Palaeogeography, Palaeoclimatology, Palaeoecology 427 (2015) 20–31

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Late Glacial and Early Holocene cyclic changes in paleowind conditions and lake levels inferred from diatom assemblage shifts in Laguna Potrok Aike sediments (southern Patagonia, Argentina)

Claudia Zimmermann [a,*], Guillaume Jouve [b,1], Reinhard Pienitz [c,2], Pierre Francus [b,1], Nora I. Maidana [d]

[a] Centre d'études nordiques (CEN), Université Laval, Pavillon Abitibi-Price, Room 1230, 2405, rue de la Terrasse, Québec, QC, G1V 0A6, Canada
[b] Centre Eau Terre Environnement, Institut National de la Recherche Scientifique (INRS-ETE), 490, rue de la Couronne, Québec, QC, G1K 9A9, Canada
[c] Centre d'études nordiques (CEN), Université Laval, Pavillon Abitibi-Price, Room 1232, 2405, rue de la Terrasse, Québec, QC, G1V 0A6, Canada
[d] DBBE-FCEN, Universidad de Buenos Aires – IBBEA (UBA-CONICET), Buenos Aires, Argentina

ARTICLE INFO

Article history:
Received 27 February 2014
Received in revised form 24 February 2015
Accepted 6 March 2015
Available online 14 March 2015

Keywords:
Paleolimnology
Diatom analysis
Microsedimentological analysis
Late Glacial–Early Holocene
Southern Hemisphere Westerly Winds (SWW)
Paleoclimate

ABSTRACT

PASADO is a multidisciplinary Potrok Aike Sediment Archive Drilling prOject, which was conducted from 2008 to 2013, focusing on the sedimentary record of the volcanic crater maar Laguna Potrok Aike (52°S, 70°W, 116 m asl) in southern Patagonia, Argentina. It represents one of the few non-glacial and extra-Andean sediment archives studied so far on the continental landmass between subtropical South America and Antarctica that covers the entire Holocene and the Late Glacial. In this study, a high-resolution diatom analysis of the Late Glacial time interval situated between 15.60 and 10.51 ka cal. BP was performed on the PASADO sediment core. This period is of particular interest as it encompasses the Antarctic Cold Reversal (ACR), as well as the Younger Dryas (YD) chronozone. To better refine the variability of environmental and climatic conditions of this Late Glacial time interval, we combined our data with those of a microsedimentological analysis conducted on the same sediments and for the same period to infer changes in lake level and water column stratification. Our study revealed that diatoms are an ideal proxy to complement microsedimentological analyses by providing important independent information on the past limnological dynamics of Laguna Potrok Aike and the paleoclimatic conditions that prevailed during the Late Glacial in the study area and allows a new way of explaining shifts in the position of Southern Hemisphere Westerly Winds (SWW) during the Late Glacial. Peaks of planktonic diatoms, particularly *Cyclostephanos patagonicus*, correspond to previously detected total organic carbon (TOC), Ca/Si, Ca and Mn peaks and support the hypothesis that relatively high lake levels and weaker SWW have prevailed during the Late Glacial. Moreover, a cyclic pattern, observed both in the biological and geochemical indicators, suggests at least five shifts in the position of the SWW from the beginning of the ACR to the end of the YD. The periodicity of these shifts seems to be related to Antarctic ice-sheet discharge (AID) events in the Scotia Sea that coincide with enhanced iceberg flux from the Antarctic ice-sheet.

1. Introduction

The Late Glacial interval, corresponding to the last deglaciation periods, contains several abrupt climate change events, such as the Antarctic Cold Reversal (ACR) from 14.80 to 13.00 ka cal. BP as defined by Pedro et al. (2011), and the Younger Dryas chronozone (YD), from 12.70 to 11.60 ka cal. BP as established by Lowe et al. (2008). Not only the nature of climate dynamics throughout the ACR in Patagonia remains still unclear, but also the signal for a YD event (glacier advance, climate cooling) is less evident and more contradictory in records at latitudes south of 49°S in Patagonia (Sugden et al., 2005; Kaplan et al., 2008). According to Blunier et al. (1997), the ACR precedes the YD cold event by at least 1.80 ka, suggesting that the climates of the Northern and Southern Hemispheres were in anti-phase during the YD. Nowadays, variations in the strength and the position of the Southern Hemisphere Westerly Winds (SWW) are considered to be an important feature of the global- and hemispheric-scale climate changes since the Last Glacial Maximum (LGM) (Toggweiler et al., 2006; Anderson et al., 2009; Denton et al., 2010; Moreno et al., 2010). Furthermore, changes in the strength and/or position of the SWW modify the upwelling of CO_2-rich deep waters around Antarctica (Le Quéré et al., 2007; Sigman et al., 2010). Southern South American lakes between latitudes 51 and 55°S, are situated between the southern limit of the SWW belt of the

* Corresponding author. Tel.: +1 418 656 2131x5809.
E-mail addresses: Claudia.Zimmermann@cen.ulaval.ca (C. Zimmermann), Guillaume.Jouve@ete.inrs.ca (G. Jouve), Reinhard.Pienitz@cen.ulaval.ca (R. Pienitz), Pierre.Francus@ete.inrs.ca (P. Francus), noramaidana@gmail.com (N.I. Maidana).
[1] Tel.: +1 418 654 3780.
[2] Tel.: +1 418 656 2131x7006.

http://dx.doi.org/10.1016/j.palaeo.2015.03.006
0031-0182/

Last Glacial period (Ledru et al., 2005), and the current southern limit of the SWW belt (Hodgson and Sime, 2010; Lamy et al., 2010; McGlone et al., 2010). However, the comparison of records often reveals inconsistencies or opposite conclusions, which appear to be related to a weakness in the understanding of the proxy and/or unavailability of modern calibration datasets (Kilian and Lamy, 2012). Yet, the comprehension of past and current variations of the SWW position and intensity remains an open question (Kohfeld et al., 2013). Therefore, reconstructing hydroclimatic conditions during the last deglaciation in Southern Patagonia, and especially during sudden climate changes, improves our understanding of the Southern Ocean's role as a source or a sink of the atmospheric carbon dioxide.

This study is part of the international and multidisciplinary Potrok Aike Sediment Archive Drilling prOject (PASADO) which was conducted from 2008 to 2013, focusing on the sedimentary record of the volcanic crater lake (maar) Laguna Potrok Aike (52°S, 70°W, 116 m asl) (Zolitschka et al., 2013). The maar is situated in the Pali Aike Volcanic Field in the Province of Santa Cruz, southern Patagonia, Argentina, and represents one of the few non-glacial and extra-Andean sediment archives studied so far on the continental landmass between subtropical South America and Antarctica that covers the entire Holocene and the Late Glacial (Zolitschka et al., 2013).

Prior to PASADO, the first high-resolution multi-proxy paleoenvironmental records from Laguna Potrok Aike have been investigated within the framework of the interdisciplinary SALSA (South Argentinean Lake Sediment Archives and Modeling) project. During field campaigns in 2002 and 2003, sediment cores were retrieved from the maar and combined to an 18.92 m long composite profile covering the last 16 ka cal. BP (Haberzettl et al., 2007). Using these cores, Massaferro et al. (2013) performed diatom and chironomid analyses for the whole profile, reconstructing lake level fluctuations and climate changes based on 174 samples with an average resolution of 8 to 16 cm along the core. Haberzettl et al. (2005) retraced climatically induced lake level changes for the last 2000 years using a multi-proxy approach (pollen, diatom, geochemical, isotopic, geophysical and XRF-scanning elemental analyses), while Haberzettl et al. (2006) reconstructed the environmental change and fire history for the last five centuries based on the same data. Wille et al. (2007) used pollen and diatom records of the composite profile to present a well-dated vegetation and climate history for the southern South American mainland, and Schäbitz et al. (2013) reconstructed paleoprecipitations from pollen transfer functions.

The interdisciplinary PASADO project focused on a 106.09 m long composite sediment profile with a basal age of 51.20 ka cal. BP (Kliem et al., 2013). Recasens et al. (2012) developed a low resolution (core catcher) multi-proxy record including geophysical, geochemical, CNS elemental, isotopic, rock magnetism, diatom and pollen analyses that provided new insights in paleoenvironmental changes in the lake and its catchment area for the entire record. Recently, Recasens et al. (2015) inferred the hydrological and climatic changes archived in the PASADO composite sediment profile since the Late Pleistocene (the last 50 ka cal. BP), based on diatom records at a spatial resolution of 32 cm and increasing to 16 cm in some sections with major changes in the assemblages.

Diatoms (class Bacillariophyta) can be found with high abundance and species diversity in mostly all aquatic habitats. Because of the robustness of their siliceous cell walls, diatoms are often well preserved in fossil deposits and can in most cases be identified to species level (Julius and Theriot, 2010). Taxa existing at the present day can be found in fossil Quaternary records and, with the knowledge of their modern ecological preferences, those microscopic algae are important indicators for documenting and reconstructing past environmental conditions and changes. Here, we present a more detailed diatom analysis than Recasens et al. (2015), focusing on the Late Glacial time interval situated between 15.60 and 10.51 ka cal. BP using the PASADO core that has a better resolution compared to the SALSA core. This time interval is of particular interest as it encompasses the ACR, as well as the YD chronozone.

To better refine the variability of environmental and climatic conditions of this Late Glacial time interval, we combined our data with those of a microsedimentological analysis that Jouve et al. (2013) performed on the PASADO composite profile for the same period (15.60–10.51 ka cal. BP). They have shown that microsedimentological data can be biased by external inputs which, however, have no influence on diatoms. For example, micropumices (small volcanic debris of highly microvesicular pyroclastic glass with very thin, translucent bubble walls of extrusive igneous rock) have the potential to significantly influence the chemical composition of sediments (e.g. iron (Fe), titanium (Ti), total organic carbon (TOC), water content (WC)) (Jouve et al., 2013). The presence of micropumices could either be linked to the 1.5 m of remobilized tephra and/or the Reclus eruption around 16 ka cal. BP (Haberzettl et al., 2007; Jouve et al., 2013). Therefore, it was impossible for Jouve et al. (2013) to relay to the TOC for any paleoenvironmental reconstructions for the period from 15.58 to 13.64 ka cal. BP or to use Ti and Fe as paleohydrological and paleowind intensity proxies for the time interval between 15.20 and 11.80 ka cal. BP.

In this paper, we used diatoms as a proxy to complement these microsedimentological analyses with the aim of providing novel and independent information on the past limnological and ecological structure and dynamics of crater lakes like Laguna Potrok Aike. More specifically, we inferred changes in the lake level and water column stratification of Laguna Potrok Aike that relate to past wind conditions in southern Patagonia.

