



Diatoms as indicators of hydrological and climatic changes in Laguna Potrok Aike (Patagonia) since the Late Pleistocene



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ABSTRACT

Southern South America is a key site to study climate variability in the Southern Hemisphere, allowing for a wide variety of climatic archives. Recently, several investigations using lacustrine sediments have provided an enormous amount of information to reconstruct past environmental changes. In the framework of the Potrok Aike Maar Lake Sediment Archive Drilling Project (PASADO) more than 500 m of sediment cores were retrieved from the center of this lake.

This contribution is centered in the diatom record of a core covering over the last 50 cal. ka BP. Nine statistically significant zones were determined based on changes in the assemblages of more than 200 species of diatoms, showing changes in productivity throughout time. Although it appears that the presence of mass waste events may have triggered some peaks in productivity, large fluctuations in diatom abundance and changes in species assemblages coincide with distinctive Antarctic warm events, A2 and A1, described for Antarctic ice cores at around 44.5 and 38.5 kyr BP respectively (Blunier and Brook, 2001). Furthermore, a smaller diatom peak may account for the A3 event compatible with a new OSL-based chronological model. Up to now they have only been described for Antarctica, but the fact that these events are recorded in southern Patagonia indicates their magnitude and importance for climate in the Southern Hemisphere.

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1. Introduction

Southern Patagonia is the southernmost continuous landmass outside Antarctica, which makes it a key location for obtaining terrestrial archives to add up to the marine and ice records in the area, and better define late Quaternary past climate changes in the Southern Hemisphere. Today, climate in southern South America is influenced by the Southern Hemisphere westerly winds and the landmass own topography. The west of the continent is wet and covered by rainforests whereas the eastern part, due to the rain shadow effect of the Andes, is much drier and covered mostly by steppe vegetation. Being geographically so close to the Antarctic continent also influenced its climatic history, which is irrefutably connected to the ice balance and climatic development of its adjacent neighbour.

Southern South America allows for a great variety of natural climatic archives, such as tree rings, glaciers, ice caps and marine and lacustrine sediments. Nevertheless, even if there has been substantial progress in

recent years, paleoclimatic studies are still relatively scarce for southern Patagonia compared to other areas of the world (Kilian and Lamy, 2012). Limnogeological investigations in southern Patagonia include the multiproxy studies of Lago Cardiel, 49°S (Gilli et al., 2001; Markgraf et al., 2003); Laguna Las Vizcachas 50°S (Mayr et al., 2009); Laguna Azul, 52°S (Mayr et al., 2005); Laguna Potrok Aike, 52°S (e.g., Haberzettl et al., 2005, 2007, 2009; Zolitschka et al., 2006; Mayr et al., 2007, 2009; Wille et al., 2007) and Lago Fagnano, 55°S (Waldmann et al., 2010, 2014; Moy et al., 2011).

In 2008, a deep drilling campaign was carried out at Laguna Potrok Aike within the framework of the ICDP (International Continental Scientific Drilling Program). The Potrok Aike Maar Lake Sediment Archive Drilling Project (PASADO, expedition N° 5022) involved an international and multidisciplinary research group and more than 500 m of sediment cores were retrieved from the center of this maar lake. The cores from PASADO are the longest continuous terrestrial sediment record in this area and multiproxy paleolimnological investigations of this record allow tackling outstanding questions dealing with Late Quaternary environmental evolution of southernmost South America (Zolitschka et al., 2013).

In this contribution, we focus on the diatom record of a long sediment core from Laguna Potrok Aike, covering the last ca. 51 cal. ka BP. Diatoms are often used in well-dated sedimentary records as a tool

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to characterize past environmental changes. These siliceous microscopic algae are extremely sensitive to changes in water-column conditions, such as variations in pH, alkalinity, nutrient balance and salinity (Battarbee, 1986). Since they have a siliceous cell cover, they are resistant to burial and generally well preserved in sediments. The combination of diatom assemblages with other proxies is a powerful tool to determine water-level changes and reconstruct the past environmental history (Millet et al., 2007). Therefore, our study allows us to infer variations in the lake's water quality and the environmental changes linked to it, as well as to estimate regional climatic fluctuations.

2. Setting

Laguna Potrok Aike is a maar lake located in the Argentinean province of Santa Cruz at 52°S and 70°W. This 0.77 million-year-old maar is part of the Pali Aike Volcanic Field, a Plio-Pleistocene back-arc volcanic field with over 100 phreatomagmatic volcanoes covering approximately an area of 4500 km² in southern Patagonia (Corbella, 2002; Ross et al., 2011). Laguna Potrok Aike is located at 116 m above sea level (asl) and is almost circular in shape, with a maximum diameter of 3.5 km. Its bowl-shaped bathymetry is characterized by a 100 m deep flat plain in the center of the basin (Fig. 1). The water body is sub-saline today, with a salinity of 2.2 g L⁻¹ and a pH of 8.8. The lake is almost exclusively groundwater-fed (Mayr et al., 2009), it has no surface outflow and receives episodic inflow through several canyons after major snowmelt events (Zolitschka et al., 2006). This lake is located in the dry Patagonian Steppe, in the rain shadow of the Andes and receives less than 300 mm of precipitation per year. Climate in this part of the world is characterized by strong westerly winds, reaching mean wind speeds of 4.6 m/s in summer (Haberzettl et al., 2007; Mayr et al., 2007). Such winds are preventing from a seasonal stratification of the lake's water body, leading to polymictic conditions, and from

development of an ice cover in winter. Several late Quaternary lake levels are documented by subaerial and submerged paleoshorelines, reaching up to 21 m above the 2003 lake level (Gebhardt et al., 2012a), and recording significant hydrological fluctuations in the past (Haberzettl et al., 2008; Anselmetti et al., 2009; Kliem et al., 2013a; Zolitschka et al., 2013).

Previous studies have been carried out on the sedimentology, geochemistry and microfossil content of the sediments of Laguna Potrok Aike, revealing climatic conditions and hydrological variations for the last ca 16 cal. ka BP (Haberzettl et al., 2007, 2008; Wille et al., 2007; Anselmetti et al., 2009; Mayr et al., 2009; Massafiero et al., 2013). Within the framework of the ongoing PASADO investigations, many publications have recently come out, covering the more than 50 ka long record (Recasens et al., 2012; Hahn et al., 2013; Kliem et al., 2013b; Lisé-Pronovost et al., 2013).

3. Methods

3.1. Field methods, sediment composition and chronology

During the PASADO field campaign, 533 m of sediment cores were recovered from the maar lake Laguna Potrok Aike. Drilling operations were carried out during the austral late winter/spring of 2008 at two different sites: Site 1, located in the center of the lake, and Site 2, positioned about 700 m towards the southern shore (Fig. 1). Four holes were drilled at Site 1 with an average core recovery of 92.1% and a maximum core depth of 100.4 m below lake floor (blf), and three holes were drilled at Site 2 with an average core recovery of 98.8% and a maximum core depth of 101.5 m blf (Zolitschka et al., 2009). Site 2 comprises a longer and less disturbed record compared to Site 1, it was thus chosen for building a reference profile and for high-resolution sampling for multiproxy analyses. Core sections of cores 2A, 2B, and

