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Environment and climate of the last 51,000 years – new insights from the Potrok Aike maar lake Sediment Archive Drilling prOject (PASADO)

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ABSTRACT

In this introductory paper we summarize the history and achievements of the Potrok Aike maar lake Sediment Archive Drilling prOject (PASADO), an interdisciplinary project embedded in the International Continental Scientific Drilling Program (ICDP). The stringent multiproxy approach adopted in this research combined with radiocarbon and luminescence dating provided the opportunity to synthesize a large body of hydrologically relevant data from Laguna Potrok Aike (southern Patagonia, Argentina). At this site, lake level was high from 51 ka until the early Holocene when the Southern Hemisphere Westerlies (SHW) were located further to the north. At 9.3 ka cal. BP the SHW moved southward and over the latitude of the study area (52°S) causing a pronounced negative water balance with a lake level decrease of more than 50 m. Two millennia later, the SHW diminished in intensity and lake level rose to a subsequent maximum during the Little Ice Age. Since the 20th century, a strengthening of the SHW increased the evaporative stress resulting in a more negative water balance. A comparison of our data with other hydrological fluctuations at a regional scale in south-eastern Patagonia, provides new insights and also calls for better chronologies and high-resolution records of climate variability.

1. Introduction

The papers published in this issue originate from the 3rd international PASADO Workshop held in Montreal, Canada, in March 2011 to combine ideas and join efforts of interdisciplinary research teams that feed into the Potrok Aike maar lake Sediment Archive Drilling prOject (PASADO). This workshop brought together not only specialists from three continents with a strong affinity to the multiproxy approach focusing on lacustrine sediment records, but also scientists with different backgrounds such as marine sedimentologists, volcanologists, climatologists and hydrological modellers. Thus, the papers of this issue span a wide field of disciplines covering aspects of Quaternary geology, hydrology, climate modelling and dating techniques. A variety of techniques was applied to the lacustrine deposits from Laguna Potrok Aike including physical properties, (micro-)sedimentological, mineralogical and geochemical but also paleomagnetic and geomicrobiological investigations as well as different paleobiological proxies (pollen, diatoms, chironomids). Some of the publications in this issue use the entire time range available (i.e. the last 51 ka spanning Oxygen Isotope Stages 1–3), others concentrate on the last 16 ka (Lateglacial to Holocene), while two papers focus on high-resolution studies of the Last Glacial-to-interglacial transition. In this introductory paper we summarize the history, scientific background and achievements of PASADO embedded in the International Continental Scientific Drilling Program (ICDP) and highlight new analytical approaches that have been successfully applied to a deep lake drilling project for the first time. Furthermore, the

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papers in this issue are described briefly. In Sections 5 and 6 of this introduction we synthesize the locally derived hydrological data from Laguna Potrok Aike, compare them on a regional scale for south-eastern Patagonia and finally link them with the Southern Hemispheric Westerlies (SHW). This contributes to one of the most challenging scientific debates about climate today: the consequences that SHW position and intensity changes have with regard to the global deep-water circulation and related ocean-to-atmosphere heat and gas fluxes (cf. Anderson et al., 2009; Toggweiler, 2009; Moreno et al., 2010; Fletcher and Moreno, 2012). How this atmospheric forcing operates is still under debate. Understanding the mechanisms that were causing a rapid natural greenhouse gas increase during the Last Glacial and the Lateglacial-to-Holocene transition would allow a much better estimation of the consequences of the currently ongoing human-induced atmospheric greenhouse gas increase.

Today, climate change is a widely used keyword to characterise trends in the annual to decadal scale variability of atmospheric conditions. In large parts due to natural forcing but increasingly modulated by human activities during the Anthropocene (Crutzen and Stoermer, 2000), climate change influences not only temperatures, the hydrological cycle or the biological system but more and more also economic as well as social and thus political systems – the “anthroposphere”. Moreover, a special threat to this anthroposphere is the combination of accelerated natural processes in vulnerable regions inhabited by humans – the natural hazards. In order to develop efficient strategies for mitigating these effects of climate change, it is crucial to better understand the direction future climate conditions might take. As a consequence of the complexity of atmospheric circulation and the resulting climate, predictions have a large degree of uncertainty and are entirely based on the reliability of climate models. To improve the credibility of climate models, their numerical outputs are often tested against climate data of the past and vice versa. However, instrumental records are short (usually in the range of 50–150 years), i.e. too short to account for low- and even medium-frequency natural variability. There is only one way to explore climate system dynamics beyond these instrumental records: the study of natural archives such as lacustrine and marine sediments, ice cores, tree rings, speleothems and corals. In this special issue we report about a continental lacustrine sediment record from Argentinean Patagonia in south-eastern South America (52°S) – an archive of climatic and environmental changes with high temporal resolution. Thus we extend our knowledge about climate variability, trends, events and their respective forcing factors into a climatically very sensitive area.

