



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



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ABSTRACT

Laguna Potrok Aike is a maar lake located in southernmost Argentina and is one of the few permanent lakes preserving a continuous climatic record from the semiarid Patagonian steppe. Furthermore, its location close to Antarctica provides a unique opportunity to compare paleoclimate from continental South America with the polar records. The analysis of subfossil chironomids and diatoms throughout a 16-m sedimentary record retrieved from this lake, combined with a well-constrained chronology of the last ca 16 ka BP, provided a high resolution paleoenvironmental reconstruction of the limnology of the lake and regional climate conditions. The combination of both bioproxies showed humid conditions during the Lateglacial, followed by drier conditions during the Holocene, resulting in large variations in lake level. Despite not showing a clear evidence of a cold reversal similar to the Antarctic Cold Reversal and/or the Younger Dryas, both records suggest high water levels and oligotrophic conditions between 16.4 and 11.5 cal. ka BP. The lake level drop that occurred at ca 8.7 ka BP is well documented by both bioproxies.

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1. Introduction

In the last twenty years southern South America has become increasingly important in paleoclimatic research due to its exceptional geographic mid- to high latitude location surrounded by the South Pacific, Atlantic and Antarctic oceans. Patagonia is particularly important for monitoring Late Quaternary climate at these latitudes since it is one of the few areas sustaining a suite of vegetation communities along altitudinal and latitudinal gradients within the belt of the southern westerly winds (Whitlock et al., 2001; Gilli et al., 2005; Mayr et al., 2007; Moreno et al., 2009). Such a location is key for investigations related to the reorganization of climate during Late Pleistocene and Holocene times, especially for testing the synchronicity of climate changes in the Northern and Southern Hemispheres and identifying their main drivers in southern Patagonia and the southern latitudes in general.

Most of the climate reconstructions using bioproxies (diatoms, pollen and chironomids) in Patagonian lacustrine records are from glacial lakes located in the subantarctic forest of the northern and central Andes in Chile and Argentina. Those records have contributed toward deciphering multi-millennial changes in temperature and precipitation of westerly origin since Lateglacial times (Cusminsky and Whatley, 1996; Bradbury et al., 2001; Massferro and Brooks, 2002; Massferro et al., 2005, 2007, 2009; Villa-Martínez and Moreno, 2007). In contrast, in the drylands of extra Andean Patagonia the number of paleo-studies is much lower. Among them, the long continuous Lateglacial record of Lago Cardiel was studied for diatoms, pollen and ostracods (Markgraf et al., 2003; Gilli et al., 2005). Several earlier publications from Laguna Potrok Aike (PTA) include pollen and diatom analyses (Wille et al., 2007; Habertzettl et al., 2005, 2007; Recasens et al., in press) and recent Holocene sequences from Laguna Las Vizcachas and Laguna Chaltel include a multi-proxy approach (Quintana et al., in prep.; Massferro et al., 2010).

Despite the increasing number of paleoclimate records recently published, the need for high resolution, well-dated paleoclimate records from sensitive locations, such as extra Andean Patagonia is

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still acute to decipher and quantify the role of past temperature and precipitation for regional climate variability. So far, most of the evidence for climate change in this area of southern South America has been derived from abiotic climate proxies and a few biotic proxies, especially pollen records (Mancini, 2001, 2009; Mancini et al., 2002; Huber et al., 2004; Quintana and Bianchi, 2010). PTA is one of the few permanent lakes enclosing a continuous climatic record from the semiarid Argentinean Patagonian steppe. Its location close to Antarctica makes it a unique place to conduct paleoclimatic research as the area is influenced by shifts in polar and mid-latitude wind and precipitation regimes (Zolitschka et al., 2006). In addition, climate reconstructions from these lakes could be compared with ocean and ice core records from Antarctica to test inter-hemispheric synchronicity. Sedimentological, geochemical and microfossil (pollen, diatoms) records of PTA (Anselmetti et al., 2009; Haberzettl et al., 2007, 2008; Mayr et al., 2007, 2009; Wille et al., 2007; Schäbitz et al., 2013) revealed hydrological variations for this lake during the last ca 16 cal. ka BP and beyond (Kliem et al., 2013). In this context, we propose a paleoenvironmental reconstruction based on the high-resolution analysis of subfossil chironomids and diatoms throughout a 16-m sediment core from PTA. This is the first high resolution chironomid and diatom record from the Patagonian steppe. Wille et al. (2007) partially presented the diatom record of PTA but mainly focused on the pollen record and only four of the main diatom taxa were discussed. In our study, we combine both the complete diatom and chironomid records together with a newly developed chronology (Kliem et al., 2013), with the aim of providing independent lines of evidence for a paleohydrological and paleoenvironmental reconstruction. Additionally, this research will help to better understand environmental changes in southern South America over the past ca 16 cal. ka BP.