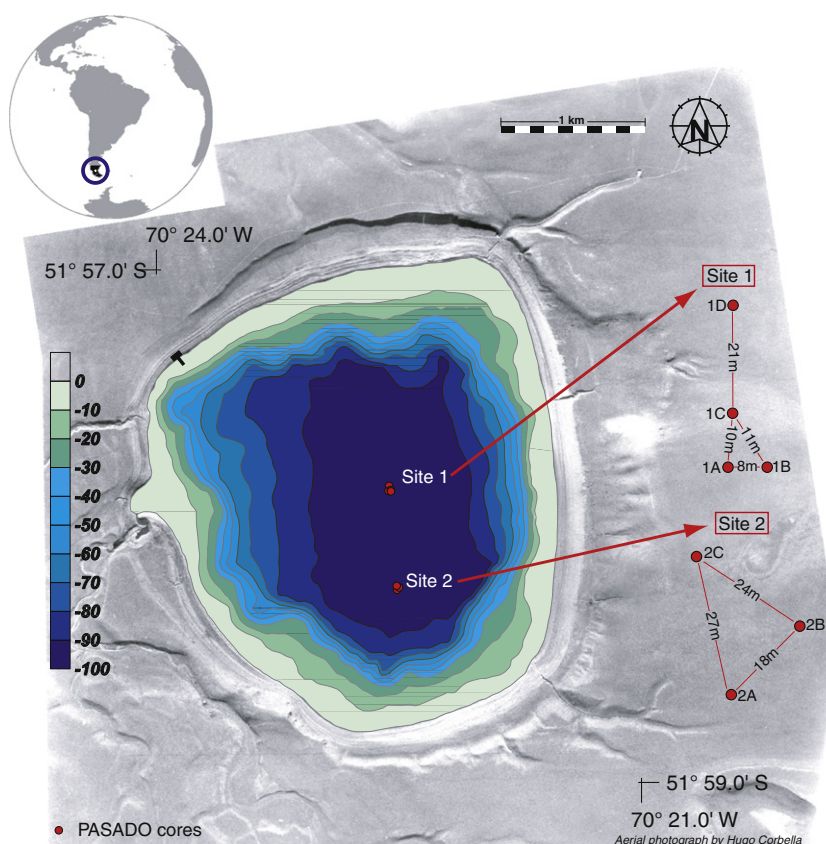


Fig. 1. Bathymetric map of Laguna Potrok Aike showing the locations of the two drilling sites and the relative position of the different holes drilled at each site. Insert on the left shows the geographical position of Southern Patagonia on a world map. Figure modified from Ohlendorf et al. (2011).

2C were correlated using macroscopic sedimentary structures, MSCL and XRF-scanning profiles and high-resolution core photographs of the unoxidized sediment surface after core splitting (Ohlendorf et al., 2011). This composite profile (2CP) was sampled every 2 cm following the sampling strategy described in (Ohlendorf et al., 2011). For diatom analyses, samples were taken from the entire core with a spatial resolution of 32 cm, increasing to 16 cm in selected sections, where major changes in the species assemblages occur. Core sections including reworked material or tephra layers were excluded from diatom studies. To establish a consistent age-depth model (shown in Fig. 2), 58 AMS radiocarbon dates were obtained along the profile from plant macro remains of aquatic mosses (Kliem et al., 2013b). For the top 18 m of core 2CP, ^{14}C dates were transferred from the composite profile PTA03/12 + 13 (Habertz et al., 2007) using lithological features and magnetic susceptibility for correlation (Kliem et al., 2013b).

3.2. Microfossil analysis

For diatom analysis between 0.2 and 1 g of dry sediment was processed. Sample treatment and slide preparation were carried out following standard procedures (Battarbee, 1986) and were the same as described in detail by Recasens et al. (2012) for the same cores. A solution containing a known concentration of microspheres was added to each sample for quantitative analyses (Battarbee & Kneen, 1982) and diatom abundance is expressed in number of valves per gram of dry sediment. Taxonomic identification to species level followed general and local descriptive diatom floras (Frenguelli, 1921, 1942; Krammer and Lange-Bertalot, 1986, 1988, 1991a,b; Round et al., 1990; Rumrich et al., 2000) and up-to-date publications describing some existing as well as new genera or species (Håkansson and Kling, 1994; Maidana, 1999; Maidana and Round, 1999; Klee et al., 2000; Guerrero and Echenique, 2002; Houk and Klee, 2004; Recasens and Maidana, 2013).

The species distribution is expressed in percent of relative abundance in the whole assemblage; all species abundances in % mentioned hereafter will refer to relative abundances. These percentages are calculated based on the total diatom diversity determined for the record. The diatom profile shown in Fig. 3 was made with the C2 software (Juggins, 2003) considering all taxa reaching 3% relative abundance at least in one sample. We consider as independent taxa each species identified and, for those non-differentiable by light microscope observation, the whole complex (for example, *Staurosirella pinnata* and related species were considered as one taxa). The diatom zones were determined based on a CONISS (Stratigraphically Constrained Incremental Sum of

Squares) cluster analysis (Grimm, 1987) and all species present were considered for the statistical analysis. The diatom record was zoned with the optimal sum of squares partitioning method (Birks and Gordon, 1985) as implemented in the program ZONE, version 1.2, written by S. Juggins (University of Newcastle). The number of statistically significant biozones was determined using the broken-stick approach (program BSTICK, version 1.0 (Bennett, 1996); Line, J. M. and Birks, H.J.B., unpublished software).

4. Results

4.1. Chronology

The age-depth model for the PASADO composite record 2CP was constructed by applying the mixed-effect regression procedure (Heegaard et al., 2005) to the event-corrected composite depth of 45.80 mcd-ec, resulting in a basal age of 51.2 cal. ka BP (Kliem et al., 2013b). The obtained chronology (Fig. 2) was validated by correlation with six dated tephra horizons from previously studied cores from Laguna Potrok Aike (Habertz et al., 2008, 2009). Nevertheless, radiocarbon dates show a considerable increase in scatter with depth, and the error bars at the bottom of the record are considerably large. New OSL dating has now extended the chronology to ~65 cal. ka BP at 96 m in core 5022-1D (Buylaert et al., 2013). Once the correlation with the composite core 5022-2CP is definitively established, the luminescence data will refine the chronological model used in this paper.

4.2. The diatom record

Over 200 species, varieties and forms were identified in the sediment record of Laguna Potrok Aike. Some species are ubiquitous and cosmopolitan, such as *Discostella stelligera* and *Staurosirella pinnata*, some are known only in America (e.g., *Cyclotella agassizensis*, *Thalassiosira patagonica*), and some are probably endemics from Patagonia (e.g., *Corbellia contorta*, *Cyclostephanos patagonicus*). This lake has allowed discovering several taxa new to science, such as the previously mentioned *Thalassiosira patagonica* (Maidana, 1999), *Corbellia contorta* (Maidana and Round, 1999) and *Cymbella gravis* (Recasens and Maidana, 2013). The species *Discostella stelligera* appears in the record in two different morphotypes; we observe the classic *D. stelligera* described in the literature but also a bigger morphotype of this same species, that we will denote as *D. stelligera* morph 1 (M1) from now on. We treat these two morphotypes as two different populations since *D. stelligera* occurs in either small size ranges or very big ones, with no continuous size variability. Several species were hard to distinguish from *Staurosirella pinnata* using light microscopy and were thus identified as such and treated as a unique taxon for the diatom analysis. Other silicic organisms such as Chrysophyte cysts and phytoliths, have been observed quite often in the record (not shown in figures).

Diatom abundance within the sediment core varies between 8×10^3 and 1.5×10^9 valves per gram dry sediment, and within the analyzed samples in the record, no sterile samples were found. Important diatom abundance peaks occur at around 50.7, 49.9, 49.3, 46.3, 45.8, 39.2, 37.5, 33, 31.1, 27.6, 16.6 and 15.4 cal. ka BP and will be discussed in the next section. The profile in Fig. 3 shows only the dominant taxa (at least 3% relative abundance) and the nine statistically significant zones are described as follows.