The site of Laguna Potrok Aike (52°S, 70°W, 116 m asl) is unique as it represents one of the few non-glacial and extra-Andean lake archives studied so far on the continental landmass between subtropical South America (38°S) and Antarctica that covers more than the Holocene and the Lateglacial. This study opens a rare opportunity to reconstruct terrestrial climatic and environmental conditions in an area subject to shifts in polar and mid-latitude wind fields and related hydrological regimes beyond the Last Glacial Maximum (LGM). Air temperatures, precipitation and wind velocities across southern Patagonia are in direct response to the exceptional air-pressure gradient between polar and subtropical southern latitudes as well as to sea-surface temperatures of the southern oceans, sea-ice dynamics and to the extension of continental ice both on Antarctica and in the Andes (Garreaud et al., 2009; Piovano et al., 2009). This complex interaction between terrestrial, marine and glacial environmental systems makes southern South America one of the most interesting and challenging locations on Earth for investigations of climate through time. Data provided for wind intensity, precipitation, hydrological variability and responding environments complement data from oceans and ice cores and offer constraints for climate models. The majority of papers in this issue focus on sediment cores obtained from the PASADO deep drilling carried out in 2008. However, all investigations build on almost a decade of earlier drilling expeditions and pre-site surveys with related analytical and technical advances.

2. PASADO: background, concept and achievements

PASADO is a multinational and interdisciplinary scientific project that has successfully drilled and analysed lacustrine sediment records from a 100 m deep maar lake in the Pali Aike Volcanic Field, of southernmost Argentina (Fig. 1). This project developed from a first field trip to this area guided by Vera Markgraf and the late Platt Bradbury in 1999, which introduced two of us (BZ, FS) to southern Patagonia and thus caught our attention to the potential of its volcanic lakes as a climate archive in this fascinating landscape. Three years later first funds were made available for the “South Argentinean Lake Sediment Archives and modelling” (SALSA) project in the framework of the German Climate Research Program (DEKLIM) to study promising deep crater lakes and dry maars (e.g. Zolitschka et al., 2006). This German project was soon accompanied by a growing number of Argentinean and Swiss research teams, which developed to become a backbone for the later PASADO project. SALSA followed an integrated research strategy for a strictly multidisciplinary study of lacustrine sediments, including monitoring of modern processes and integrating climate and ecosystem modelling. These studies started with short gravity cores in 2002 which convinced us to concentrate on the most promising site: Laguna Potrok Aike (Haberzettl et al., 2005, 2006; Mayr et al., 2005; Zolitschka et al., 2006). During and after the SALSA project, four seismic surveys have been conducted at Laguna Potrok Aike to get hold of the origin and evolution of this maar (Gebhardt et al., 2011) and provide evidence for the highly dynamic lake development since the late Pleistocene (Anselmetti et al., 2009; Gebhardt et al., 2012). Applying these seismic results, coring locations were chosen so that already in 2003 a 19 m long piston core from the lake centre and a 9 m record from a submerged littoral lake-level terrace were recovered. They provide sedimentological and geochemical as well as isotopic and palynological evidence for climatically-induced environmental changes for the lake centre (Haberzettl et al., 2007; Wille et al., 2007; Mayr et al., 2007a, 2009) and unexpected lake-level changes of ca 35 m from the littoral record (Haberzettl et al., 2008). The latter also points to the importance of eolian dust deposition during the Last Glacial (Haberzettl et al., 2009), which was confirmed by common features with marine sediment records from the Scotia Sea, which in turn compare well with Antarctic ice cores (Weber et al., 2012). Also paleomagnetic and rock magnetic (Gogorza et al., 2011, 2012) as well as ^{10}Be investigations (Kim et al., 2012) have been carried out, documenting the suitability of these sediments for multidisciplinary studies. Following the monitoring approach, the modern origin of precipitation and the evaporation of lakes along transects through southern Patagonia was studied to improve our understanding of the paleo-records (Mayr et al., 2007b). Finally, climate models were applied to support our interpretations based on the multiproxy record from this maar lake: (1) transient simulations were compared with empirical reconstructions and forcing mechanisms for the mid-Holocene hydrological climate in Southern Patagonia (Wagner et al., 2007) and (2) ecological reconstructions were linked with the downscaled model output of a global circulation model (GCM) simulation for the time window of the Little Ice Age (Meyer and Wagner, 2009). Moreover, a spatial survey of the lake’s surface sediments was conducted to distinguish areas with