2. Regional setting

Laguna Potrok Aike (51°57.337′ S, 70°22.688′ W, 116 m asl) is a volcanic maar lake located in the Pali Aike Volcanic Field in the Province of Santa Cruz, southeastern part of Patagonia, Argentina (Zolitschka et al., 2006, 2013) (Fig. 1). Climatically, it belongs to the semiarid Patagonian Steppe with annual precipitation below 300 mm a^{-1} due to the rain shadow effect of the Andes (Mayr et al., 2009). Laguna Potrok Aike's crater formed after a phreatomagmatic eruption about 770 ka years ago and filled with water (Zolitschka et al., 2006). Since its creation, the maar acts as a sediment trap and is therefore one of the few permanent lakes of the Patagonian Steppe potentially providing a continuous sedimentary and climatic record over several glacial–interglacial cycles (Zolitschka et al., 2006; Jouve et al., 2013).

The Pali Aike Volcanic Field is situated within the Magellan sedimentary basin, just beyond large Early and Middle Pleistocene moraines (Coronato et al., 2013). It is composed of alkali-olivine basalts with an age range of 3.8 Ma (Pliocene) in the western part and 0.01 Ma (Holocene) towards the Atlantic Ocean (Zolitschka et al., 2006). Laguna Potrok Aike is located in the older western section of the Volcanic Field, at a distance of ca. 300 km east of the Andes, ca. 85 km west of the city of Río Gallegos and ca. 80 km north of the Strait of Magellan (Zolitschka et al., 2006) (Fig. 1).

The maar has a maximum diameter of 3470 m, a mean water depth of about 44 m and reaches a maximum water depth of 100 m in the center of the basin. It contains a water volume of 0.41 km^3 and covers a catchment area of more than 200 km^2 (Zolitschka et al., 2006). As the lake has no outlet today and is mainly fed by groundwater and episodic surface runoff (e.g. after snowmelt in spring) which reaches the basin through deeply incised canyons, it is very sensitive to changes in the water balance and effective moisture (Ohlendorf et al., 2013). Laguna Potrok Aike displays a nearly circular trough-shaped bathymetry with an almost flat lake floor, revealing an older lake level low stand at −35 m water depth (Haberzettl et al., 2005; Zolitschka et al., 2006; Anselmetti et al., 2009). The vertical distance between the lake surface and the surrounding morainic plain is about 50 m (Coronato et al., 2013).

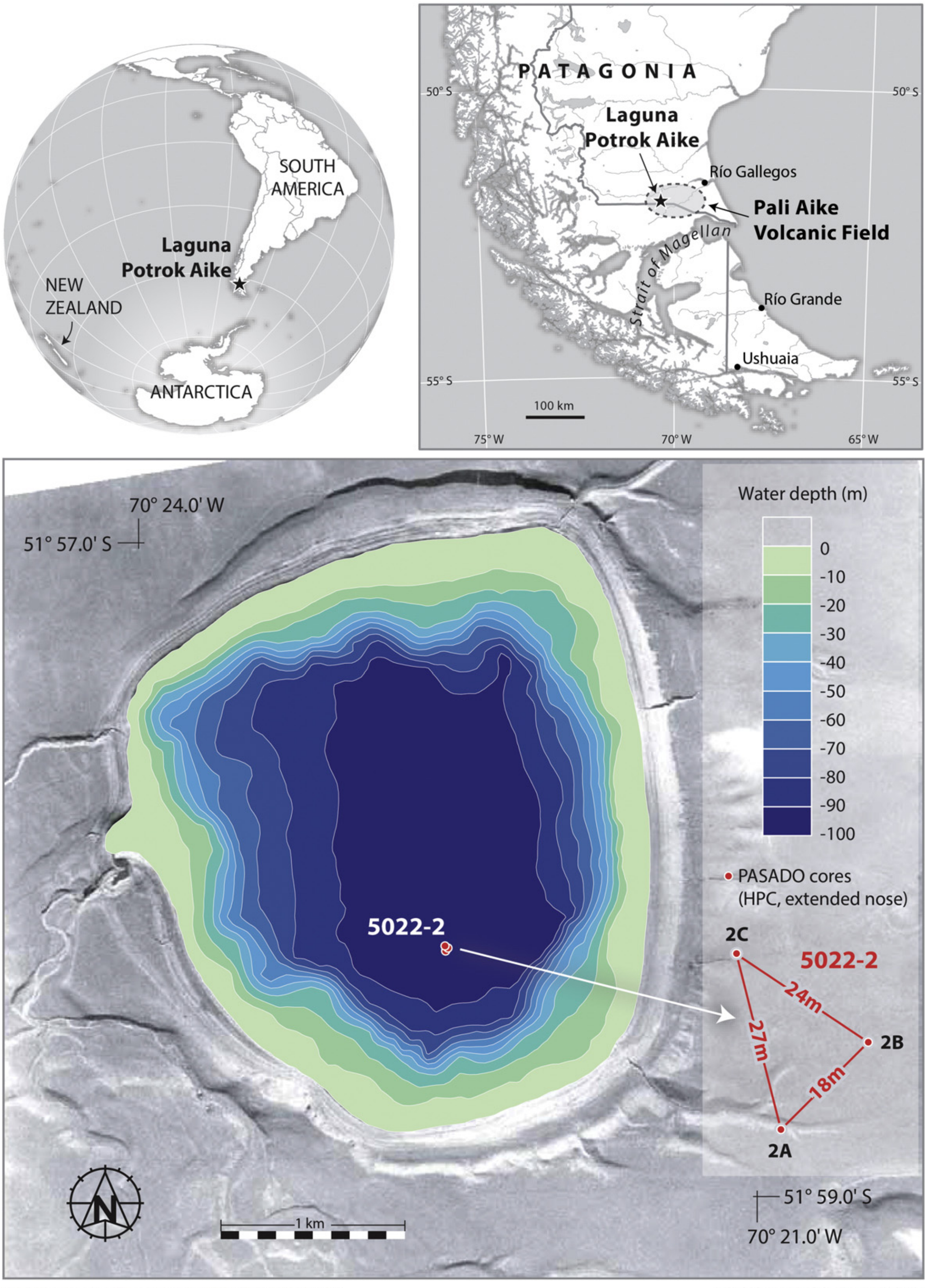

Fig. 1. Location of Laguna Potrok Aike (LPA) in southern Patagonia. Aerial photograph of the immediate catchment area of Laguna Potrok Aike (kindly provided by Hugo Corbella, Buenos Aires) and bathymetric map of the lake with the location of coring site 5022-2. Detailed map (right) indicates the relative positions of piston cores (modified from Ohlendorf et al. (2011)).

Physico-chemical field surveys completed between 2002 and 2005 reveal that Laguna Potrok Aike is a subsaline lake (salinity 2.2–2.5 g l^{-1}) with an oxygen-rich water column from top to bottom (Table 1). The brackish water conditions could be a result of the long-lasting evaporation (770 ka) in the closed lake basin, thus concentrating soluble elements (Zolitschka et al., 2006). The ionic composition of the lake water indicates particularly high concentrations of sodium (Na), chloride (Cl^{-}), magnesium (Mg) and total phosphorus (TP) (Zolitschka et al., 2006). Despite the high total phosphorus values (1300–3600 μg l^{-1} TP) which would classify the lake as hypertrophic (OECD,

Table 1
pH, electric conductivity (EC), salinity (calculated from EC according to http://ioc.unesco.org), and water chemistry (anions, cations) of surface waters from Laguna Potrok Aike, field surveys 2002–2005. [a]Water not filtered prior to analyses, resulting in overly high values for Fe, Mn, and Al related to suspended minerogenic matter (from Zolitschka et al. (2006)).

Year	pH	EC ($mS\ cm^{-1}$)	Salinity ($g\ l^{-1}$)	Cl^- ($mg\ l^{-1}$)	NO^{3-} ($mg\ l^{-1}$)	SO_4^{2-} ($mg\ l^{-1}$)	TP ($mg\ l^{-1}$)	Fe ($mg\ l^{-1}$)	Na ($mg\ l^{-1}$)	Mg ($mg\ l^{-1}$)	Si ($mg\ l^{-1}$)	K ($mg\ l^{-1}$)	Ca ($mg\ l^{-1}$)	Mn ($mg\ l^{-1}$)	Al ($mg\ l^{-1}$)
2002	8.9	3110	2.53	586.0	>0.05	27.1	2247	142.0[a]	502.0	73.0	1.20	43	32.0	7.4[a]	50[a]
2003	8.7	2970	2.22	644.0	1.73	26.3	3609	10.9	476.0	72.0	0.69	31.8	34.2	2.5	>5
2004	8.8	2980	2.23	666.0	3.07	27.2	1297	21.8	528.0	59.0	0.78	57.0	27.8	2.3	16
2005	9.0	3020	2.26												

1982), plankton studies suggest mesotrophic to eutrophic conditions (Zolitschka et al., 2006; Wille et al., 2007). These observations are also supported by Secchi depths of 6.0 m (March 2003) and 6.9 m (March 2005). As phosphorus is not the limiting factor for lacustrine productivity in the maar, the lower as expected trophic state of Laguna Potrok Aike could be explained by its high salinity, high water turbulence, high concentration of chlorides inhibiting planktonic productivity, and limited nitrogen supply for algal growth (Zolitschka et al., 2006; Mayr et al., 2009). The observed nitrate (NO^{3-}) concentrations vary considerably (>0.05–3.07 mg l^{-1}) and indicate a potential nitrate limitation for primary production (Zolitschka et al., 2006).

Presently, strong westerly winds with annual wind speeds of approximately 7.4 m s^{-1} and monthly average speeds of up to 9 m s^{-1} at the beginning of summer are the main air masses that dominate the climate of the region (Endlicher, 1993; Mayr et al., 2007, 2009). The lake is fully exposed to these strong winds that cause mixing of the water column nearly throughout the entire year (theoretical mixing depth: 52 m), leading to polymictic conditions and preventing a stratification of the water body in summer as well as the development of an ice cover in winter (Endlicher, 1993; Zolitschka et al., 2006; Kastner et al., 2010). Thus, the water column of Laguna Potrok Aike yields stable values for pH (8.7) and temperature (10.4 °C) throughout the entire depth profile of 100 m. Surface water temperatures reached between 10 and 12 °C during summer (Zolitschka et al., 2006). Total organic carbon content (mean value: 1.8% TOC, n = 97) in the surface sediments of the lake suggests low primary productivity, rapid decomposition and recycling of organic compounds, and/or dilution by inorganic particles (Zolitschka et al., 2006; Kastner et al., 2010).