Chironomidae (Diptera: Nematocera) are colloquially known as non-biting midges. Most species are stenotopic (i.e. able to adapt only to a narrow range of environmental conditions) and respond rapidly to environmental change. The head capsule, made of chitin, is the only part of the chironomid larvae being preserved in lake sediments and is used for paleolimnological studies. Chironomids are now well established as paleoecological indicators and have been used effectively to document changes in salinity (Heinrichs et al., 2001), lake productivity (Brodersen and Quinlan, 2006),

water level changes (Luoto, 2010), and past climate from Lateglacial to the last millennium (e.g., Brooks and Birks, 2000; Larocque and Hall, 2004; Larocque-Tobler et al., 2010). Fluctuations in lake level influence littoral and profundal areas causing changes in the composition and distribution of chironomid assemblages (Hofmann, 1988; Korhola et al., 2000; Massafiero and Brooks, 2002), it is thus possible to identify periods of lake level changes by looking at changes in the chironomid assemblages (Hofmann, 1988; Millet et al., 2007).

Diatoms are unicellular microscopic algae with siliceous cell walls (frustules). They are ubiquitous, occurring in almost all aquatic habitats, and due to their resistant walls, are often very well preserved in sediments. The use of diatoms in well-dated sedimentary records is an excellent tool to characterize past environmental changes. Diatom communities reflect lake water quality, since their floristic composition and productivity is sensitive to variations in pH, alkalinity, nutrient status, and salinity (Battarbee, 1986). Diatom assemblages preserved in lacustrine sedimentary records reflect the taxocenosis (set of taxa found in a given area) of the former lake diatom communities, informing, indirectly, about lake past water quality. The combination of diatom assemblages with other proxies (e.g., sedimentological, geochemical and biological) helps identifying water-level changes and reconstructing past environmental history (Millet et al., 2007).

Here, the combination of chironomids and diatoms has been used to reconstruct changes in PTA lake water level. This research, which is part of the South Argentinean Lake Sediment Archives and Modelling project (SALSA) and the Potrok Aike Maar Lake Sediment Archive Drilling Project (PASADO) (Zolitschka et al., 2009), helps to understand the key drivers of climate change in the study region and addresses the likely role of the Southern Hemisphere westerly winds and their variations in the past on lake level changes.

2. Regional setting

Laguna Potrok Aike is a maar lake (51°58'S/70°23'W) located in the southernmost Argentinean Patagonian steppe in the Pali Aike volcanic field (Fig. 1). It is part of the dry Patagonian Steppe, in the rain shadow effect of the Andes, and precipitation in the area rarely exceeds 300 mm a⁻¹. This polymictic meso- to eutrophic lake has a maximum water depth of 100 m, a diameter of 3.5 km and its

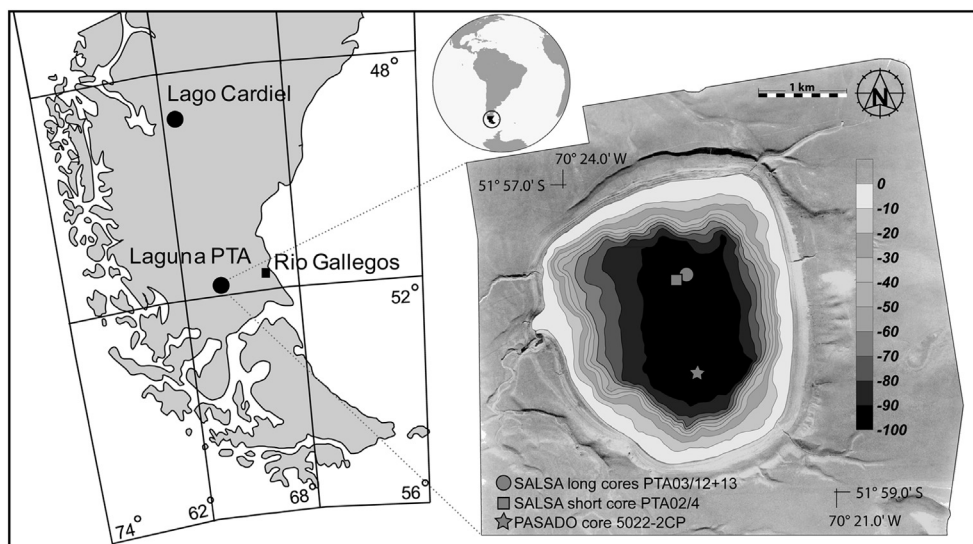


Fig. 1. Map of southern Patagonia showing the locations of Laguna Potrok Aike (PTA) and Lago Cardiel. On the right side, bathymetric map of PTA showing core locations mentioned in the text, the inset shows the geographical location of Patagonia on a world map (modified from Ohlendorf et al., 2011).

catchment area covers over 200 km². Currently it is a closed basin with neither permanent inflow nor outflow, mainly fed by groundwater and episodic spring runoff after snowmelt. Detailed geological and volcanic aspects are discussed elsewhere (Zolitschka et al., 2006; Coronato et al., 2013).