4.2.1. DZ-1: 51.2–49.4 cal. ka BP

This zone is characterized by fluctuating diatom abundances, from a minimum of 1×10^6 to a maximum of 907×10^6 valves per gram dry sediment, with several high punctual values for certain species. The assemblage is dominated by *Discostella stelligera* and *Discostella stelligera* morph 1 (M1). *D. stelligera* reaches relative abundances of 44% and *D. stelligera* M1 of 75%. Zone DZ-1 is also characterized by

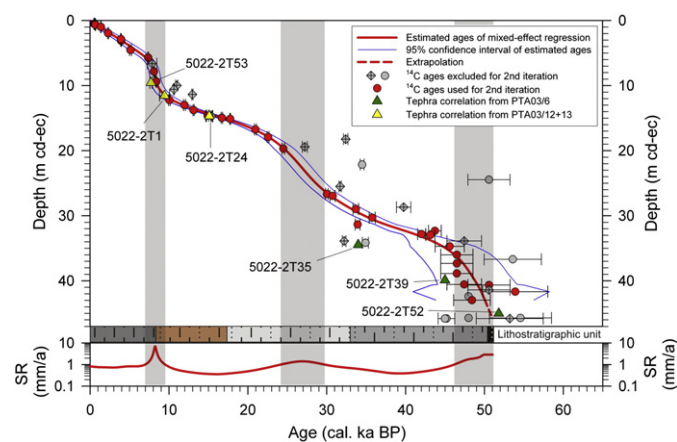


Fig. 2. Age depth model for the event-corrected 2CP profile using a mixed-effect regression (here the second iteration is shown). The lower part of the figure displays the different lithostratigraphic units and the reconstructed sedimentation rate based on this age/depth model. Gray shaded areas highlight periods of higher sedimentation rates. Figure modified from Kliem et al. (2013b).

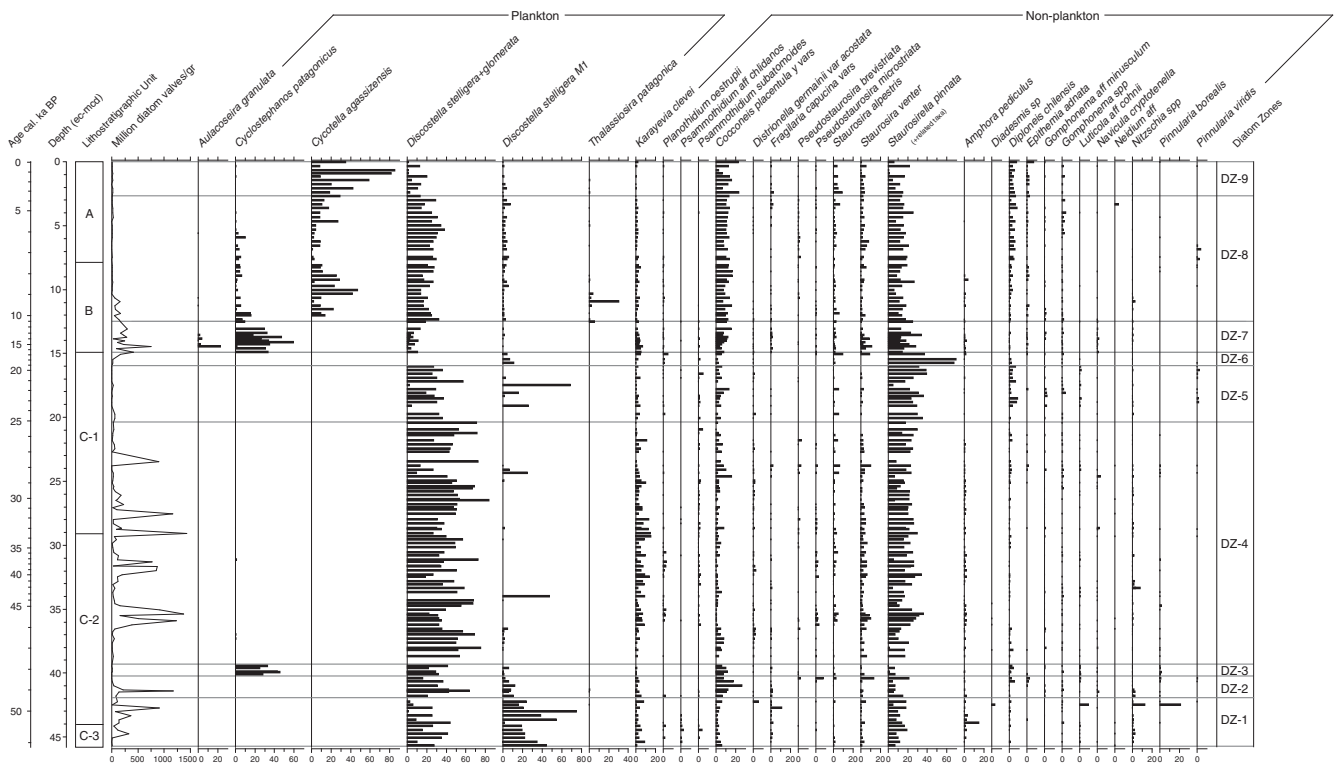


Fig. 3. Diatom diagram for the event-corrected profile 2CP showing diatom concentration (in million valves per gram dry sediment) and relative abundances for dominant taxa (relative abundance >3% in at least one sample). Lithostratigraphic units and calculated diatom biozones are shown as well as the time scale.

isolated peaks of several benthic and epiphytic species, reaching significant abundances between 10 and 20%. This occurs with some fragilarioid taxa (e.g., *Distirionella germainii*, *Fragilaria capucina*, *Pseudostaurosira microstriata*, *Staurosira venter*), *Amphora pediculus*, *Luticola aff. cohnii*, unidentified *Nitzschia* spp and *Pinnularia borealis*. *Staurosirella pinnata* (and related species) are present throughout DZ-1 with values between 5 and 20%.

4.2.2. DZ-2: 49.4–48.8 cal. ka BP

This zone is characterized by a high peak in diatom concentration, reaching 1174×10^6 valves per gram dry sediment, followed by a drop after 49.3 cal. ka BP. The species assemblages show a sudden drop in the relative abundance of *Discostella stelligera* M1 to values <12%. *Discostella stelligera* becomes more abundant, reaching values of 64%. *Cocconeis placentula* also displays higher abundances in this part of the record and increases towards the end of the zone reaching 26%. *Staurosirella pinnata* is still present in the record with relative abundances between 2 and 21 %.

4.2.3. DZ-3: 48.8–48.1 cal. ka BP

This short zone is characterized by a lower diatom content, between 0.8×10^6 and 30×10^6 valves per gram dry sediment. The species assemblages are dominated by *Cyclostephanos patagonicus*, a big planktonic diatom, and *Discostella stelligera*. *C. patagonicus* was not previously found in the record and appears here as a pronounced peak reaching 46% relative abundance. After this zone, this species drastically disappears from the record until more recent times. DZ-3 is also characterized by low amounts of non-planktonic taxa, which average less than 30% of the whole assemblage in this zone. *Cocconeis placentula* and *Staurosirella pinnata* also decrease, presenting now values of 3×10^6 to 12×10^6 and 0.5×10^6 to 7×10^6 valves per gram dry sediment respectively.

4.2.4. DZ-4: 48.1–24.8 cal. ka BP

This zone is characterized by strong fluctuations in diatom concentration, between 2×10^6 and 1475×10^6 valves per gram sediment,

displaying several peaks at different depths, such as the previously mentioned abundance peaks at 46.3, 45.8, 39.2, 37.5, 33, 31.1 and 27.6 cal. ka BP. The relative abundances of the different taxa are quite constant and show no big variations in this whole zone. The diatom assemblages are mainly dominated by *Discostella stelligera* and *Staurosirella pinnata*. Also *Karayevia clevei* occurs in relatively high abundances, reaching its maximum for the whole record at 16%. *Cocconeis placentula* and *Staurosira venter* present several slight increases along the zone.