To describe the modern algal and diatom flora of Laguna Potrok Aike, water samples have been collected in the austral summers since 1996 near the western shore (Wille et al., 2007). The algal community varied each year and several new diatom taxa with more or less well known autecology have been identified (Maidana, 1999; Maidana and Round, 1999; Maidana et al., 2005). In 1996 and 1997, the assemblages were dominated by *Navicula gregaria*, *Fragilaria capucina* var. *vaucheriae*, *Cocconeis placentula* var. *lineata*, *Thalassiosira patagonica* and *Corbellia contorta* (Maidana, 1999; Maidana and Round, 1999). Since 2002, *Cyclotella agassizensis* has increased its relative abundance and has become the dominant species in 2003 (Maidana et al., 2005), accompanied by the desmid algae *Closterium* sp. In 2004, *C. agassizensis* was still the most frequent diatom species but the community was dominated by small coccoid cyanobacteria, *Nostoc aggregates*, coccoid chlorophytes (*Oocystis*, *Lobocystis* and *Dictyosphaerium* spp.) and *Euglena* sp. (Wille et al., 2007).

The Pali Aike Volcanic Field, including the catchment area of Laguna Potrok Aike, is characterized by a dry (xeric) type of the Magellanic steppe composed of Poaceae, herbs, occasional shrubs and *Festuca gracillima* as dominant species being the result of overgrazing due to sheep farming during the last 100 years (Oliva et al., 2001; Wille et al., 2007; Mayr et al., 2009). Today, several concentric lake terraces surrounding Laguna Potrok Aike, which indicate past lake level fluctuations, are colonized by different plant communities. The immediate zone above the water line is devoid of vegetation, followed by a belt of almost pure stands of *Acaena* sp. This evergreen, herbaceous, perennial plant is typical for sites with frequent disturbances (Wille et al., 2007). As the western lake shore is less wind exposed, 30 to 100 cm high stands of the shrub *Adesmia boronioides* are able to grow, thus protecting the surface of the slopes from wind and wave erosion (Wille et al., 2007). On the northern, eastern and southern lake shores the terraces above the *Acaena* belt are colonized by a plant community composed of grasses (e.g. *Festuca* sp., *Poa* sp. and *Stipa* sp.), the herbaceous plant *Perezia recurvata*, cushions of *Colobanthus subulatus* and *Nardophyllum bryoides*, as well as few bushes of *Berberis heterophylla* (Wille et al., 2007). Patches of *Empetrum rubrum* have been observed on the northwestern shore (Wille et al., 2007). Within the lake basin, the littoral zone below the base of wind-induced waves is densely covered with aquatic macrophytes (e.g., *Potamogeton pectinatus*, *Myriophyllum* cf. *quitense*) from water depths of 1.5 to 15 m (Wille et al., 2007; Mayr et al., 2009).

3. Materials and methods

From August to November 2008, PASADO drilled a total of seven holes at two different sites (5022-1; 5022-2) in Laguna Potrok Aike, using the Global Lake Drilling to 800 m (GLAD800) coring system. Coring was entirely conducted with a hydraulic piston corer (Ohlendorf et al., 2011; Zolitschka et al., 2013). Average core recovery for the hole of site 5022-1 was 92.1% and 98.8% for site 5022-2 (Ohlendorf et al., 2011). A total of 533 m of sediment was recovered at the two sites. Then, a sediment profile of 106.09 m composite depth (cd) was compiled from the best core sections retrieved in three holes at site 5022-2 by correlating stratigraphic markers, facies and magnetic susceptibility of each core (Kliem et al., 2013; Zolitschka et al., 2013). Kliem et al. (2013) established a consistent age-depth model (version 3) for the composite profile using 58 radiocarbon dates, with a basal age of 51.20 ka cal. BP.

3.1. Preparation and identification of fossil diatoms

For diatom analysis, 57 bulk samples were retrieved at every 2 cm from the sedimentary composite profile, covering the interval from 16.31 to 14.08 m cd, corresponding to the time interval between 15.60 and 10.51 ka cal. BP. For reasons of methodological consistency within the PASADO project, diatom slides were prepared at the University of Buenos Aires, Argentina. For each sample, between 0.08 and 0.50 g of dry sediment was tested with 10% HCl for carbonate content, digested with hot 30% H_2O_2 and then washed repeatedly with distilled water to adjust the siliceous solution to pH 7. The final siliceous solution was calibrated to a volume of 10 ml and a known quantity of polystyrene microspheres was added in order to estimate the diatom concentration (Battarbee and Kneen, 1982). Then, 0.5 ml of the slurry was transferred onto 22 × 22 mm square glass coverslips, air-dried for 24 h and mounted onto microscope slides with Naphrax© resin (Refraction Index (RI) = 1.74). In the Aquatic Palaeoecology Laboratory at Université Laval (Québec, Canada), a minimum of 500 diatom valves was counted in each sample using a Leica DM RX light microscope at a magnification of 1000× under oil immersion. Taxonomic identification is mainly based on the following literature: Krammer and Lange-Bertalot (1986, 1988, 1991a,b); Rumrich et al. (2000); Díaz-P. and Maidana (2005).

3.2. Numerical analysis

The diatom model was developed based on relative diatom abundances, using the computer program C2 (Juggins, 2007). The diatom concentration was calculated for one gram per dry weight (dgw) sediment following the method of Battarbee and Kneen (1982). For detecting major trends in the fossil diatom assemblages, principal components analysis (PCA) with intersample distance scaling and covariance matrix was carried out on species percentage data with the computer program CANOCO 5 (ter Braak and Šmilauer, 2012). Furthermore, the diatom zones were established using a stratigraphically constrained incremental sum of squares cluster analysis (CONISS) with the software environment R for data analysis and graphics, version 2.15.3 (Venables et al., 2013).

4. Results

4.1. Diatom analysis

A total of 224 diatom taxa in 49 genera were encountered in the 57 samples selected for diatom analysis (Fig. 2). The fossil siliceous material was in most cases heavily fragmented. Chrysophyte cysts were completely absent or only present at trace level. The diatom concentration ranges between 25 million and 683 million valves per gram of dry sediment with prominent peaks at 15.63 m cd (13.77 ka cal. BP), 15.27 m cd (12.86 ka cal. BP) and 14.31 m cd (10.91 ka cal. BP). The diatom stratigraphy displays only taxa exceeding a total relative abundance of all analyzed core levels of 0.75% and a relative abundance of 2% in at least one core level. Based on a CONISS cluster analysis and a PCA, four distinct diatom zones (DZ) with major changes in the composition of the diatom assemblages could be distinguished.

4.1.1. Diatom Zone 1 (16.31–16.11 m cd, ca. 15.60–15.05 ka cal. BP, 6 samples)

The lowermost diatom zone is characterized by small alkaliphilic, benthic, oligohalobus fragilarioids (e.g. *Pseudostaurosira* spp., *Staurosira* cf. *alpestris*, *Staurosira venter*, *Staurosirella pinnata*) with combined relative abundances of those fragilarioids ranging from 45 to 62%. *Opephora* taxa display abundances between 6 and 12%. The centric diatoms are only represented with abundances ranging from 13 to 26% and mainly composed of *Aulacoseira granulata* (2–14%) and *Cyclostephanos patagonicus* (1–11%), while *Discostella stelligera* & *D. glomerata* never exceed 4%. The two periphytic alkaliphilic diatoms *Cocconeis placentula* (3–8%) and *Karayevia clevei* (6–10%) (Hofmann et al., 2011) also appear in Zone 1. In this zone, the benthic diatoms (58–76%) clearly dominate over epiphytic (7–22%) and planktonic taxa (13–27%).

4.1.2. Diatom Zone 2 (16.11–15.25 m cd, ca. 15.05–12.81 ka cal. BP, 22 samples)

Diatom Zone 2 can be divided into the two Sub-zones 2a (16.11–15.61 m cd, ca. 15.05–13.72 ka cal. BP) and 2b (15.61–15.25 m cd, ca. 13.72–12.81 ka cal. BP). In general, Zone 2 is characterized by a decline of *A. granulata* from 7 to < 1%. The centric plankter *C. patagonicus* becomes the dominant taxon and displays cyclic abundance variations (14–79%) with a peak in the middle of each sub-zone. The abundances of *D. stelligera* & *D. glomerata* are increasing to 28%. Fragilarioids (e.g. *Pseudostaurosira* spp., *S.* cf. *alpestris*, *S. venter*, *S. pinnata*) show values between 6 and 44%, with *Opephora* spp. (1–17%) and *S. pinnata* (1–11%) as the most frequent fragilarioid taxa in the two sub-zones. *D. stelligera* & *D. glomerata* and fragilarioids, particularly *Opephora* spp., display an inverse abundance pattern as compared to *C. patagonicus*. *C. placentula* (2–12%) and *K. clevei* (1–6%) occur with a constant abundance throughout the entire zone. The abundance of epiphytic diatoms remains relatively stable throughout Sub-zone 2a with a significant increase (38%) towards the top of the zone. The planktonic taxa fluctuate between 27 and 69% with highest values in the center of this zone. The benthic diatoms are represented with values between 14 and 51%. In Sub-zone 2b, epiphytic and benthic diatoms show the highest abundances at the lower (27 and 48%, respectively) and upper limit (24 and 44%, respectively) of the zone. They decrease significantly in the center, where the planktonic taxa reach a peak of 83%.

4.1.3. Diatom Zone 3 (15.25–14.57 m cd, ca. 12.81–11.31 ka cal. BP, 17 samples)

Diatom Zone 3 is also characterized by the cyclic pattern of the dominant taxon *C. patagonicus* (9–73%) dividing it into the following two Sub-zones: 3a (15.25–14.89 m cd, ca. 12.81–11.97 ka cal. BP) and 3b (14.98–14.57 m cd, ca. 11.97–11.31 ka cal. BP). *D. stelligera* & *D. glomerata* increase in abundance (7–46%). Fragilarioids show similar values (10–38%) as in Zone 2, yet with a slight shift in the dominant fragilarioid taxa. *S. pinnata* decreases in abundance, while *Opephora* spp. is still dominant in Sub-zone 3a (2–11%) accompanied by *S. venter* (5–12%). The latter becomes the fragilarioid taxon with the highest abundance (1–15%) in Sub-zone 3b. The most frequent fragilarioid taxa of the two sub-zones show an inverse abundance pattern as compared to *C. patagonicus*. *C. placentula* (4–13%) and *K. clevei* (1–6%) still occur with constant abundances throughout diatom Zone 3. *Nitzschia paleacea* has an isolated peak (32%) at the base of Zone 3 at 15.23 m cd. In Sub-zone 3a, after a maximum of 52% at the base, the epiphytic diatoms display relatively stable values between 16 and 23%. Planktonic taxa abundances vary between 25 and 62% with a peak at 14.82 m cd. This peak is framed by a maximum abundance of the benthic diatoms between 37 and 41%. Sub-zone 3b is characterized by higher fluctuations of the three fractions, and a clear dominance of planktonic taxa (43–82%).