The hydrological balance of southern Patagonia is controlled by the southern westerlies that constitute 50% of the wind influence. At these latitudes, the west coast of the continent (southern Chile) receives abundant precipitation associated with the passage of frontal systems moving eastward from the Pacific. Little moisture is left in these air masses after they cross the southern Andes toward Argentina and the annual mean precipitation decreases to less than 100 mm within 100 km east of the Andean ridge. Downslope winds further contribute to the drying of the Argentinean Patagonia, characterized by a cold, windy steppe (Garreaud et al., 2009). Most of the Pali Aike volcanic field is covered by xeric vegetation dominated by the species *Festuca gracillima* (Wille et al., 2007).

3. Material and methods

Sediment samples analyzed for this study were obtained from a composite profile composed of two parallel and overlapping cores PTA 03/12 and PTA 03/13 and a short core for the top section (PTA 02/04). PTA 03/12 and 03/13 were retrieved from the center of the lake using a UWITEC piston coring system whereas the short core PTA 02/04 was recovered with an ETH gravity corer. These cores were obtained within the framework of the SALSA project during the field campaigns in 2002 and 2003. The stratigraphic correlation of these cores was facilitated by geochemical data (Ca) and photographs which resulted in a 1892 cm long composite stratigraphy that spans the last ca 16 cal. ka BP (Haberzettl et al., 2007). Detailed descriptions of the sites, core lithologies, radiocarbon chronology, and paleoenvironmental evolution are discussed in Mayr et al. (2007, 2009), Haberzettl et al. (2007, 2008) and Wille et al. (2007). The chronology used here is based on the PASADO age model developed by Klien et al. (2013) which was constructed based on 58 AMS ¹⁴C dates of aquatic mosses along the 106.09 m long 5022-2CP composite core. The top 18 m were not sampled for radiocarbon dating, instead ¹⁴C dates from the profile PTA 03/12 + 13 (Haberzettl et al., 2007) were transferred to the top section of core 5022-2CP using lithological features and magnetic susceptibility data to correlate the cores. Calibration of all AMS ¹⁴C data was achieved with the Cal-Pal_2007_HULU calibration dataset (Weninger and Jöris, 2008) and the downloaded version of the CalPal calibration software (Weninger et al., 2010). Validation of the chronology was achieved with geomagnetic relative paleointensity data and tephrostratigraphy. Further details on the full methodology can be found in Klien et al. (2013).

Chironomid and diatom analyses were performed on different samples, taken at different depths in the core, however the high sampling resolution allows for comparison at centennial scale.

A set of 153 samples for chironomid analysis was chosen to obtain approximately one sample for every century while accounting for the changes in accumulation rate (AR). From 0 to 650 cm (AR: 0.89 mm a⁻¹) samples were taken every 10 cm, from 650 to 1300 cm (AR: 6.5 mm a⁻¹) samples were taken every 50 cm and from 1300 to 1900 cm (AR: 0.52 mm a⁻¹) samples were taken every 5 cm.

Samples of 5–10 g were prepared following the methodology of Walker et al. (1991). Sediment was deflocculated using 10% KOH and sieved through 100 and 200 μm meshes. The material retained was hand-sorted from a modified Bogorov counting tray under a dissecting microscope at 25–40× magnification. Individual chironomid head capsules were placed onto microscope slides and mounted using Hydro-Matrix[®] mounting medium. Identifications

were made using a Nikon phase microscope at 400× magnification. Head capsules were identified with reference to available taxonomic literature (Wiederholm, 1983; Cranston and Reiss, 1983) and a Patagonian subfossil chironomid taxonomic identification guide (Massafiero et al., in prep.).

For diatoms, a set of 174 samples with centennial resolution was used. Samples were analyzed at varying spacing along the core, every 8–16 cm on average. The sample treatment and slide preparation were carried out following standard procedures (Battarbee, 1986). A known amount of a solution of microspheres was added to each sample in order to estimate the diatom concentration (Battarbee and Kneen, 1982). The final suspension was mounted onto permanent slides for light microscopy using Naphrax[®]. A minimum of 400 valves was counted per slide at 1000× magnification under oil immersion in order to calculate relative frequencies.

Chironomid and diatom profiles (Fig. 2) were plotted using the software C2 (Juggins, 2003). Chironomid and diatom zones were determined based on a CONISS cluster analysis (Stratigraphically Constrained Incremental Sum of Squares; Grimm, 1987) considering all taxa reaching 3% relative abundance at least in one sample.