4.2.5. DZ-5: 24.8–18.7 cal. ka BP

This zone is mainly characterized by lower diatom abundances, between 1×10^6 and 29×10^6 valves per gram dry sediment and, as in DZ-4, an overall dominance of *D. stelligera* and *S. pinnata*. *D. stelligera* M1 displays a few isolated peaks reaching 69% but is quite irregularly distributed. *Diploneis chilensis* becomes more abundant, reaching maximum relative abundances of 9% together with *Cocconeis placentula*, reaching 13%. *Karayevia clevei*, which was consistently present in the previous zone, decreases here to relative abundances under 5%.

4.2.6. DZ-6: 18.7–16.6 cal. ka BP

In this zone, diatom abundances start to increase slowly again. The species distribution is characterized by an overall dominance of benthic and epiphytic taxa, in particular by small fragilarioids such as those similar to *Staurosirella pinnata*. In this zone, the underrepresented plankton is almost exclusively constituted by *D. stelligera* M1, with abundances between 5 and 11%, leading to an overall dominance of non-planktonic species of over 89% (also shown in the plankton/non-plankton ratio in Fig. 5).

4.2.7. DZ-7: 16.6–10.5 cal. ka BP

This zone coincides with an increase of diatom concentration, which fluctuates but stays high, between 21×10^6 and 749×10^6 valves per gram dry sediment, during the entire DZ-7. The assemblage is characterized by reoccurrence of *Cyclostephanos patagonicus* that reaches

maximum relative abundances of 60%. A peak of *Aulacoseira granulata*, another freshwater planktonic species, occurs at ca. 15.5 cal. ka BP and reaches maximum values of 23%. *D. stelligera* also returns to the record after being absent from the previous zone but with abundances under 30%. *D. stelligera* M1 decreases and stays at very low levels for the rest of the record.

4.2.8. DZ-8: 10.5–3.5 cal. ka BP

Since ca. 10.5 cal. ka BP, diatom concentration dramatically drops. Up to 8.75 cal. ka BP, values fluctuate between 51×10^6 and 168×10^6 valves per gram dry sediment, but after 8.75 cal. ka BP, they stay under 26×10^6 valves. This biozone is characterized by the fast decline of *Cyclotella patagonicus* and the appearance of *Cyclotella agassizensis* and *Thalassiosira patagonica* in the plankton. *C. agassizensis* becomes one of the dominant taxa at the beginning of the zone reaching maximum abundances of 42% at 8.6 cal. ka BP, it then declines to minimum values of 2% and from 7.8 cal. ka BP onwards starts increasing again to values of around 30% towards the end of the zone. *Discostella stelligera* is also permanently present in the floristic assemblage. The benthos and epiphyton are dominated by *Staurosirella pinnata* and *Cocconeis placentula*, which both show relatively stable abundances, averaging 10–20%, and *Diploneis chilensis* in low but stable amounts between 0.6 and 8.5% until the end of the record. Poor diatom preservation starts in this zone. Diatom valves, especially those of the bigger *C. agassizensis* and *D. chilensis*, appear to be strongly affected by chemical dissolution.

4.2.9. DZ-9: 3.5 cal. ka BP to present

This last biozone presents the same low diatom concentrations as the previous zone, with total abundances less than 18×10^6 valves per gram dry sediment. It is characterized by the overall dominance of *C. agassizensis*, with up to 85% relative abundance. *Discostella stelligera* decreases to values <20%. Non-planktonic species are represented mostly by *Staurosirella pinnata*, *Cocconeis placentula* and *Diploneis chilensis*. Signs of valve dissolution, particularly affecting *C. agassizensis* and *D. chilensis*, are still strongly present.

Fig. 4 shows the diatom abundance plotted against total sediment depth, therefore including the sections classified as reworked and tephra layers. The event-corrected depth (as in Fig. 3) is given only for comparison. The diatom record shows a completely different trend from this point of view, with more extended stratigraphic zones in the lower part of the record, where most of the sediment is reworked and has not been analyzed (gray shaded areas in the figure). Often in the record, peaks of diatom concentration seem to occur directly after a mass movement deposit or a tephra layer, especially in the lower half of the record where these events are more frequent and occur as thicker layers.

The diatom record is also compared to previously analyzed biogeochemical parameters, as shown in Hahn et al. (2013). Fig. 5 compiles the diatom data with the biogenic silica record, expressed in %, and with geochemical parameters of total organic carbon (TOC) and total inorganic carbon (TIC), both expressed in %, and the TOC to total nitrogen (TN) ratio, referred to as C/N; all data from Hahn et al. (2013). Diatom concentration is shown on normal and also on logarithmic scales to facilitate comparison to the other datasets. The proportion of planktonic species (expressed in %) shows fluctuations along the record but generally stays around 50%. Two exceptions occur in this distribution, in zone DZ-6 where plankton drops to 11% and in DZ-9 where plankton (especially *C. agassizensis*) dominates with up to 88%. Relative abundances of several species are also shown in Fig. 5. *Cyclotella agassizensis* shows a good correspondence with TIC in zones DZ-8 and 9, TIC occurs predominantly in the top of the record, which is when *C. agassizensis* appears in the record and dominates until the present. *Cyclotella patagonicus* (with the addition of the peak in *Aulacoseira granulata*) seems to follow the trend of the total diatom abundance between 16.6 and 8.6 cal. ka BP. There is also quite a good correspondence between

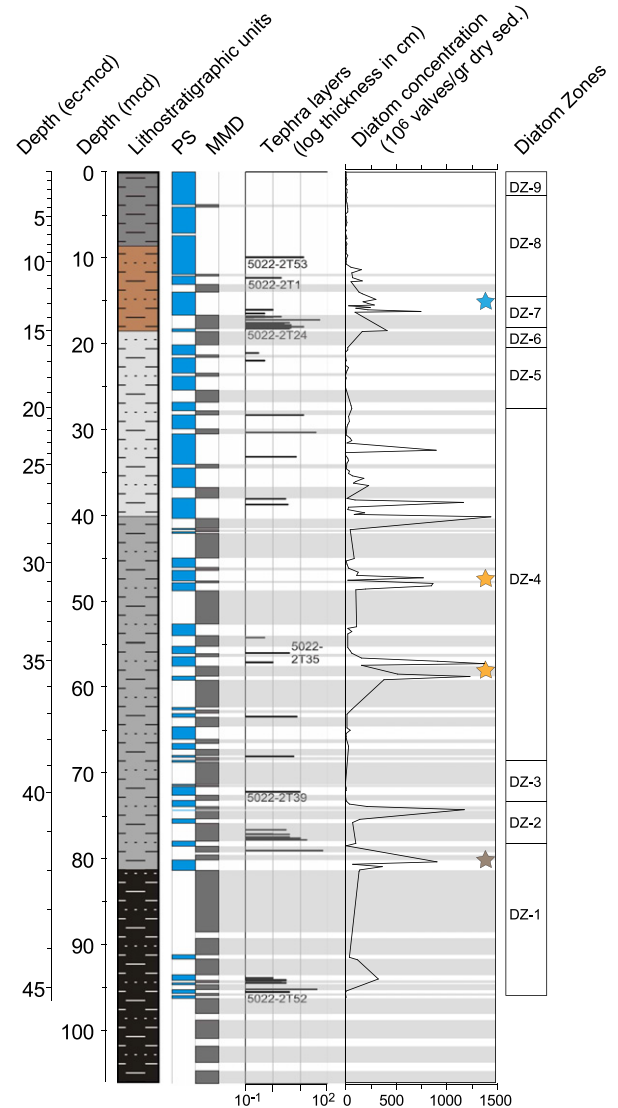


Fig. 4. Depth comparison between total composite depth (mcd) and event-corrected composite depth (ec-mcd). PS: pelagic sediment; MMD: mass movement deposits and gaps in the record. Tephra layers are indicated according to their average depths (modified from Kliem et al., 2013b; added some layers <10 cm that were not shown in the original figure). Reworked events are shown on the diatom record (marked in gray) and plotted against mcd. The stars correspond to the Antarctic events (Antarctic Cold Reversal: ACR, Antarctic warm events A1, A2 and A3).