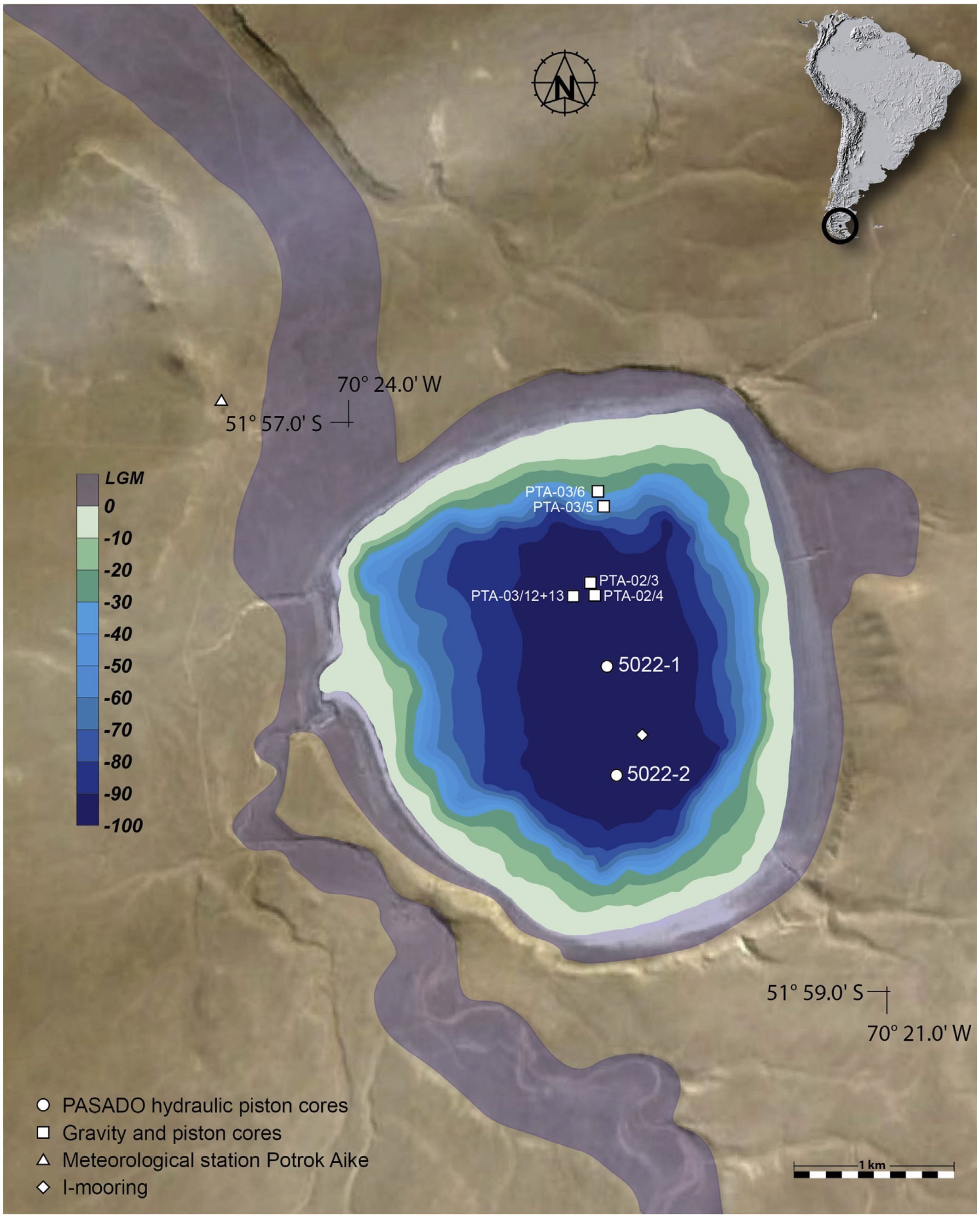

Fig. 1. Bathymetric map of Laguna Potrok Aike merged with a satellite image from Google Earth (obtained in January 2012). Locations of all discussed sediment cores are indicated. The highest possible lake-level was reached with overflow conditions to the north during the LGM and is marked in pink. The inset map of South America shows the location of the studied site. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

redeposition from those with quiet sedimentation (Kastner et al., 2010). The latter, after having been confirmed by seismic data, became the target site for the PASADO deep drilling.