4. Results

4.1. Chironomids

Only four genera of chironomids (*Phaenopsectra*, *Cricotopus*, *Smittia* and *Polypedilum*) were recorded in the 153 samples analyzed from PTA sediments. The low number of species is related mainly to the harsh environment in which PTA is located. The hydrological balance of the lake, the winds, the chemical composition of the water and its organic content amongst others, do not favor the development of many species of chironomids. Only the ones that are resistant to those hydrological and atmospheric changes can survive. Four chironomid zones (CZ1–4) were established using the CONISS analysis. While *Phaenopsectra* was registered in 95% of the samples, *Polypedilum* appeared only after ca 9 cal. ka BP and *Smittia* showed a cyclic pattern. *Cricotopus* maximum abundances (60–80%) were recorded in the lower half of the core from 16.2 to 9.5 cal. ka BP. *Polypedilum* appeared in zone 3 and *Cricotopus* gradually declined at stable values of around 40% for the rest of the sequence. *Smittia* showed a clear increase in the last 2000 years, reaching values of near 20% of abundance while the rest of the morpho-taxa remained stable at that time.

Chironomid zone 1, CZ1 (from ca 16.2 to 12.1 cal. ka BP) is clearly dominated by *Cricotopus* reaching values up to 80%, followed by *Phaenopsectra* reaching values of 70% (100% in one sample). The semi-terrestrial *Smittia* is also present during this period, at percentages lower than 20%.

Chironomid zone 2, CZ2 (from ca 12.1 to 9.3 cal. ka BP) is characterized by the decrease of *Cricotopus* from >80% to ca 50%, the increase of *Phaenopsectra* reaching 80% and the near disappearance of *Smittia*.

During Chironomid zone 3, CZ3 (from ca 9.3 to 5.5 cal. ka BP), *Polypedilum* appears and reaches a maximum abundance of 60% between 8 and 7 cal. ka BP. This *Polypedilum* peak is coincident with low abundances of *Cricotopus* and *Phaenopsectra* (20%) but also with a first maximum in the total number of head capsules (HC). Despite its low abundance, several occurrences of *Smittia* are observed during this zone.

Chironomid zone 4, CZ4 spans from ca 5.5 cal. ka BP up to the present (AD 2002, year when the core was retrieved). From 3.5 to 2 cal. ka BP the total HC attained its second maximum value (50–70 HC). Although not statistically significant a zone within CZ4 between 1.3 and 0.7 is obvious with decreases in the total number