4.1.4. Diatom Zone 4 (14.57–14.08 m cd, ca. 11.31–10.51 ka cal. BP, 12 samples)

In diatom Zone 4, the cyclic pattern of fragilarioids and centric diatoms is no longer apparent. The abundance of *C. patagonicus* declines to values between 8 and 14%, while *D. stelligera* & *D. glomerata* (16–42%) become the dominant taxa with a peak at 14.31 m cd. This peak correlates with the highest diatom concentration ($34.13 \times 10^{10}\ g^{-1}$) of the whole diagram. Non-planktonic taxa, such as fragilarioids (17–38%), *C. placentula* (6–10%) and *K. clevei* (3–6%), display relative constant percentages throughout the entire zone. Abundances of the epiphytic diatoms increase in Zone 4 and range between 20 and 33%, while those of planktonic taxa fluctuate between 30 and 50% with a single peak of 60%. The benthic fraction shows values between 20 and 48%.

4.2. Combination of diatom record with microsedimentological data

For a more holistic interpretation of Late Glacial environmental and climatic variability in southern Patagonia, we combined our diatom record with data of a microsedimentological analysis performed by Jouve et al. (2013) on the PASADO composite profile for the same period (15.60–10.51 ka cal. BP). Fig. 3 compiles diatom data with results of X-Ray Fluorescence (XRF) analyses: Ca/Si ratio, Ca and Mn expressed in kilo count per second (kcps), total organic carbon (TOC) expressed in % and micropumices in % of black pixel counts. Occurrence of the green alga with calcite lorica, *Phacotus lenticularis*, between 15.35 and 14.34 m cd (ca. 13.51–10.95 ka cal. BP) is simply indicated by a gray square for more clarity. The five gray zones (A, B, C, D, E) indicate major peaks occurring simultaneously in the planktonic diatoms and the TOC profile.

5. Discussion

5.1. Paleolimnological variations

As our diatom diagram (Fig. 2) displays the presence of *A. granulata* from the bottom of Zone 1 and we did not find any traces of the

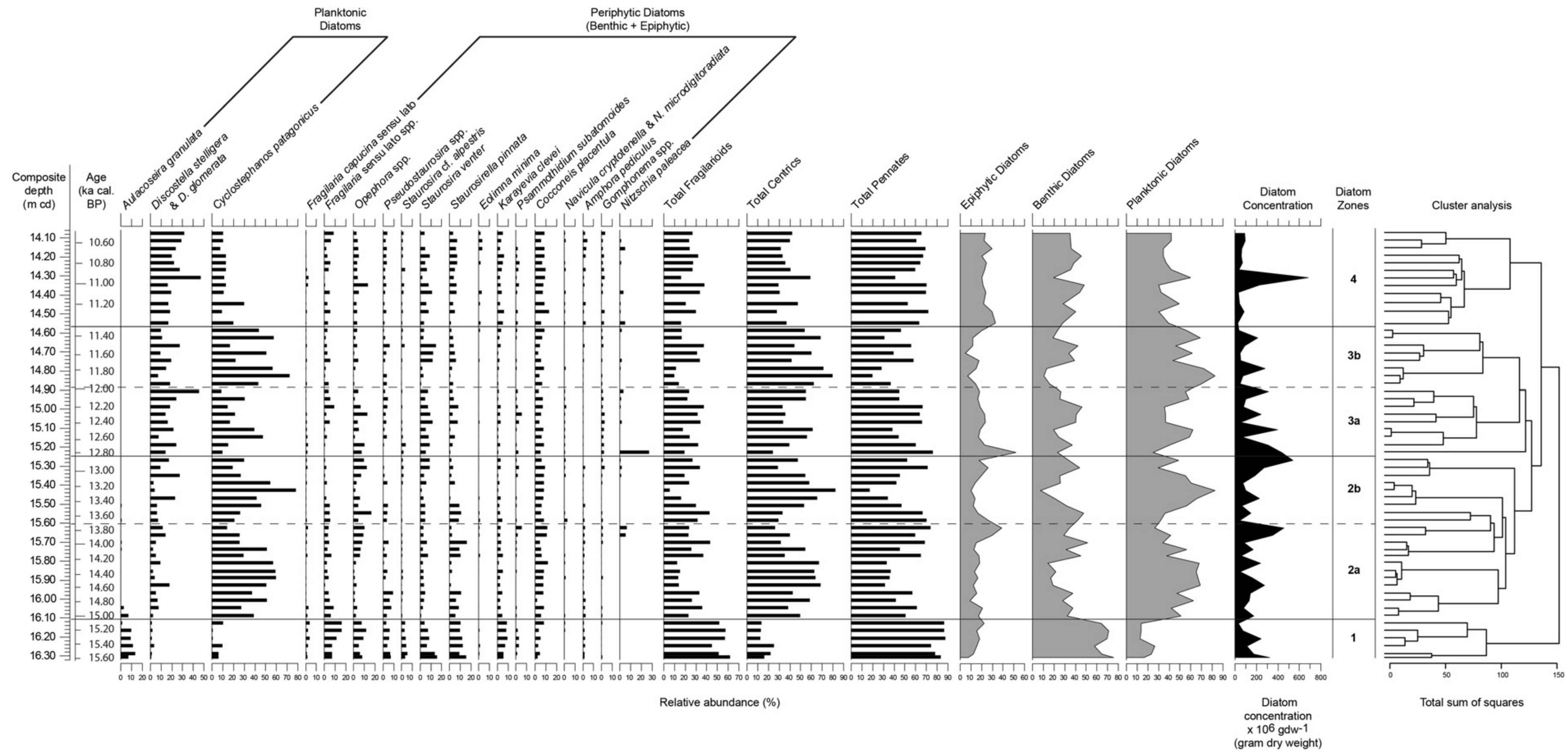

Fig. 2. Diatom valve concentration and relative abundances of dominant taxa for the PASADO sedimentary composite profile, covering the interval from 16.32 to 14.06 m cd (15.50–10.50 ka cal. BP). The diatom stratigraphy displays only taxa exceeding a total relative abundance of all analyzed core levels of 0.75% and a relative abundance of 2% in at least one core level.

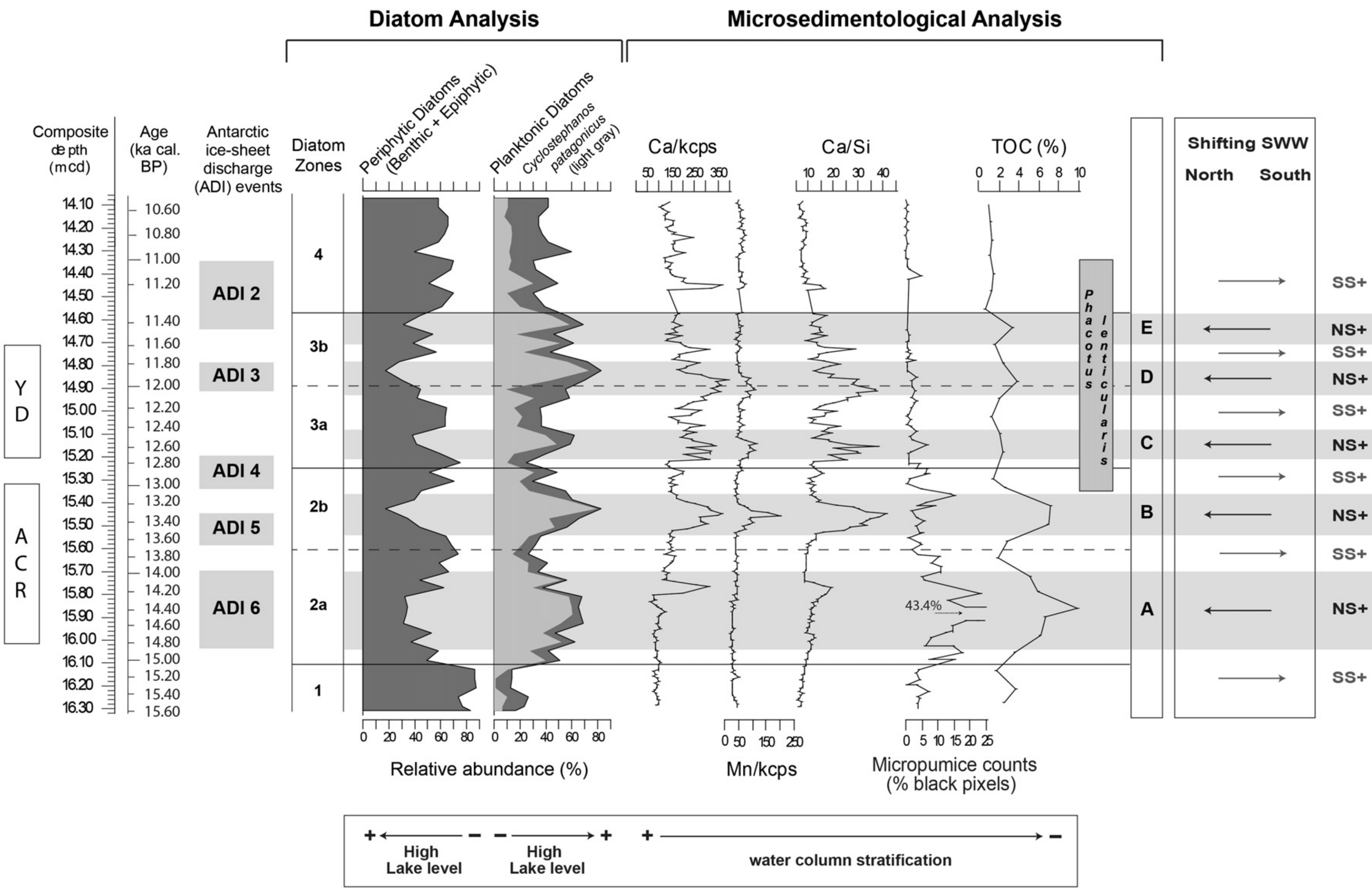

Fig. 3. Relative diatom abundances and microsedimentological analyses from Jouve et al. (2013) for the PASADO sedimentary composite profile, covering the interval of 15.50 to 10.50 ka cal. BP (16.32–14.06 m cd). From left to right: YD (Younger Dryas) as defined by Lowe et al. (2008); ACR (Arctic Cold Reversal) as defined by Pedro et al. (2011); composite depth scale; age scale from the PASADO age model version 3 (Kliem et al., 2013); Antarctic ice-sheet discharge (ADI) events (Weber et al., 2014); diatom zones (DZ); relative abundances of periphytic (benthic + epiphytic) and planktonic diatom taxa; Mn/kcps; Ca/kcps; Ca/Si ratio; Total organic carbon (TOC%); micropumice counts (% black pixels) and occurrence of *Phacotus lenticularis* (Jouve et al., 2013). Environmental and/or climatic significance of each proxy is indicated at the bottom of each profile. Interpretations in the position of the SWW in relation with prevailing north-shifters (NS+) or prevailing south-shifters (SS+) periods. (kcps = kilo count per second; SWW = Southern Hemisphere Westerly Winds; A, B, C, D, E = gray zones indicate major peaks occurring simultaneously in planktonic diatoms and TOC profile.)

brackish-water diatom *Thalassiosira patagonica* in the whole record, the analyzed sediment core section of our study should correspond to the period of approximately 14.75 to 11.50 ka cal. BP (diatom Zone 1) of the diatom diagram presented in Massaferro et al. (2013), and to the interval between 14.50 and 12.25 ka cal. BP (part of pollen zone PTA 1 and PTA 2) of the diagram shown in Wille et al. (2007). Both diagrams derive from the SALSA composite profile. When compared to the diatom diagram presented by Recasens et al. (2015) for the PASADO composite sediment profile, our diatom record corresponds to diatom Zone DZ-7 (16.60–10.50 ka cal. BP).