diatom abundance and biogenic silica records for most of the studied profile (more clearly seen when diatom data is plotted in logarithmic scale). The records are in accordance for the abundance peaks in zones DZ-1 and DZ-2 and the two lowermost peaks in DZ-4. The following three isolated peaks in zone DZ-4 are very prominent in the diatom record but almost not distinguishable in the biogenic silica record, although the assemblages are quite stable in these zones. Lower abundances are visible in both proxies for zones DZ-5, –6–8 and –9 and higher diatom concentration and biogenic silica occur in zone DZ-7.

5. Discussion

5.1. Stratigraphical record and paleoproductivity

The first parameter that we observe from the diatom analysis is the diatom abundance, or number of valves found in the sediment. It can be argued if the diatom concentration in the record is a direct reflection of

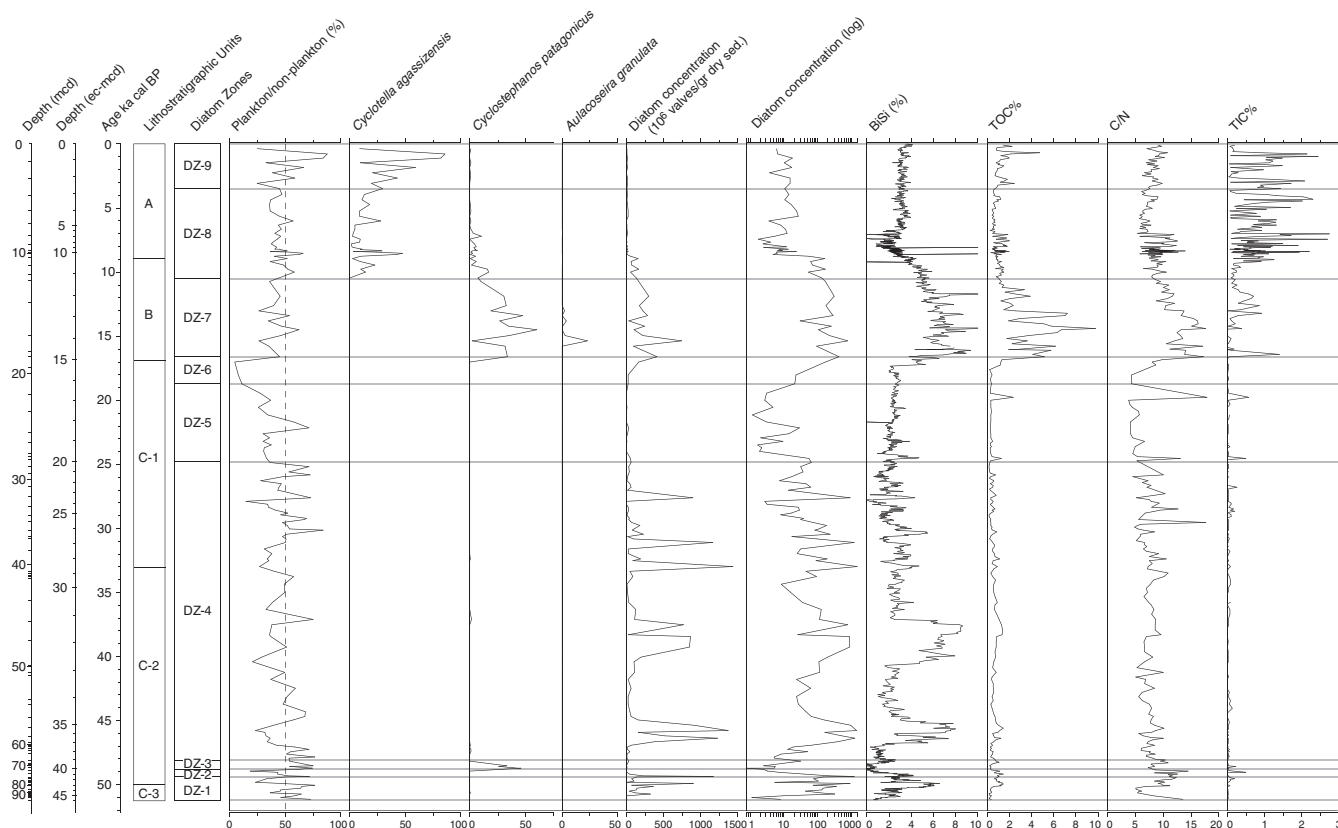


Fig. 5. Comparative diagram showing diatom concentration in million valves/g dry sediment (data also shown in logarithmic scale to facilitate comparison), Planktonic to non-planktonic species ratio, biogenic silica (in %), the relative abundance of selected species (%), TOC (in %), C/N ratio, TIC (in %). Data from Hahn et al. (2013).

the former lake's productivity, since this can be influenced by other organisms, or if it is biased by diagenetic processes or the effect of different sedimentation rates and material input into the lake (Battarbee, 1986). In previous studies on Laguna Potrok Aike from the same sedimentary record, Hahn et al. (2013) linked the biogenic silica results to diatom productivity. However, our records show that the two profiles are not always in agreement. Fig. 5 displays the two datasets, and even if the general trends seem to coincide, not all the peaks are correspondent and comparable in amplitude. The sampling resolution, for example, might be an explanation to that; diatoms were sampled every 16 to 32 cm along the event corrected record and biogenic silica was measured for the same sections at 2 cm resolution. The different sampling interval explains the greater variability of the biogenic silica records compared to the diatom record. Nevertheless, it does not justify that at some levels diatoms dramatically increase and the biogenic silica record does not show large fluctuations. Biogenic silica measurements take into account all silicic organisms present in the lake sediments and not only diatoms. As mentioned before, Chrysophyte cysts and phytoliths, for example, have been observed quite often in the record. This could be another reason as to why sometimes the two proxies do not match. In addition to this, diatom abundance accounts for the number of diatom valves present in the sediment, whereas the biogenic silica accounts for the amount of silica and therefore is dependent on the size and weight of diatoms and their degree of silicification; if the absolute diatom abundance is lower but the assemblage is characterized by bigger and more silicified diatoms, then the biogenic silica record might not show the same fluctuations as the absolute diatom abundance. The lowermost peaks, centered at around 50.7, 49.9, 49.3, 46.3, 45.8, 39.2 and 37.5 cal. ka BP occur quite consistently in both records. The next diatom increases, at 33, 31.1 and 27.6 cal. ka BP, even if bigger in amplitude, are relatively blurred by the general variability of the

biogenic silica record at this time. For the remaining part of the record, both proxies agree quite well. Dissolution, as previously reported in this lake (Recasens et al., 2012; Massaferrero et al., 2013), could also account for dissimilarities as well as for a bias in the productivity signal. If diatom valves are not well preserved, one cannot rely on this proxy alone for valid reconstructions.