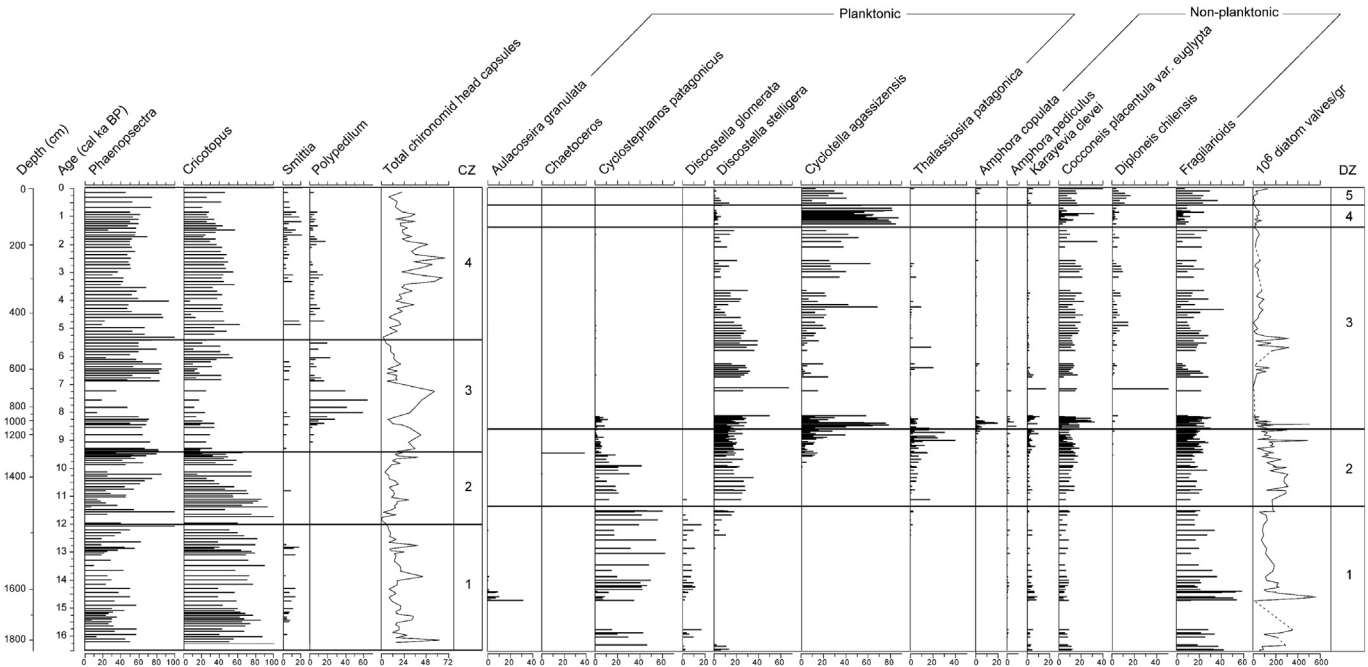


Fig. 2. Chironomid total head capsules (HC), diatom valves concentrations and the taxonomical relative abundances (%) of each proxy from the studied PTA core. Data is plotted against age, following the PASADO age/depth model (Kliem et al., 2013). Chironomid zones (CZ) and diatom zones (DZ) were determined based on a CONISS cluster analysis on the different species relative abundances.

of head capsules, *Phaenopsetra* and *Cricotopus* and an increase in *Smittia* near to 20%. Toward the end of the zone at ca 500 cal BP, a decrease in the overall chironomid fauna is observed by a low number in HC.

4.2. Diatoms

The quantitative analysis of 174 samples reveals a diatom abundance ranging between 2×10^6 and 565×10^6 valves g^{-1} dry sediment (Fig. 2). Diatom abundances are generally higher before ca 8.3 cal. ka BP. Any gap in the diagram is due to differential sample resolution along the record and not to a lack of diatom valves in the sample. Based on the CONISS cluster analysis five main diatom zones (DZ1–5) were identified and are shown in Fig. 2. While non-planktonic taxa remained relatively stable throughout the record, the planktonic communities underwent major changes during the last 16 cal. ka BP. *Cyclostephanos patagonicus* and *Discostella glomerata*, dominating the plankton in zones DZ1 and DZ2 slowly declined in favor of *Cyclotella agassizensis* and *Discostella stelligera* in zones DZ3 to DZ5. *D. stelligera* is a cosmopolitan planktonic species that occurs in a wide range of water bodies and tolerates different water quality conditions.

Diatom Zone 1, DZ1 (from ca 16.4 to 11.3 cal. ka BP), is characterized by the dominance of *C. patagonicus*, which occurs from the bottom of the record to ca 11.5 cal. ka BP with approximate values of 40%. *D. glomerata* occurs with values between 0 and 17% up to ca 11.1 cal. ka BP and disappears thereafter. *D. stelligera* is poorly represented in this zone; it is present at the bottom of the record with values under 20%, then disappears, and occurs again at the top of the zone with values ca 20%. *Aulacoseira granulata* only occurs in significant amounts in this zone, reaching a maximum value of 31.7% at ca 14.7 cal. ka BP, then decreasing and disappearing almost completely after 11.8 cal. ka BP. A peak in small fragilarioid taxa (mostly consisting of the species *Staurosira venter*, *Staurosirella pinnata*, and *Pseudostaurosira brevistriata*) is observed at ca 14.4 cal. ka BP, reaching values of 58.77%. The record of *Thalassiosira*

patagonica starts at the top of this zone but never reaches values above 3% here.

Diatom Zone 2, DZ2 (from ca 11.3 to 8.6 cal. ka BP), shows a decline of *C. patagonicus* from average values of ca 20–30% up to 9.5 cal. ka BP to less than 10% for the rest of the zone. *D. stelligera* is present throughout the zone with values averaging 30%. *T. patagonica* becomes a dominant taxon and increases to a maximum value of 40.5% at 8.9 cal. ka BP. The record of *C. agassizensis* starts at ca 10 cal. ka BP with 1.3% and reaches a maximum value of 39.6% at ca 8.8 cal. ka BP. *Cocconeis placentula* var. *euglypta* slightly increases in this zone with values averaging 10–15%, compared to 5–10% in the previous zone. An isolated peak of *Chaetoceros* aff. *muelleri* occurs at ca 9.4 cal. ka BP with a value of 38.6%.

In Diatom Zone 3, DZ3 (from ca 8.6 to 1.4 cal. ka BP), *C. patagonica* percentages are low (with a maximum value of 11.5%) and after ca 8 cal. ka BP the species is practically absent in this record. *D. stelligera* reaches a maximum value of 66% at 7.1 cal. ka BP and then declines to values around 20–30% until approximately 3.6 cal. ka BP and decreasing to values averaging 10% for the end of the zone. Percentages of *T. patagonica* dramatically drop to values under 10% with two exceptional peaks of 20.8% and 19.1% at ca 6.4 and ca 5.7 cal. ka BP, respectively. *C. agassizensis* records very high values in this zone reaching 77.8% and 75.0% at ca 8.4 cal. ka BP. A peak of *Diploneis chilensis* reaching 50% of relative abundance occurs at ca 7.2 cal. ka BP, and this species is present onwards in the record with abundances varying between 1 and 16%. From ca 4.5 cal. ka BP and onwards in the record, we observed a high degree of valve dissolution, in particular on *C. agassizensis* and *D. chilensis*.