During the period between 15.60 and 15.05 ka cal. BP (diatom Zone 1), water conditions in Laguna Potrok Aike seem to have been alkaline and electrolyte-rich with increased lake primary production, probably due to higher temperatures and nutrient inputs. Wind conditions around the maar have probably been intensified. The diatom assemblage of this zone is mainly dominated by small alkaliphilic, benthic, oligohalobus fragilarioids (e.g., *Fragilaria* sensu lato spp., *Pseudostaurosira* spp., *S.* cf. *alpestris*, *S. venter*, *S. pinnata*) and *Opephora* taxa, which are often numerous in littoral habitats and indicators of electrolyte-rich waters (Sabbe and Vyverman, 1995; Witkowski et al., 2000). The presence of the two periphytic alkaliphilic diatoms *C. placentula* and *K. clevei* also suggests alkaline water conditions (Hofmann et al., 2011). The high abundance of benthic taxa could be explained by high lacustrine productivity and an important influx of allochthonous organic matter in Laguna Potrok Aike, following the deglaciation in Patagonia, which started around 17 ka cal. BP (Hahn et al., 2013; Zolitschka et al., 2013). Zhu et al. (2013) observed a significant shift in isotopic records of bulk organic matter for the period between 17.30 and 13.00 ka cal. BP, which also points to increased lake primary productivity, and which Zhu et al. (2013) attribute to warmer temperatures and increased nutrient input. Small benthic *Fragilaria* sensu lato taxa have been described as pioneer species, since they are often found with great abundance in the initial lake phases following deglaciation (Pienitz et al., 1991; Saulnier-Talbot et al., 2003). They are considered opportunists, as they quickly form blooms because of their high turnover rates, and temporarily outcompete larger diatom species with slower growth rates due to the very short growing season. As they are well adapted to alkaline conditions, they easily take advantage of high initial supplies of allochthonous nutriments (Laing et al., 1999; Saulnier-Talbot et al., 2003; Köster and Pienitz, 2006). Hahn et al. (2013) suggest a warm, humid and windy environment for the Late Glacial to Early Holocene with vast littoral areas, favoring the growth of aquatic mosses. The presence of *A. granulata* between 15.60 and 15.05 ka cal. BP also points to warming temperatures and/or turbulent waters as this large and heavily silicified, thread-like colony building centric diatom requests high water turbulence in order to achieve buoyancy (Fernández et al., 2013; Recasens et al., 2015) and remain suspended in the photic zone of the lake (Bradbury and Dieterich-Rurup, 1993). It could therefore be a proxy for high and/or increasing wind speeds during this period. *A. granulata* is described as a taxon of eutrophic epilimnetic and low-light, turbid habitats which tolerates C deficiency and is sensitive to Si depletion (Bradbury and Dieterich-Rurup, 1993; Gómez et al., 1995; Reynolds et al., 2002; Wille et al., 2007; Massaferro et al., 2013). Wille et al. (2007) also suggest higher temperatures in combination with increased wind speeds in the steppe surrounding Laguna Potrok Aike starting around 14.60 ka cal. BP.

The time interval between 15.05 and 12.81 ka cal. BP (diatom Zone 2) is characterized by oscillations of the lake water level and hence varying habitat availability, lake water conductivity and trophic conditions. Higher lake levels associated with cool oligotrophic freshwater conditions and higher wind activity are alternating with more nutrient-rich water conditions and lower water levels, as well as lower wind speeds. The cyclic pattern displayed by the relative abundances of the centric taxa *C. patagonicus* on the one hand and *D. stelligera* & *D. glomerata*, *Fragilaria* sensu lato spp., *Opephora* spp. and *S. venter* on the other hand in diatom Zone 2 is likely related to variations in the interactions between wind activity, precipitation, temperature and/or hydrological changes (e.g. groundwater input, surface water inflow due to permafrost). These parameters influence directly the lake water balance and hence varying habitat availability, lake water conductivity, trophic conditions and the stratification of the water column. Both diatoms *C. patagonicus* and *D. stelligera* have been found in oligotrophic mountain lakes of western Patagonia, Argentina, with bicarbonate and calcium as predominant ions, water temperatures between 7 and 21 °C, circumneutral to slightly alkaline pH (6.9–7.4), low conductivity (20–60 μS cm^{-1}) and reactive silica concentrations of 7 to 30 mg l^{-1} (Guerrero and Echenique, 2002, 2006). As *D. stelligera* is described as a cosmopolitan and ubiquitous diatom that tolerates a wide range of water bodies and water quality conditions, it can probably better tolerate more extreme water conditions than *C. patagonicus*, a taxon that is currently known only from a few oligotrophic freshwater ecosystems in southern Patagonia (Guerrero and Echenique, 2002, 2006; Recasens et al., 2012, 2015; Massaferro et al., 2013). In diatom Zone 2, higher lake levels associated with cool and more transparent oligotrophic freshwater conditions are indicated by the dominance of *C. patagonicus*, whereas more nutrient-rich waters, lower water levels and a stratified water column are marked by increases in *D. stelligera* & *D. glomerata* and small benthic taxa (e.g. *Fragilaria* sensu lato spp., *Opephora* spp., *S. venter*) (Guerrero and Echenique, 2002, 2006; Wille et al., 2007; Recasens et al., 2012, 2015; Massaferro et al., 2013). High abundances of benthic taxa (e.g. *Fragilaria* sensu lato spp., *Opephora* spp., *S. venter*), indicate greater availability of shallower water habitats and substrates in the littoral zone of lakes (Moser et al., 2000). Furthermore, these associations are supported by the fact that larger and more heavily silicified planktonic diatoms (e.g. *C. patagonicus* with a diameter of 19–30 μm, compared to the significantly smaller *D. stelligera* & *D. glomerata* with diameters of 5–10 μm) are generally favored by more extensive open water (pelagic) zones. They normally need a deeper water column with higher turbulence due to higher wind speeds and/or colder and denser water to stay suspended in the photic zone (Recasens et al., 2012).

During the period from 12.81 to 11.31 ka cal. BP (diatom Zone 3), the water level of Laguna Potrok Aike is still oscillating, however, water temperature as well as nutrient and electrolyte contents seem to have increased. The diatom assemblage of this zone mirrors the same cyclic pattern already observed in Zone 2, except that the abundance of *D. stelligera* & *D. glomerata* increases significantly, probably indicating higher water conductivity and trophic conditions. This observation corroborates the results of Zolitschka et al. (2013), suggesting high lake-levels for the onset of the deglaciation at 17.00 ka cal. BP with a slightly but constant lake-level lowering till 11.60 ka cal. BP. Between 13.60 and 11.10 ka cal. BP (15.34–14.44 m cd), Jouve et al. (2013) observed peaks of Ca/Si, Ca and Mn as well as the presence of the green alga *P. lenticularis*, which has been associated with variations in the ventilation of the water column (Fig. 3). The Ca/Si and Ca peaks in diatom Zone 3 are indeed related to the calcite lorica of *P. lenticularis* (Haberzettl et al., 2007; Jouve et al., 2013). Mild climatic conditions with only relatively weak SWW would have favored the thermal stratification of the waterbody with higher water temperatures in the epilimnion, as *P. lenticularis* only occurs at water temperatures >15.8 °C and prefers alkaline conditions (pH between 8.3 and 9.6). In case of a stratified water column, Mn peaks are suggested to be related to the preservation of diagenetic Mn-oxides due to oxygen depletion in the deep basin (Jouve et al., 2013). Haberzettl et al. (2007) also noted a drier and warmer climate for the zone corresponding to the period between 12.80 and 11.40 ka cal. BP in the pollen diagram of Wille et al. (2007). As no brackish or saline diatoms were encountered in the diatom diagram, the lake level variations during Zones 2 and 3 can be considered as moderate.

Between 11.31 and 10.51 ka cal. BP (diatom Zone 4), the lake level of Laguna Potrok Aike seems to decrease progressively, increasing the availability of littoral habitats as well as the trophic water conditions. In this zone, the proportion of epiphytic diatoms increases at the expense of planktonic taxa while the benthic fraction remains stable. Epiphytic diatoms are associated with littoral lake habitats that support prolific macrophyte growth (Fernández et al., 2013). Enhanced conditions for macrophyte growth may be due to better availability of nutrients and/or light penetration in the water column, as well as expansion of the littoral habitat (Fey et al., 2009). Epiphytic taxa are often the major primary producers and provide an important supply of autochthonous carbon and energy to higher trophic lake levels. Their quantity and productivity are mainly affected by light, temperature, nutrients, wave action, water-level fluctuations and plant architecture. A higher proportion of epiphytic diatoms in the sediment samples could be explained with stronger wind-induced lateral water movements and stronger wave action which favors the transport of macrophytes and epiphytic diatoms from the littoral habitat towards the lake center and coring position, where epiphytic diatoms deposit together with planktonic taxa in the sediment (Bradbury and Dieterich-Rurup, 1993; Fey et al., 2009; Kastner et al., 2010). Furthermore, the abundance of *D. stelligera* & *D. glomerata* steadily increases at the expense of *C. patagonicus*, probably also indicating higher water conductivity and trophic conditions. Even if Zolitschka et al. (2013) assume a stepwise lake-level increase for the time between 11.50 and 10.50 ka cal. BP, diatom assemblages rather point to a continuing lake level lowering with higher availability of littoral habitats and higher trophic water conditions. Our findings corroborate with the observations of Massaferro et al. (2013) for the same period, who also stated a gradual change from high water level and oligotrophic conditions towards more nutrient rich waters and decreasing water levels at the transition between DZ1 and DZ2 of their diatom diagram.