The international project PASADO consists of senior and junior scientists, technicians and logistical operators from six nations (Argentina, Canada, Germany, Sweden, Switzerland and the USA). The project was established within the ICDP and supported by corresponding national financial contributions. Scientific goals formulated in early 2007 focused on understanding climate changes of high and low frequencies during the Last Glacial–interglacial cycles. The assumed time coverage of such a deep drilling was anticipated with 700 ka, based on a preliminary Ar/Ar age on the phreatomagmatic tephra of the maar eruption (Zolitschka et al., 2006). However, a much shorter record has eventually been recovered due to weather-related and technical downtime of the coring equipment (Zolitschka et al., 2009).

The scientific objectives of PASADO were tackled with an integrative approach, combining on-site monitoring with multiproxy reconstructions and modelling efforts. The scientific objectives to be accomplished include:

- Development of a sound chronology for all analyses using radiocarbon and luminescence dating as well as stratigraphic techniques (tephrochronology, paleomagnetics).

- Understanding of proxies by comparing monitoring data of environmental and climatic conditions with the paleo-record.
- High-resolution quantitative reconstruction of climatic variables (temperature, precipitation, hydrological variations) based on biological parameters (chironomids, diatoms, and pollen), stable isotopes and biomarkers.
- Quantitative reconstruction of terrestrial vegetation and fire history applying pollen and charcoal analyses.
- Development of high-resolution dust and volcanic tephra records based on mineralogical and geochemical fingerprints.
- Reconstruction of the paleosecular variation record of the Earth's magnetic field.
- Studying the subsurface biosphere using a geomicrobiological approach to identify microbial activity throughout depth and its relationship with environmental changes in the past.
- Establishing ice core – marine – continental linkages focusing on transitions and periodicities during the Last Glacial and the current interglacial – the Holocene.
- Evaluation of proxy-based hypotheses with GCM climate simulations to establish mechanistic links between climate variability and forcing factors.

To achieve these goals PASADO drilled seven holes in Laguna Potrok Aike (Zolitschka et al., 2009). Drilling was carried out with the Global Lake Drilling to 800 m (GLAD800) coring system operated by the Consortium for Drilling, Observation and Sampling of the Earth's Continental Crust (DOSECC) from September to November 2008 (Fig. 2). All coring was done with the Hydraulic Piston Corer (HPC). Labelled as ICDP expedition 5022, a total of 533 m of cores were taken at two sites: Site 1 (51.96403°S, 70.37595°W) at 98 m water depth was drilled to a maximum hole depth of 100.4 m with 91.1% core recovery and Site 2 (51.97053°S, 70.37551°W) at 95 m water depth to a maximum hole depth of 101.5 m with 98.8% core recovery (Zolitschka et al., 2009). Prior to core opening, core-catcher samples were analysed with an interdisciplinary approach to provide first insights into environmental changes (Recasens et al., 2012). After splitting the cores those from Site 2 were compiled to become the master composite profile (2CP) with its base at a composite depth (cd) of 106.09 m cd.

As a legacy of PASADO there is an archive of well-dated and well-documented lake-sediment samples stored at the University of Bremen, Germany, which are available for further analyses such as the currently ongoing determination of Beryllium isotopes, phytoliths, eolian dust or lipid biomarkers and their isotopes.