Diatom Zone 4, DZ4 (from ca 1.3 to 0.6 cal. ka BP), is dominated by *C. agassizensis*, which showed values between 56.3 and 84.2% relative abundance. *T. patagonica* is practically absent in this zone, with maximum values of 0.5%. Toward the end of this zone, *C. agassizensis* slightly declines and the relative abundance of non-planktonic species increases. *D. stelligera* is also present in this zone but with values between 0.3 and 13.6%.

Diatom Zone 5, DZ5 (from ca 0.6 cal. ka BP to AD 2002) is characterized by an increased significance of non-planktonic species, in particular *C. placentula* var. *euglypta*, *D. chilensis* and the small fragilarioid taxa. *D. stelligera* is present in this zone with values under 6%. The abundance of *C. agassizensis* decreases in this part of the record to values between 9.7 and 53.5%. The record of *T. patagonica* starts again in the uppermost sample, with a value of 3.5%.

5. Discussion

This study aims to reconstruct the Lateglacial and Holocene palaeoenvironmental history of Laguna Potrok Aike, based on the analysis of diatom and chironomid assemblages, combined with previous multi-proxy investigations, including sedimentological, geochemical and microfossil studies. The first interesting result to point out from the diatom and chironomid stratigraphies is the consistency in the changes occurring in both biological proxies during the Lateglacial and early-Holocene, as the zones obtained for both records are very comparable (Fig. 2). Both indicators responded almost synchronously to external forcings considering differences in timing due to different sampling intervals. We propose that a combination of wind activity, precipitation, temperature and resulting lake level changes is responsible for these changes.

Diatom and chironomid records suggest that between 16.4 and 11.5 cal. ka BP, lake level was high, and water was fresh and oligotrophic, as indicated by the dominance of *C. patagonicus* (Guerrero and Echenique, 2002; Wille et al., 2007). This species has only been found so far in two locations in Patagonia and seems to develop in freshwater and oligotrophic conditions. The transition between DZ1 and DZ2 is characterized by the gradual change from high level oligotrophic freshwater (indicated by *C. patagonicus*) toward more nutrient rich waters (indicated by *D. stelligera*) and lowering water levels. The presence of *A. granulata* between ca 14.7 and 14.2 cal. ka BP could be associated with warming temperatures (Stoermer, 1993) and/or with water turbulence since this heavy diatom needs turbulent waters to achieve buoyancy. Hence, in this case, this could be an indicator of increasing wind speeds during that period. This is consistent with the increase (<10–20%) in *Smittia*, a semi-terrestrial chironomid (Armitage et al., 1995). Its increase in the record at that time and during the entire CZ1 could be explained by maximum in-wash from the coastal zone due to wind activity and/or increasing rainfall. *Cricotopus* percentages were higher during this zone. The genus comprises many littoral species and species associated with macrophytes (Brooks et al., 2007) which would thrive during high lake levels.

The first peak of the brackish-water diatom *T. patagonica* (Maidana, 1999) at ca 11.1 cal. ka BP, together with the decrease of *C. patagonicus* by that time, is interpreted as the beginning of the lake's salinization and lake level lowering. This transition in the diatom flora is coincident with a change in chironomid assemblage. The disappearance of *Smittia* together with the gradual decrease of the littoral *Cricotopus* and the increase of the more profundal *Phaenopsectra* support the lake level lowering hypothesis from the diatom record. *Phaenopsectra* has also been described as a taxon favored with increase in salinity following a tephra deposit (Araneda et al., 2007) and in the slow-moving areas of the streams with increasing salinity (Tasdemir et al., 2010), which also supports the interpretation of salinization brought by the diatom analysis.