Fig. 4 presents the previously discussed diatom abundance throughout depth using the entire composite record, showing reworked sediment sections and tephra events. The biggest diatom peak in the DZ-1 zone, at 80.38 mcd (49.9 cal. ka BP), overlies a several meter thick mass movement deposit, which might have caused a resuspension of sediment material and therefore recycling of nutrients into the water column, triggering a punctual increase in diatom productivity. Likewise, a smaller peak at 94.07 mcd (50.7 cal. ka BP) is associated to several tephra layers, another possible source of nutrient input into the system (Harper et al., 1986; Birks and Lotter, 1994). The mechanism behind this productivity peaks does not seem to trigger the increase of the relative abundance of any particular species but more of a reaction from the entire diatom flora; we therefore could interpret it as a reactivation of productivity due to resuspension combined with nutrient input from volcanic ash layers. Very high diatom concentrations are also registered at 74.27 mcd (49.3 cal. ka BP), corresponding to a relative increase of *Discostella stelligera*. This peak occurs at a time when mass movement deposits were abundant in the lake and sediment was often resuspended provoking a mixing of nutrients into the water column, becoming more available to the plankton communities. In zone DZ-3, from 48.8 to 48.1 cal. ka BP, the record reflects relatively stable conditions. Nothing in particular is revealed from the diatom assemblages and other proxies such as TOC, TIC and C/N. All proxies remain low and stable in this zone, as shown in Fig. 5. Diatom concentration (and also biogenic silica) shows several fluctuations, with peaks centered at 46.3, 45.8, 39.2, 37.5, 33, 31.1

and 27.6 cal. ka BP. The first five of these peaks directly follow mass movement events and could be interpreted as mentioned above. Additionally, the diatom species distribution shows that during these events plankton slightly decreases in favour of more littoral species, which could have been brought to the center of the lake with reworked material and by increased wave action due to turbulence in the water column caused by these events. The two remaining diatom concentration peaks (at 31.1 and 27.6 cal. ka BP) do not seem to be associated with mass movement deposits or any other variation recorded by either geochemical indicators. In terms of species assemblages, the peak at 27.6 cal. ka BP corresponds to an increase of *Discostella stelligera* M1 to a maximum abundance of 73%.

Several interpretations rise from our observations that some diatom peaks could be an expression of productivity triggered by resuspension of sediments and input of nutrients by reworking and tephras. It can also be partially due to a mechanical effect of sediment resuspension and deposition of highly concentrated beds of diatoms (due to the low density and preferential buoyancy of the valves). Moreover, if it is due to sediment reworking, what is the cause for these mass movement deposits? Can a changing climate trigger this massive input of meter-thick deposits into the lake? If this was the case, what is the feedback of climate on former diatom productivity?

5.2. Paleoclimatic and paleoenvironmental implications

5.2.1. Glacial to LGM conditions (DZ1-5)

The part of the record corresponding to the full glacial extends from 51.2 to approximately 18.7 cal. ka BP, covering diatom zones DZ1 to 5 and lithostratigraphic unit C (the whole of C-3, C-2 and most of C-1). Zone DZ-1 (Fig. 3), covering from 51.2 to 49.4 cal. ka BP, shows a highly diversified benthos and plankton dominated by *D. stelligera* and especially *D. stelligera* morph 1. This taxon, which we consider as a larger sized population of the typical *D. stelligera*, can be also interpreted as a meroplanktonic species, which due to its large size would have difficulties to achieve buoyancy in the water column and would live lying on the sediment, in a similar manner than benthos. If this were the case, this zone would be largely dominated by non-planktonic taxa such as the isolated peaks of some *Pinnularia*, *Nitzschia*, *Luticola* and *Amphora* species. The occurrence of these benthic species, including several aerophilic taxa such as *Pinnularia borealis* at 49.8 cal. ka BP, could be an indicator of increased diatom productivity in the shallow littoral zone. Lake level was high during the glacial (Hahn et al., 2013; Kliem et al., 2013a), and due to the lake's morphology, there would be a larger shallow water area with inundated terrace levels, promoting benthic diatom productivity in the lake. Moreover, if during the glacial the shallow littoral zone was ice-covered, the occurrence of this species could indicate a temporary melting and relatively warmer or interstadial-like conditions. Nevertheless, no climatic event has been previously registered in this time interval. Zone DZ-2, from 49.4 to 48.8 cal. ka BP, is marked by a slight increase in *Cocconeis placentula*, an epiphytic taxon, and there are no occurrences of benthic taxa, as previously noted. In zone DZ-3, from 48.8 to 48.1 cal. ka BP, the diatom assemblages are characterized by a peak of *Cyclotephanos patagonicus*, a big planktonic diatom that has so far been found only in Lago Puyehue (Nora Maidana, pers. comm.) and in freshwater and oligotrophic ecosystems in southern Patagonia (Guerrero & Echenique, pers. comm.). In zones DZ-4 and DZ-5, from 48.1 to 18.7 cal. ka BP, the record displays low TOC, TIC and C/N values, reflecting stable glacial conditions (Hahn et al., 2013) and corresponding to a cold and low productivity glacial environment. Diatom concentration peaks several times in this glacial interval, in particular at 46.3, 45.8, 39.2, 37.5, 33, 31.1 and 27.6 cal. ka BP. The diatom species distribution shows that during these events, plankton slightly decreases and other species like *Karayevia clevei*, *Planothidium oestrupii* and several fragilarioids (e.g., *Pseudostaurosira brevistriata*, *Staurosira alpestris*, *S. venter* and *Staurosirella pinnata*) show transitory increases.

Several diatom peaks seem to overlay some metric mass-movement deposits (Fig. 4), which might have triggered punctual diatom blooms by resuspension of nutrients into the system. Nevertheless, the floristic changes in some intervals could suggest an additional climatic forcing. Fig. 6 shows the position of the previously documented Antarctic warm events (A1, A2, A3 and A4) based on the EPICA Dome C ice core record. The comparison of our record with the dust record, δD and temperature estimates from the EPICA record (Jouzel et al., 2007; Lambert et al., 2012) shows noteworthy correlations. Based on the latest PASADO chronology (Kliem et al., 2013b), there is quite a good correspondence between diatom concentration and Antarctic warm events A1 and A2 (Fig. 6). A2 corresponds to a diatom abundance peak centered at ca. 46 cal. ka BP that is equally visible in the biogenic silica record. The same occurs for A1 at about 38 cal. ka BP. Both parts of the record are characterized by a slight increase of fragilarioid taxa and a synchronous decrease of *D. stelligera*, with their proportions returning to normal after the events. The slight increase in benthic taxa could be an indicator of temporarily more favorable conditions. Additionally, ice wedges were reported in the vicinity of the lake, witnessing of the development of permafrost during the last glaciations (Kliem et al., 2013a). We could raise the hypothesis that during these cold periods the shores of the lake could have been occasionally ice-covered, leading to a decline in benthic taxa abundances. Episodic warming, such as the documented Antarctic warm events, could temporarily warm littoral areas, accounting for the development of more benthos. The fact that we have productivity increases and benthos development in the period coinciding with the Antarctic warm events A1 and A2 directs future investigations towards these time periods. Yet, there is a discrepancy at the lowermost part of the record since the observed diatom assemblages do not seem to match with full glacial conditions but rather correspond to interstadial conditions.