Another important observation is, that for the entire time span from 15.60 to 10.51 ka cal. BP the TOC profile positively mirrors the fluctuations in abundance of planktonic diatoms, particularly *C. patagonicus*, which is the species driving the changes in our diatom diagram, whereas there is a negative correlation between the TOC percentage and periphytic (benthic + epiphytic) diatom abundances (Fig. 3). The gray zones (A, B, C, D, E) are indicating major peaks occurring simultaneously in planktonic diatoms and the TOC profile. Furthermore, zones A, B, C and D in our figure correspond to zones P, a, b and c of Ca/Si, Ca and Mn peaks in Jouve et al. (2013). The increase in mineral and geochemical parameters reflects the presence of turbid conditions due to higher wind activity and less water column stratification (Bradbury and Dieterich-Rurup, 1993). Hausmann et al. (2011) showed that diatom community composition changes in response to mixing of the water column and they argue that diatom-inferred lake circulation reflects wind rather than thermal conditions. As demonstrated in Jouve et al. (2013), the TOC profile between 13.64 and 11.64 ka cal. BP can be used as an indicator of organic matter (OM) preserved in sediments as it is correlated to Mn peaks. Indeed, the hypothesis of oxygen depletion at the water-sediment interface explains the preservation of Mn-oxides and OM in sediments and was favored by Jouve et al. (2013) and Zolitschka et al. (2013). In this context, relatively weak SWW resulted in a stratified water column and subsequent changes in water column dynamics. Though the presence of micropumices is anticipated to subdue the TOC signal between 15.59 and 13.64 ka cal. BP (Jouve et al., 2013), the positive correlation between the TOC values and the abundance of planktonic diatoms, independent of the micropumice presence, suggests that TOC peaks also infer past changes in water column stratifications.

5.2. Implications for the position of the SWW since the Last Glacial

The current position of the SWW belt is located south of Laguna Potrok Aike (Hodgson and Sime, 2010; Lamy et al., 2010; McGlone et al., 2010), while its LGM position (Ledru et al., 2005) was located north of Laguna Potrok Aike (Fig. 4). Throughout the Late Glacial, Laguna Potrok Aike was therefore under the influence of the shifting SWW belt, and its sediment archive is likely to have recorded these changes (Fig. 3). The cyclic pattern in the diatom signal is interpreted accordingly, concomitant with Ca/Si, Ca, Mn and TOC peaks (Jouve et al., 2013), thus proposing a new way of explaining shifts in SWW position during the Late Glacial. For instance, as the position of the SWW influences the water balance at Laguna Potrok Aike (Garreaud, 2007; Mayr et al., 2007), and because high lake levels are associated with wetter climate conditions (more easterly winds) and low lake levels with dryer periods (more westerly winds) (Haberzettl et al., 2005), our study depicts at least five rapid SWW oscillations (gray zones A, B, C, D, E in Fig. 3) at latitude 52°S between the Last Glacial and Early Holocene periods.

Along the deglaciation, several global, hemispherical and regional climatic conditions likely had opposite effects/influences on the position of the SWW. Indeed, increased post-LGM global mean temperature and decreased post-LGM global ice-sheet growth acted as “south-shifters” (Williams and Bryan, 2006; Toggweiler, 2009; Cartwright et al., 2011; Fletcher and Moreno, 2012; Razik et al., 2013), while increased sea-ice cover around Antarctica during the ACR and global cooling during the YD acted as “north-shifters” (Hudson and Hewitson, 2001; Williams and Bryan, 2006). In this context, peaks of planktonic diatoms, in particular those *C. patagonicus*, reveal a higher lake level due to prevailing north-shifters (NS+) whereas those of periphytic (benthic + epiphytic) taxa infer a lower lake level due to prevailing south-shifters (SS+) (Fig. 3), from the beginning of the ACR to the end of the YD. Therefore, transition between the LGM-northward- and the Early Holocene-southward-position of the SWW was interrupted several times by “north-shifters” actors. The post-glacial establishment in a southward position of the SWW seems to have occurred just at the end of the YD chronozone (Fig. 3).

In our diatom diagram, most of the diatom zones (DZ) appear to have a fairly similar duration (DZ1: 600 yr, DZ2a: 1330 yr, DZ2b: 900 yr, DZ3a: 800 yr, DZ3b: 700 yr; DZ4: 800 yr). As the lower limit of DZ1 and the upper limit of DZ4 are not determined by major changes in the diatom assemblages, yet are truncated by the selected sediment section, we have to focus on DZ2 and DZ3. A well-constrained solar cycle of about 900 years (i.e. Sonett, 1984; Stuiver and Braziunas, 1989) could be the origin of such environmental changes. In fact, changes in the position of the SWW are known to be related to sea-ice extent around Antarctica (Hudson and Hewitson, 2001), which in turn is related to temperature conditions in Antarctica. In this case, the ~900 year solar cycle may have induced changes in the position of the SWW belt. Weber et al. (2014) have provided evidence for millennial-scale variability in Antarctic ice-sheet discharge (AID) during the last deglaciation. In particular in Scotia Sea and Antarctica sediment cores, they have recognized five phases of Antarctic ice-sheet discharges. The following AID events are corresponding to our time interval (15.5–10.5 ka cal. BP): AID 6 (14.86–13.94 ka), AID 5 (13.65–13.28 ka), AID 4 (13.04–12.71 ka), AID 3 (12.03–11.78 ka) and AID 2 (11.46–11.00 ka) (Fig. 3). These intervals correlate with ice-rafted debris events in the Scotia Sea that coincide with enhanced iceberg flux from the Antarctic ice-sheet. Because increased sea-ice extent around Antarctica results in a northward movement of the SWW position, we can hence relate AID events to increased precipitation at Laguna Potrok Aike. Indeed, if Laguna Potrok Aike is not influenced by the Westerlies during these events, then the Easterlies transport more humidity and bring more precipitation to the region and the lake. Our planktonic diatom taxa, particularly *C. patagonicus*, are interpreted in terms of higher lake levels and more oligotrophic conditions, which is in agreement with the results presented by Weber et al. (2014). Future scientific research efforts in this region, and around Antarctica, should therefore focus on achieving additional high-resolution analyses on oceanic and atmospheric paleo-circulations, in order to refine the position of the SWW during past interglacials and sudden climate changes.

6. Conclusions

Detailed diatom analyses of the Late Glacial time interval between 15.60 and 10.51 ka cal. BP allowed to distinguish four different diatom

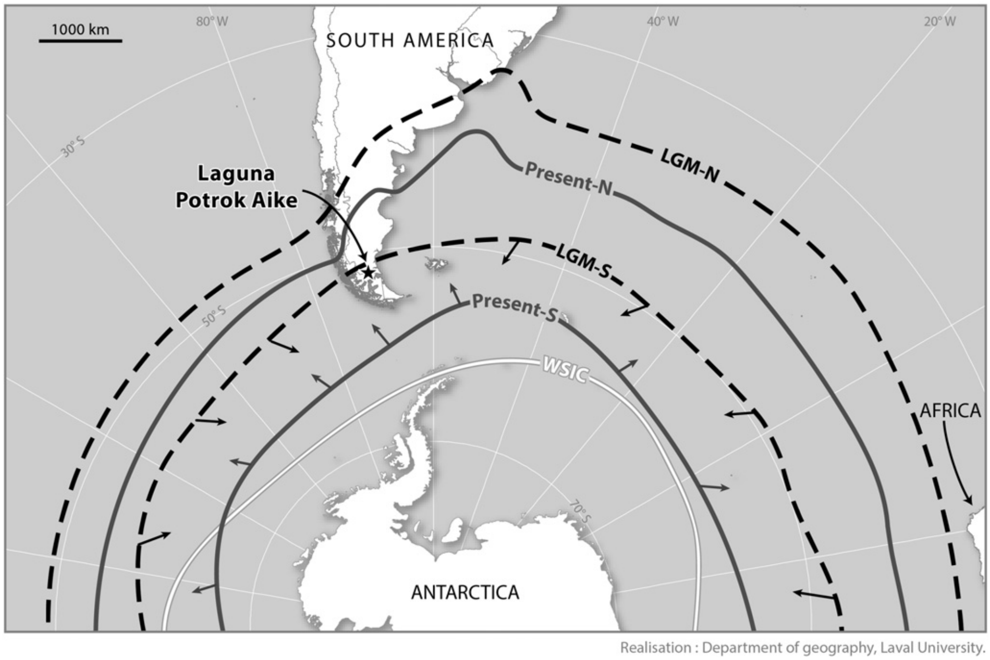

Fig. 4. SeaWiFS (Sea-viewing Wide Field-of-view Sensor) image of ocean color during austral summer with the position of Laguna Potrok Aike; northern and southern limit of the current strongest annual mean winds at 10 m above the surface for the period 1979 to 1999 (modified from Hodgson and Sime (2010); Lamy et al. (2010); McGlone et al. (2010)) (gray lines); the 5–9° migration northwards of the southwesterly winds during the LGM according to Ledru et al. (2005) (black lines); current Winter Sea Ice Cover (WSIC) around Antarctica (white line), according to the NASA Goddard Space Flight Center; the fluctuation zone of the SWW position during the deglaciation (area between gray and black arrows).

zones that correspond to variations in the lake water level of Laguna Potrok Aike, providing evidence for a high lake level stand during most of the Late Glacial period. In this paper, we demonstrated that diatoms are an ideal proxy to complement microsedimentological analyses by providing important independent information on the past limnological dynamics of Laguna Potrok Aike and the paleoclimatic conditions that prevailed in the study area during the Late Glacial. The presence of micropumices has previously been suggested to subdue the TOC signal for the oldest Late Glacial period, i.e. from 15.59 to 13.64 ka cal. BP in Jouve et al. (2013). We now get a better understanding of the variations in the water column ventilation for the entire Late Glacial interval from the positive correlation between TOC values and the abundance of planktonic diatoms. However, as we are not yet able to quantify the impact of diatoms on the TOC signal, this aspect should be investigated in more detail in future studies. Furthermore, the high-resolution study of the PASADO core that combines detailed microsedimentological data with new high-resolution diatom analyses, reinforced the assumption expressed by Jouve et al. (2013) and Zolitschka et al. (2013) that the Late Glacial interval was characterized by relatively high lake levels and weaker SWW, thereby favoring anoxia in the bottom waters of Laguna Potrok Aike. It also revealed a recurrent shifting pattern of the SWW position in southern Patagonia that appears to be related to changes in sea-ice extent and ice-sheet discharge events in Antarctica from the beginning of the ACR to the end of the YD.

Acknowledgments

We would like to thank S. Bustos Hasta for the laboratory preparations and A.-M. Wagner for the assistance with diatom analyses. We are also grateful to S. St-Jacques and L. Marcoux (Department of Geography, Laval University) for providing the geographic figures. This research was supported by the International Continental Scientific Drilling Program (ICDP) within the framework of the “Potrok Aike Maar Lake Sediment Archive Drilling Project” (PASADO). Funding for drilling was provided by the ICDP, the German Science Foundation (DFG), the Swiss National Funds (SNF), the Natural Sciences and Engineering Research Council of Canada (NSERC), the Swedish Research Council (VR) and the University of Bremen. We also acknowledge, the Centre for Northern Studies (CEN) and the Institut National de la Recherche Scientifique – Centre Eau, Terre, Environnement (INRS-ETE) for their technical support. This research was partly financed by grants from the Natural Sciences and Engineering Research Council (NSERC) awarded to R. Pienitz (Discovery grant) and to P. Francus (Discovery and Special Research Opportunity grants).