The most abrupt change of the entire record is detected at ca 9.4 cal. ka BP. The appearance of *C. agassizensis* together with a peak of *T. patagonica* is associated with higher salinities (Maidana, 1999; Risberg et al., 1999; Wille et al., 2007). *C. agassizensis* suggests low lake levels, pointing to a lake-level low stand, and consequently more saline conditions around ca 8.4 to 8.3 cal. ka BP. Whether the

species is indicative of lake level and/or salinity is still poorly known, observations in PTA modern water samples showed that *C. agassizensis* was abundant when the lake level was low in 2002 and practically disappeared from the plankton when the lake level was higher in 2004. This interpretation is consistent with the overall decrease of *Cricotopus*, a littoral genus, after ca 9.4 cal. ka BP and the introduction of drought-resistant *Polypedilum* (Armitage et al., 1995) at ca 9 cal. ka BP. This transition is also shown by other proxies (Haberzettl et al., 2007, 2008; Mayr et al., 2007; Wille et al., 2007) like the sudden increase in sedimentation rates, as well as the onset of carbonate precipitation in the lake revealed by total inorganic carbon (TIC) content increasing from nearly 0 to values reaching 2% (Fig. 3; Hahn et al., 2013). A major lake level drop was inferred by Haberzettl et al. (2007) and Anselmetti et al. (2009) at ca 8.6 cal. ka BP but the new PASADO age-depth model suggests an age of 9.3 ± 0.7 cal. ka BP (Kliem et al., 2013).

Around ca 9.4 cal. ka BP a peak of *Chaetoceros muellerii* cells, a typically brackish diatom, occurs. However, the single sample where this diatom is found in significant amounts (52×10^6 cells g^{-1} dry sediment; 38.5%) is embedded in a tephra deposit identified as Hudson tephra (Haberzettl et al., 2007). Therefore, its peak could be associated to the input of this tephra and reworked material from the catchment area into the lacustrine system. The introduction of tephra material in the system would temporarily alter the nutrient and ionic balance of the water column. This peak is also associated with an increase in *Phaenopsectra*, a taxon which has been shown to increase following tephra layers (Araneda et al., 2007).

Between ca 8.7 and 7.3 cal. ka BP sedimentation rates are the highest and geochemical proxies suggest dry conditions with low lake levels (Haberzettl et al., 2007; Anselmetti et al., 2009). Furthermore, the pollen record indicates that this was the driest and windiest part of the Holocene (Wille et al., 2007). The diatom and chironomid records agree with these assumptions, with the highest values of *C. agassizensis* between ca 8.9 and 8.2 cal. ka BP and the sharp increase of *Polypedilum* starting at 9 cal. ka BP, both associated to lower lake levels. The presence of both indicators suggests that the lake level remained low compared to pre-9 cal. ka BP levels. *Polypedilum* is a drought-resistant genus that produces cocoons during phases of desiccation (Armitage et al., 1995). Likewise, the increase of *C. agassizensis*, one of the dominant species in the diatom assemblage after 9 cal. ka BP, and high TIC concentrations were previously associated to low lake levels (Wille et al., 2007).

The gradual decrease of *Polypedilum* and the fluctuations of *Smittia* from ca 6.8 to 4.8 cal. ka BP can be associated to transport of sediments from the lake shore into the lake probably due to increasing precipitation. Around 6.8 cal. ka BP the stepwise lake level increase described by Anselmetti et al. (2009) starts and this event is also documented by other proxies (Haberzettl et al., 2007). This lake-level increase coincides with the increase of diatom cell concentrations in DZ3 (Fig. 3).

From ca 5 cal. ka BP onwards, diatom concentration drops dramatically and stays low (on average 42×10^6 valves g^{-1}) for the rest of the record. The diatom assemblages are dominated by *C. agassizensis* with up to 80% relative abundance. In contrast, the total chironomid head capsules starts to increase. High values of the semi-terrestrial *Smittia* suggest a wide littoral zone due to high lake level. Previous studies (Anselmetti et al., 2009) indicated that high water levels and humid conditions prevailed after 6 cal. ka BP and were synchronous with an increase in the intensity of the west-erlies and a change in the precipitation regime by that time. It is important to mention that during the last ca 4.5 cal. ka BP, most of the big heavily silicified diatoms such as *C. agassizensis* and *D. chilensis* appeared highly eroded. The strong valve dissolution

