8650 cal. BP (D-1). A major shift in Ca/Ti ratio points to a lake recession (Figure 7) intercepted by two short transgressions (8350–8100 and 7640–7500 cal. BP). A displacement of the shoreline further away from the coring location during these two transgressions can also be inferred from the C/N ratio (Figure 7). The general recession is confirmed by decreasing minerogenic input (Ti) and a trend to more oxic conditions (lower Fe/Mn ratio). The high sedimentation rates likely point to the erosion of emergent former littoral sediments that were easily eroded. Further evidence for this hypothesis comes from the rejected radiocarbon dates from this section of the core, which probably contained reworked carbon. Furthermore, the abundance of gastropods and high C/N ratios point to a shoreline generally closer to the coring location. Severe dry conditions are also corroborated by the occurrence of monohydrocalcite in all XRD samples from unit D-1, indicating high ion concentrations resulting from a low lake level.

These drier conditions might have been intensified by the thermal optimum related to orbital parameters (Renssen *et al.*, 2005). An increase in temperature and aridity in southern South America during the mid Holocene has also been inferred from pollen records (Mancini *et al.*, 2005). For Lago Cardiel it is concluded that the lake level fell below the present-day value from 8490 cal. BP to the present (Stine and Stine, 1990).

Late mid-Holocene lake level rise

Unit C (7300–6300 cal. BP) marks environmental changes towards moister conditions, with a higher lake level observable in all proxies from Laguna Potrok Aike (Figure 7). Moist conditions prevailed until 7000 cal. BP. All proxies indicate that this phase was followed by a drier period including lake recessions with short humid pulses in between. In the sediment core from the lake level terrace (PTA06/6, Figure 1, Haberzettl *et al.*, 2007) reworked material dated to 6790 cal. BP was found immediately above sediments deposited during Oxygen Isotope Stage 3. Together with the presented evidence from the deeper sediments in this study, this indicates that there must have been a transgression starting before 7000 cal. BP, followed by a regression to the base level. The reworked layer seems to be the result of the proposed drier period with short humid pulses (7000–6500 cal. BP) resulting in lake level fluctuations. However, the record from the lake level terrace points to continuous sedimentation after 6750 cal. BP (Haberzettl *et al.*, 2007) indicating a lake level rise during the humid pulses followed by a high lake level from 6500 cal. BP on. This transgression is also indicated by the C/N and Ca/Ti ratios (Figure 7). Moreover, the higher lake levels resulted in more reducing conditions deduced from the Fe/Mn ratio.

For Lago Cardiel, dates reveal a maximum age for a transgression at 6780 cal. BP and evidence a high lake level thereafter (Stine and Stine, 1990).

Variable late Holocene conditions

Starting from moist conditions with a high lake level at 6300 cal. BP, less minerogenic input and increasing oxic conditions (Fe/Mn ratio) show a trend towards a lower lake level. Lake level indicators (TIC, Ca, Ca/Ti ratio and C/N ratio) in contrast show an increased variability with periods of water abundance, which can also be traced by increased minerogenic input (Ti). The moist periods were 4800 cal. BP, 3900–3700 cal. BP, around 3000 cal. BP, 2500 cal. BP and 1980 cal. BP, as well as around 950–750 cal. BP and 530–20 cal. BP. However, units A and B are dominated by drier conditions with lower or receding lake levels. Nevertheless, the sediment record from the lake level terrace of Laguna Potrok Aike points to a continuous deposition for this period (Haberzettl *et al.*, 2007), which excludes a lake level lower than 30 m below present.

Attention should be paid particularly to the last moist period ascribed to the ‘Little Ice Age’ (Haberzettl *et al.*, 2005). According to the TIC record, such a long duration of moist conditions has only been observed during the early Holocene and the Lateglacial prior to 8650 cal. BP. Similar lake level fluctuations, although with less temporal resolution, were assumed for Lago Cardiel (Stine and Stine, 1990).

Conclusions

The 16 000 yr sedimentary record from Laguna Potrok Aike reveals an unprecedented high-resolution archive of hydrological variability in southeastern Patagonia. Based on a consistent age–depth model, this maar lake record also provides continuous information at 13 120 cal. BP, when Lago Cardiel was desiccated.

The geochemical proxies TIC, Ca and Ca/Ti ratio reflect lake level variations and are supported by the palaeoshoreline proximity indicators C/N ratio and gastropod index, by Ti as indicator for minerogenic input and by changes in redox conditions inferred from Fe/Mn ratios assumed to react to lake level variations. Many proxies cause or react to lake level changes at Laguna Potrok Aike and hence reflect hydrological changes in the Patagonian steppe. They indicate moist conditions starting at the beginning of the record at 16 000 cal. BP until 8700 cal. BP, interrupted by a warm and dry phase lasting from 13 100–11 400 cal. BP. This record provides terrestrial evidence for a warming during the Younger Dryas chronozone for Southern Hemispheric mid to high latitudes. Unfortunately, the Laguna Potrok Aike record does not comprise information about cold events such as the Antarctic Cold Reversal or the Huelmo-Mascardi Cold Reversal (Hajdas *et al.*, 2003). However, this study documents the potential of Laguna Potrok Aike, which will be complemented by stable isotope, pollen and diatom records performed on the same samples as well as the envisaged ICDP project PASADO (Potrok Aike Lake Sediment Archive Drilling Project).

The most drastic depositional changes are coincident with the deposition of the Mt Burney tephra, an event that generated intensive erosion. Thereafter, from ~8650 cal. BP, the lake level fell to its lowest Holocene position. After a transgression the lake level was extremely variable, with a few moist periods. The last lake level high stand is ascribed to the 'Little Ice Age', which was the longest humid phase since the early Holocene lake level high stand before 8650 cal. BP.

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