References

Anderson, R.F., Ali, S., Bradtmiller, L.I., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., Burckle, L.H., 2009. Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO_2. Science 323 (5920), 1443–1448.

Anselmetti, F.S., Ariztegui, D., De Batist, M., Gebhardt, C.A., Haberzettl, T., Niessen, F., Ohlendorf, C., Zolitschka, B., 2009. Environmental history of southern Patagonia unraveled by the seismic stratigraphy of Laguna Potrok Aike. Sedimentology 56 (4), 873–892.

Battarbee, R.W., Kneen, M.J., 1982. The use of electronically counted microspheres in absolute diatom analysis. Limnol. Oceanogr. 27 (1), 184–188.

Blunier, T., Schwander, J., Stauffer, B., Stocker, T., Dällenbach, A., Indermühle, A., Tschumi, J., Chappellaz, J., Raynaud, D., Barnola, J.-M., 1997. Timing of the Antarctic Cold Reversal and the atmospheric CO_2 increase with respect to the Younger Dryas event. Geophys. Res. Lett. 24 (21), 2683–2686.

Bradbury, J.P., Dieterich-Rurup, K.V., 1993. Holocene diatom paleolimnology of Elk Lake, Minnesota. In: Bradbury, J.P., Dean, W.E. (Eds.), Elk Lake, Minnesota: evidences for rapid climate change in the north-central United States. Geological Society of America Special Paper 276, pp. 215–236.

Cartwright, A., Quade, J., Stine, S., Adams, K.D., Brocker, W., Cheng, H., 2011. Chronostratigraphy and lake-level changes of Laguna Cari-Laufquén, Río Negro, Argentina. Quat. Res. 76 (3), 430–440.

Coronato, A., Ercolano, B., Corbella, H., Tiberi, P., 2013. Glacial, fluvial and volcanic landscape evolution in the Laguna Potrok Aike maar area, Southern Patagonia, Argentina. Quat. Sci. Rev. 71, 13–26.

Denton, G.H., Anderson, R.F., Toggweiler, J.R., Edwards, R.L., Schaefer, J.M., Putnam, A.E., 2010. The last glacial termination. Science 328, 1652–1656.

Díaz-P., C., Maidana, N., 2005. Diatomeas de los salares: Atacama y Punta Negra, II Región – Chile. Centro de Ecología Aplicada Ltda. y Minera Escondida Ltda, Santiago, Chile (148 pp.).

Endlicher, W., 1993. Klimatische Aspekte der Weidedegradation in Ost-Patagonien. Geographische Gesellschaft Trierpp. 91–103.

Fernández, M., Björck, S., Wohlfahrt, B., Maidana, N.I., Unkel, I., Van der Putten, N., 2013. Diatom assemblage changes in lacustrine sediments from Isla de los Estados, southernmost South Amerika, in response to shifts in the southwesterly wind belt during last deglaciation. J. Paleolimnol. 50 (4), 433–446.

Fey, M., Korr, C., Maidana, N.I., Carrevedo, M.L., Corbella, H., Dietrich, S., Haberzettl, T., Kuhn, G., Lücke, A., Mayr, C., Ohlendorf, C., Paez, M.M., Quintana, F.A., Schäbitz, F., Zolitschka, B., 2009. Palaeoenvironmental changes during the last 1600 years inferred from the sediment record of a cirque lake in southern Patagonia (Laguna Las Vizcachas, Argentina). Palaeogeogr. Palaeoclimatol. Palaeoecol. 281 (3–4), 363–375.

Fletcher, M.-S., Moreno, P.I., 2012. Have the Southern Westerlies changed in a zonally symmetric manner over the last 14,000 years? A hemisphere-wide take on a controversial problem. Quat. Int. 253, 32–46.

Garreaud, R.D., 2007. Precipitation and circulation covariability in the Extratropics. J. Clim. 20, 4789–4797.

Gómez, N., Riera, J.L., Sabater, S., 1995. Ecology and morphological variability of *Aulacoseira granulata* (Bacillariophyceae) in Spanish reservoirs. J. Plankton Res. 17 (1), 1–16.

Guerrero, J.M., Echenique, R.O., 2002. *Cyclostephanos patagonicus* sp. Nov., a new freshwater diatom from Western Patagonia (Argentina). Diatom Res. 17 (1), 141–151.

Guerrero, J.M., Echenique, R.O., 2006. *Discostella* taxa (Bacillariophyta) from the Río Limay basin (northwestern Patagonia, Argentina). Eur. J. Phycol. 41, 83–96.

Haberzettl, T., Fey, M., Lücke, A., Maidana, N., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M., Zolitschka, B., 2005. Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). J. Paleolimnol. 33 (3), 283–302.

Haberzettl, T., Wille, M., Fey, M., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Zolitschka, B., 2006. Environmental change and fire history of southern Patagonia (Argentina) during the last five centuries. Quat. Int. 158, 72–82.

Haberzettl, T., Corbella, H., Fey, M., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M., Wulf, S., Zolitschka, B., 2007. Lateglacial and Holocene wet-dry cycles in southern Patagonia: chronology, sedimentology and geochemistry of a lacustrine record from Laguna Potrok Aike, Argentina. The Holocene 17 (3), 297–310.

Hahn, A., Kliem, P., Ohlendorf, C., Zolitschka, B., Rosén, P., The PASADO Science Team, 2013. Climate induced changes as registered in inorganic and organic sediment components from Laguna Potrok Aike (Argentina) during the past 51 ka. Quat. Sci. Rev. 71, 154–166.

Hausmann, S., Larocque-Tobler, I., Richard, P.J.H., Pienitz, R., St-Onge, G., Fye, F., 2011. Diatom-inferred wind activity at Lac du Sommet, southern Québec, Canada: a multiproxy paleoclimate reconstruction based on diatoms, chironomids and pollen for the past 9500 years. The Holocene 21 (6), 925–938.

Hodgson, D.A., Sime, L.C., 2010. Southern westerlies and CO_2. Nat. Geosci. 3 (10), 666–667.

Hofmann, G., Werum, M., Lange-Bertalot, H., 2011. Diatomeen im Süßwasser-Benthos von Mitteleuropa. A.R.G. Gantner Verlag, Rugell, Liechtenstein (908 pp.).

Hudson, D.A., Hewitson, B.C., 2001. The atmospheric response to a reduction in summer Antarctic sea-ice extent. Clim. Res. 16 (2), 76–99.

Jouve, G., Francus, P., Lamoureux, S., Provencher-Nolet, L., Hahn, A., Haberzettl, T., Fortin, D., Nuttin, L., The PASADO Science Team, 2013. Microsedimentological characterization using image analysis and m-XRF as indicators of sedimentary processes and climate changes during Lateglacial at Laguna Potrok Aike, Santa Cruz, Argentina. Quat. Sci. Rev. 71, 191–204.

Juggins, S., 2007. User Guide C2. Software for ecological and palaeoecological data analysis and visualisation. User Guide Version 1.5. University of Newcastle, Newcastle upon Tyne, U.K. (73 pp.).

Julius, M.L., Theriot, E.C., 2010. The diatoms: a primer. In: Smol, J.P., Stoermer, E.F. (Eds.), The Diatoms: Applications for the Environmental and Earth Sciences, Second edition Cambridge University Press, Cambridge, United Kingdom, pp. 3–7.

Kaplan, M.R., Moreno, P.I., Rojas, M., 2008. Glacial dynamics in southernmost South America during Marine Isotope Stage 5e to the Younger Dryas chron: a brief review with a focus on cosmogenic nuclide measurements. J. Quat. Sci. 23 (6–7), 649–658.

Kastner, S., Ohlendorf, C., Haberzettl, T., Lücke, A., Mayr, C., Maidana, N.I., Schäbitz, F., Zolitschka, B., 2010. Southern hemispheric westerlies control the spatial distribution of modern sediments in Laguna Potrok Aike, Argentina. J. Paleolimnol. 44 (4), 887–902.

Kilian, R., Lamy, F., 2012. A review of Glacial and Holocene paleoclimate records from southernmost Patagonia (49–55°S). Quat. Sci. Rev. 53, 1–23.

Kliem, P., Enters, D., Hahn, A., Ohlendorf, C., Lisé-Pronovost, A., St-Onge, G., Wastegård, S., Zolitschka, B., The PASADO Science Team, 2013. Lithology, radiocarbon chronology and sedimentological interpretation of the lacustrine record from Laguna Potrok Aike, southern Patagonia. Quat. Sci. Rev. 71, 54–69.

Kohfeld, K.E., Graham, R.M., de Boer, A.M., Sime, L.C., Wolff, E.W., Le Quéré, C., Bopp, L., 2013. Southern Hemisphere westerly wind changes during the Last Glacial Maximum: paleo-data synthesis. Quat. Sci. Rev. 68, 76–95.

Köster, D., Pienitz, R., 2006. Late-Holocene environmental history of two New England ponds: natural dynamics versus human impacts. The Holocene 16 (4), 519–532.

Krammer, K., Lange-Bertalot, H., 1986. Bacillariophyceae. 1. Teil: Naviculaceae. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Süßwasserflora von Mitteleuropa, Band 2/1. Gustav Fischer Verlag, Stuttgart/New York (876 pp.).

Krammer, K., Lange-Bertalot, H., 1988. Bacillariophyceae. 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Süßwasserflora von Mitteleuropa, Band 2/2. Gustav Fischer Verlag, Stuttgart/New York (611 pp.).

Krammer, K., Lange-Bertalot, H., 1991a. Bacillariophyceae. 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. In: Ettl, H., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Süßwasserflora von Mitteleuropa, Band 2/3. Gustav Fischer Verlag, Stuttgart/New York (536 pp.).

Krammer, K., Lange-Bertalot, H., 1991b. Bacillariophyceae. 4. Teil: Achnanthaceae, Kritische Ergänzungen zu *Navicula* (Lineolata) und *Gomphonema*. In: Ettl, H., Gärtner, G., Gerloff, J., Heynig, H., Mollenhauer, D. (Eds.), Süßwasserflora von Mitteleuropa, Band 2/4. Gustav Fischer Verlag, Stuttgart/New York (468 pp.).

Laing, T.E., Pienitz, R., Smol, J.P., 1999. Freshwater diatom assemblages from 23 lakes located near Norilsk, Siberia: a comparison with assemblages from other circumpolar treeline regions. Diatom Res. 14 (2), 285–305.

Lamy, F., Kilian, R., Arz, H.W., Francois, J.-P., Kaiser, J., Prange, M., Steinke, T., 2010. Holocene changes in the position and intensity of the southern westerly wind belt. Nat. Geosci. 3 (10), 695–699.

Le Quéré, C., Rödenbeck, C., Buitenhuis, E.T., Conway, T.J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N., Heinmann, M., 2007. Saturation of the Southern Ocean CO_2 sink due to recent climate change. Science 316 (5832), 1735–1738.