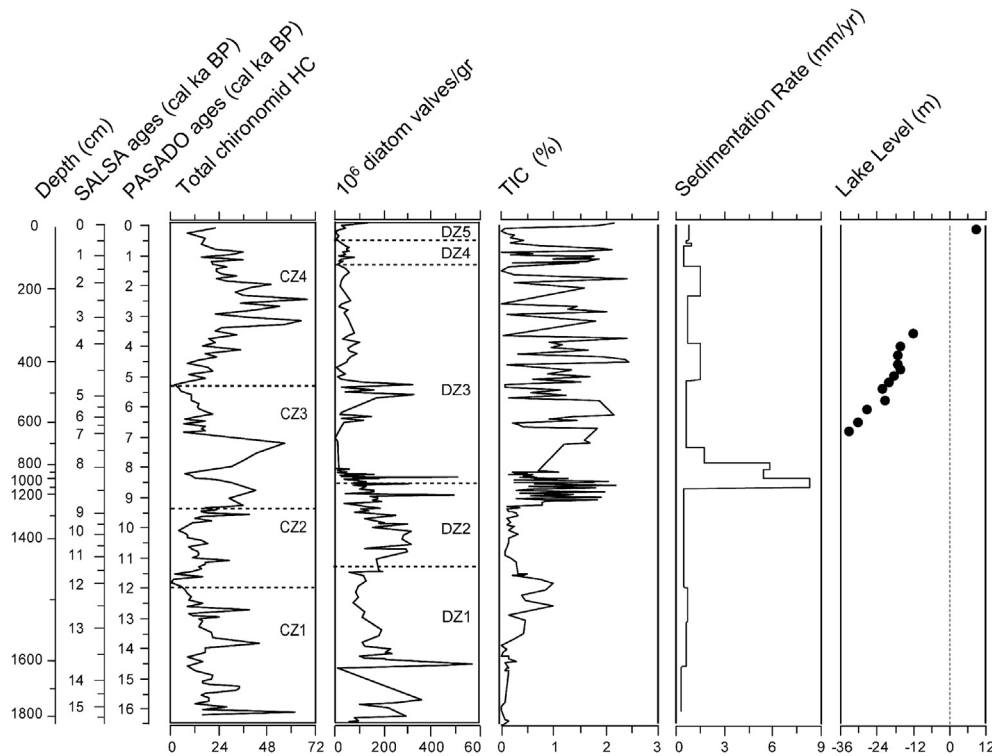


Fig. 3. Comparative diagram showing total chironomids, total diatoms, total inorganic carbon (TIC) and sedimentation rates of Laguna Potrok Aike. Diatom and chironomid total abundances and the TIC profile were plotted using the PASADO chronology (Kliem et al., 2013). Sedimentation rates and lake level variations are based in the previous SALSA age model (cited in Anselmetti et al., 2009).

coupled to the fact that diatom concentration was at its minimum, could imply that smaller taxa might have been partially dissolved and difficult to see and identify, and thus introduce a bias in this analysis. Moreover, pH values in the sediment pore-water are significantly higher in this part of the record (Recasens et al., 2011), which could be a driving mechanism for silica dissolution; further investigations will clarify this matter. Therefore, any paleoclimatic interpretation of this interval must be handled with precaution and contrasted with other proxies. However, both *C. agassizensis* and *D. chilensis* are indicators of brackish conditions (Risberg et al., 1999; Inda et al., 2006) and this assumption is coherent with the brackish character of the lake described for that time (Wille et al., 2007).

5.1. Comparison with other studies in the area

In Lago Cardiel, Gilli (2003) showed that low lake water levels occurred from 16 to 12.6 cal. ka with a desiccation phase at around 13.1 cal. ka BP, covering probably the period of the Lateglacial transition and indicating dry climatic conditions by that time. During the Holocene transition, a massive and rapid lake level rise of about 135 m resulted in water levels reaching the present-day shoreline. Our results show a different situation at PTA. Our data suggests wet conditions during the Lateglacial and the early Holocene. High values of *C. patagonicus* from ca 16.4 to 11.5 cal. ka BP suggest high water levels, humid environments and oligotrophic conditions. The presence of *Smittia* during this time is also indicative of high water levels and rainfall. The occurrence of *A. granulata* and the increase of *Smittia* between ca 14.7 and 14.2 cal. ka BP both reflect increasing wind speeds. The decline of *C. patagonicus* and its slow replacement by the brackish species *C. agassizensis* and *T. patagonica* from ca 12 up to 8.7 cal. ka BP is consistent with the documented lower lake level at that time. The lake reached the

minimum water level recorded ca 8.7 cal. ka BP and this dry period lasted until 6.8 cal. ka BP when lake waters started to increase gradually (Anselmetti et al., 2009). At 4.7 cal. ka BP, the reappearance of *Smittia* it is related to increasing rainfall and humid conditions since that time up to the present. The differences recorded in the hydrological reconstructions of Lago Cardiel and PTA during Holocene times were interpreted as differences in timing of maximum moisture due to differences in latitudinal position and intensity of the southern westerlies (Markgraf et al., 2003; Mayr et al., 2007).

6. Conclusions

This high resolution record of diatom and chironomid assemblages provided a history of paleohydrological changes during the last ca 16 cal. ka BP in Laguna PTA. Diatom and chironomid results combined with the well-constrained chronology of the last ca 16 cal. ka gave information about the limnology of the lake and climate conditions in the area, showing more humid conditions during the Lateglacial followed by increasing wind speeds and lower moisture availability during the early and middle Holocene, resulting in lake level variations. They also confirm the abrupt lake level drop that occurred at ca 8.7 ka BP, previously recorded by other geochemical and sedimentological investigations giving a further signal of warming at these latitudes.

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