The cluster of diatom abundance peaks at the bottom of the record, at ca. 49–50 cal. ka BP, could quite possibly correspond to an older warm event, such as Antarctic warm event A3, especially if considering the large error bars of our chronological model. Fig. 6 shows a hypothetical correlation of our record to the A3, or even A4 events (since we observe several peaks at the bottom of the record) registered in the Antarctic ice cores from EPICA Dome C. Taking into consideration that the age of 2CP could possibly be extended to at least 10 ka older (Buylaert et al., 2013), we would be able to correlate our record to these two Antarctic warm events. Nevertheless, in terms of floristic composition only one additional event is recognizable, detected in zone DZ-1, and related to increases in some benthic species. Additionally, the two lowermost peaks in diatom concentration seem to correspond to small increases in TIC (Fig. 5) that would imply an input of material or minor carbonate precipitation in the system. Fig. 4 shows that these increases in diatom abundances occur in a part of the record with recurrent and extensive mass wasting events, indicating frequent redeposition of large volumes of sediment within the lake and/or clastic input of minerogenic matter into the lake. Warmer conditions could have triggered a melting of the permafrost, inducing mass wasting events in the lake that would have generated resuspension of nutrients leading to diatom blooms. Moreover, the sudden peak of *C. patagonicus* between 48.8 and 48.5 cal. ka BP could be interpreted as a return of cooler and more oligotrophic conditions (Wille et al., 2007) after this short-termed warming event. Its decline could then be associated to even colder conditions, characteristic of full a glacial, and in particular to a lack of movement in the water column, as at this time the westerly winds were weaker and fur (Lamy and Kaiser, 2009; Kohfeld et al., 2013; Sime et al., 2013) and thus a disappearance of this taxon which would need stronger currents to maintain its buoyancy. Besides the small variations related to A1 and A2 (and eventually A3) events, the record stays quite stable during the whole glacial interval. Preliminary unpublished results of the pollen and stable isotopes analyses (Lücke et al., 2012; Wille et al., 2012) show unusual conditions for a glacial in the lowermost part of the record. It therefore seems likely that the increase

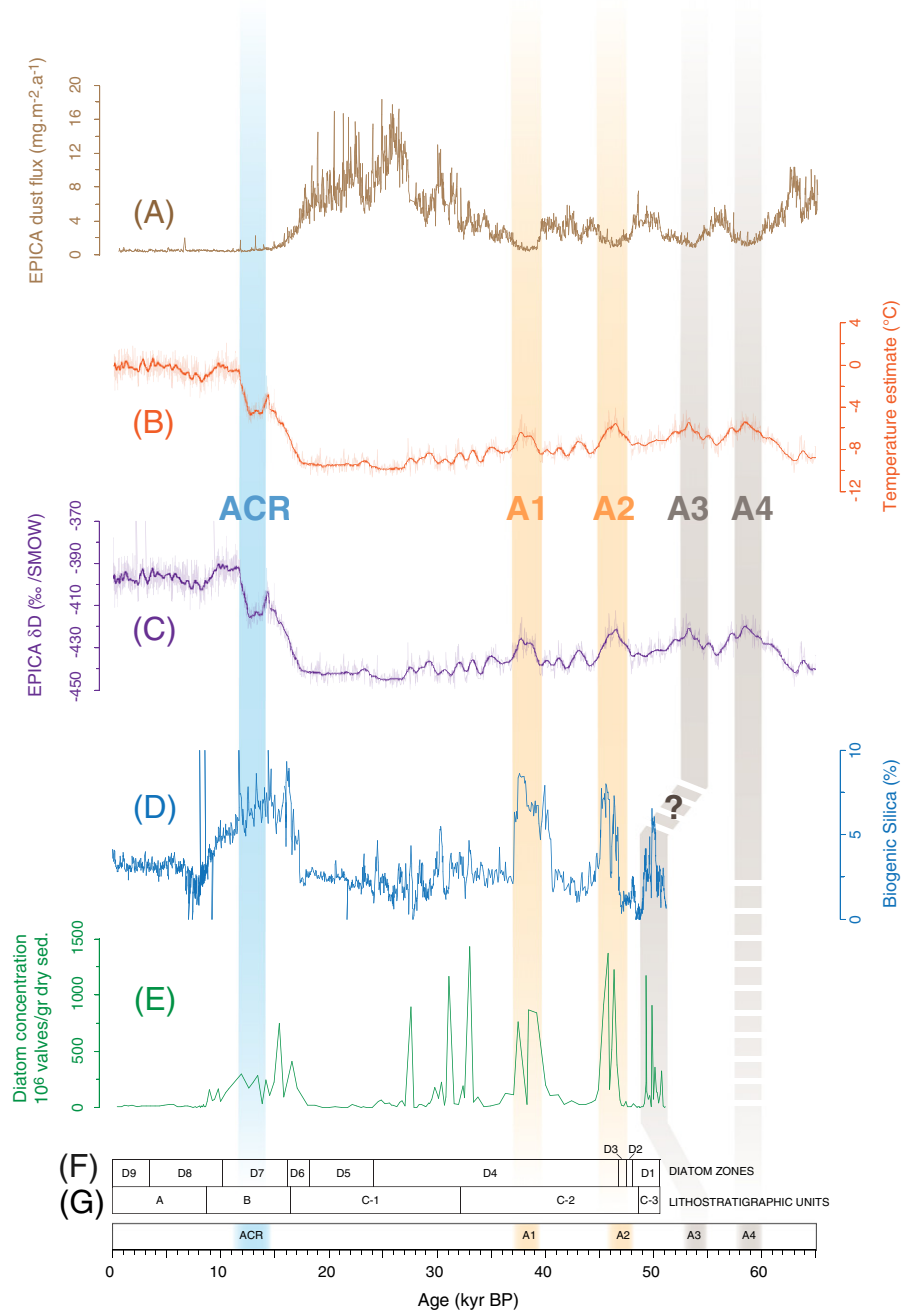


Fig. 6. Comparative diagram showing the EPICA Dome C dust record (A), the EPICA Dome C temperature estimate (B) and δD (C) records and biogenic silica (D) and diatom concentration (E) from core 2CP of Laguna Potrok Aike. Diatom zones DZ1–9 (F) and lithological units (G) are also shown. Color-shaded bars represent the Antarctic climatic events ACR and A1–A4. EPICA data from Jouzel et al. (2007) and Lambert et al. (2012).

in total diatom abundance and the benthos occurrences are related to another forcing other than only mass movement events, since it is not the only proxy recording those events. Ongoing investigations on pollen and stable isotopes records will provide more information and allow a more detailed interpretation for this time period in Laguna Potrok Aike. Furthermore, a validation of the age model using OSL dating is underway and will shed new light on the precise timing of these particular events in the record (Gebhardt et al., 2012b; Buylaert et al., 2013).

Zone DZ-5, covering the time period from 24.8 to 18.7 cal. ka BP, is characterized by low diatom abundance and a relatively stable flora. This time window corresponds to the Last Glacial Maximum (LGM), conventionally defined from sea-level records as the part of the last Ice Age with maximum ice coverage (Mix et al., 2007) and lasting from ca. 26 to 19 ka, synchronously in both hemispheres (Clark and

Mix, 2002; Clark et al., 2009). In Patagonia, records of the LGM are consistent with this timing, with maximal glacial advances recorded between 23 and 18 cal. ka BP (Lowell et al., 1995; Simonsen, 2004). Hahn et al. (2013) reported for Laguna Potrok Aike, that productivity indicators (biogenic silica and TOC) remain low and constant in lithostratigraphic unit C-1, after ca. 24 cal. ka BP. The diatom record, scarce but stable in abundances and floristic composition, is characterized by cosmopolitan and resistant taxa such as *Discostella stelligera* and *Staurosirella pinnata*. This is consistent with cold and nutrient depleted conditions in the lake.