Ledru, M.-P., Rousseau, D.-D., Cruz Jr., F.W., Riccomini, C., Karmann, I., Martin, L., 2005. Paleoclimate changes during the last 100,000 yr from a record in the Brazilian Atlantic rainforest region and interhemispheric comparison. Quat. Res. 64 (3), 444–450.

Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J.C., Yu, Z.C., the INTIMATE group, 2008. Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. Quat. Sci. Rev. 27 (1-2), 6–17.

Maidana, N.I., 1999. *Thalassiosira patagonica* sp. nov. (Thalassiosiraceae, Bacillariophycaea), a new lacustrine centric diatom from Santa Cruz, Argentina. Diatom Res. 14 (2), 323–329.

Maidana, N.I., Round, F.E., 1999. *Corbellia contorta* gen. nov. and sp. nov. (Bacillariophyceae): a new diatom genus and species from Santa Cruz Province, Argentina. Diatom Res. 14 (2), 331–336.

Maidana, N.I., Izaguirre, I., Vinocur, A., Mataloni, A., Pizarro, H., 2005. Diatomeas en una transecta patagónico-antártica. Ecol. Austral 15, 159–176.

Massaferro, J., Recasens, C., Larocque-Tobler, I., Zolitschka, B., Maidana, N., 2013. Major lake level fluctuations and climate changes for the past 16,000 years as reflected by diatoms and chironomids preserved in the sediment of Laguna Potrok Aike, southern Patagonia. Quat. Sci. Rev. 71, 167–174.

Mayr, C., Lücke, A., Stichler, W., Trimborn, P., Ercolano, B., Oliva, G., Ohlendorf, C., Soto, J., Fey, M., Haberzettl, T., Janssen, S., Schäbitz, F., Schleser, G.H., Wille, M., Zolitschka, B., 2007. Precipitation origin and evaporation of lakes in semi-arid Patagonia (Argentina) inferred from stable isotopes ($\delta^{18}O$, $\delta^{2}H$). J. Hydrol. 334 (1–2), 53–63.

Mayr, C., Lücke, A., Maidana, N.I., Wille, M., Haberzettl, T., Corbella, H., Ohlendorf, C., Schäbitz, F., Fey, M., Janssen, S., Zolitschk, B., 2009. Isotopic fingerprints on lacustrine organic matter from Laguna Potrok Aike (southern Patagonia, Argentina) reflect environmental changes during the last 16,000 years. J. Paleolimnol. 42 (1), 81–102.

McGlone, M.S., Turney, C.S.M., Wilmshurst, J.M., Renwick, J., Pahnke, K., 2010. Divergent trends in land and ocean temperature in the Southern Ocean over the past 18,000 years. Nat. Geosci. 3 (9), 622–626.

Moreno, P.I., Francois, J.P., Moy, C.M., Villa-Martínez, R., 2010. Covariability of the Southern Westerlies and atmospheric CO_2 during the Holocene. Geology 38 (8), 727–730.

Moser, K.A., Korhola, A., Weckström, J., Blom, T., Pienitz, R.N., Smol, J.P., Douglas, M.S.V., Hay, M.B., 2000. Paleohydrology inferred from diatoms in northern latitude regions. J. Paleolimnol. 24, 93–107.

OECD, 1982. Eutrophication of Waters. Monitoring, Assessment and Control. Organization for Economic Cooperation and Development (OECD), Paris, France (154 pp.).

Ohlendorf, C., Gebhardt, C., Hahn, A., Kliem, P., Zolitschka, B., 2011. The PASADO core processing strategy — a proposed new protocol for sediment core treatment in multidisciplinary lake drilling projects. Sediment. Geol. 239 (1–2), 104–115.

Ohlendorf, C., Fey, M., Gebhardt, C., Haberzettl, T., Lücke, A., Mayr, C., Schäbitz, F., Wille, M., Zolitschka, B., 2013. Mechanisms of lake-level change at Laguna Potrok Aike (Argentina) — insights from hydrological balance calculations. Quat. Sci. Rev. 71, 27–45.

Oliva, G., González, L., Rial, P., Livraghi, E., 2001. El ambiente en la Patagonia Austral. In: Borrelli, P., Oliva, G. (Eds.), Ganadería Ovina Sustentable en la Patagonia Austral. INTA Centro Regional Patagonia Sur, Buenos Aires, Argentina, pp. 19–82.

Pedro, J.B., van Ommen, T.D., Rasmussen, S.O., Morgan, V.I., Chappellaz, J., Moy, A.D., Masson-Delmotte, V., Delmotte, M., 2011. The last deglaciation: timing the bipolar seesaw. Clim. Past 7, 671–683.

Pienitz, R., Lortie, G., Allard, M., 1991. Isolation of lacustrine basins and marine regression in the Kuujjuaq area, northern Québec, as inferred from diatom analysis. Géog. Phys. Quatern. 45 (2), 155–174.

Razik, S., Chiessi, C.M., Romero, O.E., von Dobeneck, T., 2013. Interaction of the South American Monsoon System and the Southern Westerly Wind Belt during the last 14 kyr. Palaeogeogr. Palaeoclimatol. Palaeoecol. 374, 28–40.

Recasens, C., Ariztegui, D., Gebhardt, C., Gogorza, C., Haberzettl, T., Hahn, A., Kliem, P., Lisé-Pronovost, A., Lücke, A., Maidana, N., Mayr, C., Ohlendorf, C., Schäbitz, F., St-Onge, G., Wille, M., Zolitschka, B., The PASADO Science Team, 2012. New insights into paleoenvironmental changes in Laguna Potrok Aike, southern Patagonia, since the Late Pleistocene: the PASADO multiproxy record. The Holocene 22 (11), 1323–1335.

Recasens, C., Ariztegui, D., Maidana, N.I., Zolitschka, B., The PASADO Science Team, 2015. Diatoms as indicators of hydrological and climatic changes in Laguna Potrok Aike (Patagonia) since the Late Pleistocene. Palaeogeogr. Palaeoclimatol. Palaeoecol. 417, 309–319.

Reynolds, C.S., Huszar, V., Kruk, C., Naselli-Flores, L., Melo, S., 2002. Towards a functional classification of the freshwater phytoplankton. J. Plankton Res. 24 (5), 417–428.

Rumrich, U., Lange-Bertalot, H., Rumrich, M., 2000. Diatoms of the Andes. From Venezuela to Patagonia/Tierra del Fuego. Iconogr. Diatomol. 9, 1–649.

Sabbe, K., Vyverman, W., 1995. Taxonomy, morphology and ecology of some widespread representatives of the diatom genus *Opephora*. Eur. J. Phycol. 30 (4), 235–249.

Saulnier-Talbot, É., Pienitz, R., Vincent, W.F., 2003. Holocene lake succession and palaeo-optics of a subarctic lake, northern Québec (Canada). The Holocene 13 (4), 517–526.

Schäbitz, F., Wille, M., Francois, J.-P., Haberzettl, T., Quintana, F., Mayr, C., Lücke, A., Ohlendorf, C., Mancini, V., Paez, M.M., Prieto, A.R., Zolitschka, B., 2013. Reconstruction of palaeoprecipitation based on pollen transfer functions — the record of the last 16 ka from Laguna Potrok Aike, southern Patagonia. Quat. Sci. Rev. 71, 175–190.

Sigman, D.M., Hain, M.P., Haug, G.H., 2010. The polar ocean and glacial cycles in atmospheric CO_2 concentration. Nature 466 (7302), 47–55.

Sonett, C.P., 1984. Very long solar period and the radiocarbon record. Rev. Geophys. Space Phys. 22 (3), 239–254.

Stuiver, M., Braziunas, T.F., 1989. Atmospheric ^{14}C and century-scale solar oscillations. Nature 338, 405–407.

Sugden, D.E., Bentley, M.J., Fogwill, C.J., Hulton, N.R.J., McCulloch, R.D., Purves, R.S., 2005. Late-glacial glacier events in southernmost South America: a blend of 'northern' and 'southern' hemispheric climatic signals? Geogr. Ann. 87 A (2), 273–288.

ter Braak, C.J.F., Šmilauer, P., 2012. Canoco Reference Manual and User's Guide: Software for Ordination, Version 5.0. Microcomputer Power, Ithaca, USA (496 pp.).

Toggweiler, J.R., 2009. Shifting westerlies. Science 323 (5920), 1434–1435.

Toggweiler, J.R., Russell, J.L., Carson, S.R., 2006. Midlatitude westerlies, atmospheric CO_2, and climate change during the ice ages. Paleoceanography 21 (2), PA2005.

Venables, W.N., Smith, S.M., the R Core Team, 2013. An introduction to R - Notes on R: A Programming Environment for Data Analysis and Graphics, version 3.0.0 (103 pp.).

Weber, M.E., Clark, P.U., Kuhn, G., Timmermann, A., Sprenk, D., Gladstone, R., Zhang, X., Lohmann, G., Menviel, L., Chikamoto, M.O., Friedrich, T., Ohlwein, C., 2014. Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation. Nature 510 (7503), 134–138.

Wille, M., Maidana, N.I., Schäbitz, F., Fey, M., Haberzettl, T., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schleser, H.G., Zolitschka, B., 2007. Vegetation and climate dynamics in the southern South America: the microfossil record of Laguna Potrok Aike, Santa Cruz, Argentina. Rev. Palaeobot. Palynol. 146, 234–246.

Williams, G.P., Bryan, K., 2006. Ice age winds: an aquaplanet model. J. Clim. 19 (9), 1706–1715.

Witkowski, A., Lange-Bertalot, H., Metzeltin, D., 2000. Diatom flora of marine coasts I. Iconogr. Diatomol. 7, 7–925.

Zhu, J., Lücke, A., Wissel, H., Müller, D., Mayr, C., Ohlendorf, C., Zolitschka, B., The PASADO Science Team, 2013. The last Glacial–Interglacial transition in Patagonia, Argentina: the stable isotope record of bulk sedimentary organic matter from Laguna Potrok Aike. Quat. Sci. Rev. 71, 205–218.

Zolitschka, B., Schäbitz, F., Lücke, A., Corbella, H., Ercolano, B., Fey, M., Haberzettl, T., Janssen, S., Maidana, N., Mayr, C., Ohlendorf, C., Oliva, G., Paez, M.M., Schleser, G.H., Soto, J., Tiberi, P., Wille, M., 2006. Crater lakes of the Pali Aike volcanic field as key sites for paleoclimatic and paleoecological reconstructions in southern Patagonia, Argentina. J. S. Am. Earth Sci. 21 (3), 294–309.

Zolitschka, B., Anselmetti, F., Ariztegui, D., Corbella, H., Francus, P., Lücke, A., Maidana, N., Ohlendorf, C., Schäbitz, F., Wastegård, S., 2013. Environmental and climate of the last 51,000 years — new insights from the Potrok Aike maar lake sediment archive drilling project (PASADO). Quat. Sci. Rev. 71, 1–12.