5.2.2. Late Glacial to Holocene transition (DZ6–7)

Zone DZ-6, starting at 18.7 cal. ka BP, is characterized by a change in most of the analyzed proxies. Hahn et al. (2013) reported that the

uppermost part of unit C-1 was marked by a positive trend in productivity indicators denoting the termination of the LGM. Indeed, this event has been recorded more or less synchronously all over the world between 19 and 17 cal. ka BP (Schaefer et al., 2006). Cosmogenic exposure dates all over Patagonia have allowed to locally constrain the deglaciation and reconstruction of the glacial retreat show that it happened synchronously throughout Patagonia at about 17 cal. ka BP (Kaplan et al., 2004; Rabassa, 2008; Hein et al., 2010). Murray et al. (2012) have demonstrated that at least one third of the total southern Patagonian deglacial climate warming occurred between ca. 18.9 and 17 ka ago. Zone DZ-6 spans from 18.7 to 16.6 cal. ka BP and is characterized by diatom assemblages composed almost exclusively of benthic taxa. As previously observed in this record, the increases in non-planktonic taxa seem to be associated to warmer conditions (e.g., as discussed for the Antarctic warm events in the previous section). Nonetheless, this part of the record is unique as the non-planktonic species, in this case mostly benthic and epiphytic, represent up to 88% of the whole assemblage. The plankton is almost reduced to only one diatom species, *Discostella stelligera* morph 1. This taxon, as previously discussed, is suspected to be meroplanktonic, which would result in a near absence of plankton for a time period of almost 2 ka. A possible explanation could be that increasing temperatures recorded in the Antarctic records since ca. 18 cal. ka BP (Fig. 6) would initiate a melting of permafrost in the catchment area triggering mass movement events from littoral areas towards the profundal plain of the lake. This would relocate reworked benthic diatoms from their former habitat and generate turbidity in the water column, preventing light to penetrate. Indeed, the lithostratigraphy (Fig. 4) shows that thick and frequent mass movement deposits characterize the transition between units C-1 and B. Other possible explanations for this response from the diatom flora could be a lake-level drop and desiccation of the lake, allowing only for the development of small benthic and aerophilic taxa, or the development of an ice-cover, impeding water turbulence and light penetration, and hence the lack of plankton. Nevertheless, none of these alternative hypotheses seem to be supported by other regional data or records, hence the high-resolution analysis of other proxies is necessary for a consistent interpretation of this event.

At the end of this episode, at ca. 16.5 cal. ka BP, all datasets show clear signs of the ongoing deglaciation and the onset of warmer conditions. TOC and C/N ratios increase (Fig. 5) and diatom abundance starts to increase and stays high until ca. 9 cal. ka BP. We observe a return and diversification of the plankton characterized by the reappearance of *Cyclotella patagonica* and the short termed occurrence of *Aulacoseira granulata*. The dominance of *C. patagonica* suggests that between 16.5 and 10.5 cal. ka BP the lake level was high and water was fresh and oligotrophic, since this endemic species has only been found so far in two locations in Patagonia and seems to develop under such conditions (Guerrero and Echenique, 2002). The incidence of *A. granulata* is characteristic of warmer conditions (Stoermer, 1993) and has sometimes also been associated to increased wind strengths since this big and heavy diatom requires a significant water turbulence to avoid sinking. Previous studies in Laguna Potrok Aike have reported these conditions (Recasens et al., 2012; Wille et al., 2012; Massafiero et al., 2013) and interpreted this interval as a freshwater and oligotrophic high-level lake and a prevailing humid environment. Increased wind speeds between ca. 14.7 and 14.2 cal. ka BP have been suggested by the presence of *A. granulata* and the increase of several genera of chironomids (Massafiero et al., 2013).

The slight decrease in diatom concentration, together with the disappearance of *A. granulata* from the record at about 13 cal. ka BP could be due to episodic colder conditions associated to the Antarctic Cold Reversal (ACR). This cold event during the warming Late Glacial has been defined as a period of abrupt cooling in Antarctica from ca. 14.5 to 12.7 cal. ka BP (EPICA Community Members, 2004). A cold event occurring in the ACR chronozone has been reported in Antarctic ice cores (Jouzel et al., 1995), marine sediment cores off Chile (Lamy

and Kaiser, 2009) and in Patagonian continental archives. The Younger Dryas chronozone, previously reported in this lake as warmer and drier (Haberzettl et al., 2007) is characterized by the onset of TIC precipitation at ca. 13.1 cal. ka BP. Moreover, the pollen based-precipitation reconstruction suggests a dry phase in the area during that time (Schäbitz et al., 2013). As for the diatom record, no particular signs of this event are detectable.

5.2.3. Early Holocene to present times (DZ8-9)

From 10.5 cal. ka BP onwards, the record reflects warmer Holocene conditions. Our results are in agreement with previous microfossil investigations for Laguna Potrok Aike (Wille et al., 2007; Recasens et al., 2012; Massafiero et al., 2013).

The appearance of the brackish-water diatoms *Thalassiosira patagonica* (Maidana, 1999) at 10.5 cal. ka BP and *Cyclotella agassizensis* (Risberg et al., 1999) is interpreted as the beginning of the lake's salinization and as an indicator of lower lake levels. Moreover, we observe a synchronous decline and disappearance of the freshwater taxon *Cyclotella patagonica*. This part of the record is marked by a restriction in plankton to species that favour saline conditions associated with *Discostella stelligera*, which has a broad tolerance range. This assemblage remains relatively stable up to the last ca. 3.5 cal. ka BP where its relative abundance declines.

Zone DZ-8, from 10.5 to 3.5 cal. ka BP, corresponds to the time when sedimentation rate dramatically increased (Anselmetti et al., 2009), due to a larger amount of sediment input and to the lowered lake level mobilizing sediment from the exposed terraces. This part of the record reveals a very low diatom concentration; however, since this proxy is expressed in valves per gram of dry sediment, it could be argued that the signal is just diluted by the increased sedimentation rate. Nevertheless, after ca. 5 cal. ka BP the sedimentation rate decreases again and the diatom signal remains low. As previously discussed, diatom valve dissolution occurs in the record since the onset of more saline conditions (Massafiero et al., 2013). One can therefore argue if this bad preservation can be a bias for the dataset and erroneously reflects low diatom concentrations during the Holocene. Nevertheless, even if bad preservation occurs, the climatic signal inferred from the diatom record for the last part of the record seems in agreement with other proxies, such as pollen and chironomids (Wille et al., 2007; Massafiero et al., 2013). This indicates that if it was the effect of valve dissolution, this might have happened in a generalized way over the record, including the whole diatom assemblage and avoiding a serious bias in the quantitative reconstructions and paleoclimatic interpretations.

6. Conclusion

The study of the diatom record archived in the long sedimentary record from Laguna Potrok Aike has allowed us to infer the former lake's water quality and the environmental changes linked to it, as well as to get a first hint on climatic fluctuations in Southern Patagonia for the last ca. 50 cal. ka BP. The Late Glacial and Holocene history of this lake had already been thoroughly studied. Now also the glacial part of the record reveals unprecedented information to be compared to marine and Antarctic counterparts. Using the diatom record, we suggest that the climatic events described for the Southern Hemisphere during the last glacial-interglacial interval (such as the Antarctic Cold reversal or the Antarctic warm events) are reflected in Laguna Potrok Aike's sedimentary record, in particular by fluctuations in diatom abundance and changes in the species assemblages. Some of these fluctuations seem to be associated to the Antarctic warm events A1 and A2. Considering the age uncertainty of the current age model for the lowermost part of the sediment core and the behaviour of the diatom record (and ongoing pollen and isotopic analyses), we can argue in favour a signal tentatively relatable to A3 at the base of the record. Further studies involving an improvement of the current age model using OSL dating and several multiproxy analyses will allow a better comprehension of

this record and the forcings behind it. The upcoming results from ongoing multiproxy investigations on this sediment core will help to validate the hypothesis exposed in this study and improve our understanding of the environmental history of Laguna Potrok Aike. This will add another piece to the puzzle of Southern Hemispheric paleoclimate and will allow comparisons with Antarctic and Northern Hemisphere studies, and in a broader scale help determine their significance for the global climate system.

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