3. Methodological advances

Drilling of deep lakes is not only a scientific challenge, even more so, it is a technological quest for constant improvements. During ICDP expedition 5022 the DOSECC platform "Kerry Kelts" in combination with the GLAD800 drill rig reached their limits with PASADO being the last project carried out under this configuration. The moderate water depth of 100 m in combination with considerable wind forces caused multiple failures of the drilling equipment and the anchoring system. DOSECC used these experiences to design and build the new Deep Lake Drilling System (DLDS, 2010),

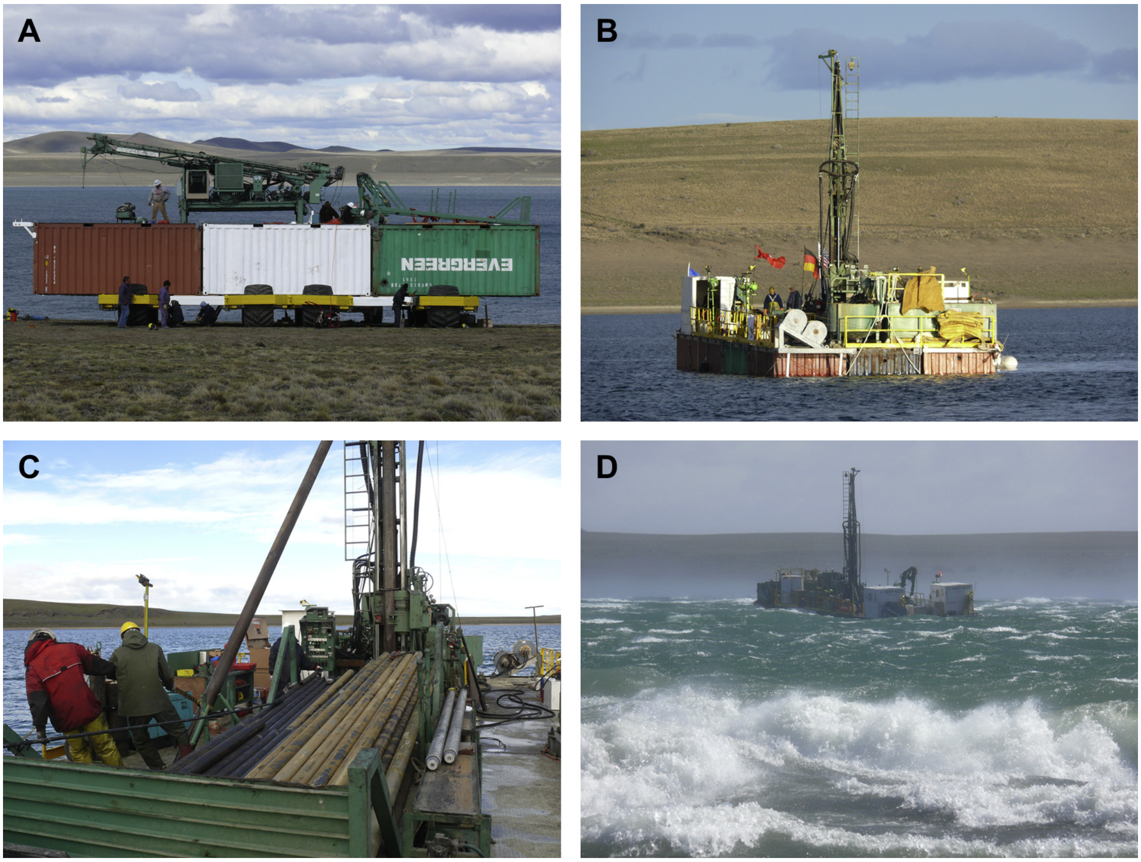

Fig. 2. A: The main obstacle at Laguna Potrok Aike was the lack of harbour facilities as well as the inaccessibility of the lake shore. Thus, the drilling platform was launched in a unique manner with an especially designed carriage. This device allowed assembling the platform on land including drill-rig and other heavy parts of equipment. Then this pre-assembled barge was lowered to a water depth sufficient for flotation. B: Platform "Kerry Kelts" afloat and ready for operation. C: Deep lake drilling at Laguna Potrok Aike. D: Distress at lake – unseasonably strong winds caused us once to abandon the platform.

which made its maiden voyage during the deep lake drilling project on Lake Van, Turkey, in July 2010 (Litt et al., 2012).

For the first time in a deep lake drilling project an *in situ* sampling procedure was developed to recover aseptic samples from sediment cores before their exposition to atmospheric conditions and to determine their biological activity in the field laboratory (Vuillemin et al., 2010). In addition, samples were conserved for transportation to the respective home laboratory where more sophisticated geomicrobiological investigations were carried out to study the role of microbial activity in early diagenetic processes. Characterisation of living microbial groups and the detection of early diagenetic signals produced by these organisms allowed studying links between climate conditions and microbial populations. In a first study of a gravity core covering the last 1500 years with the well-known climatic history at Laguna Potrok Aike (cf. Haberzettl et al., 2005), Vuillemin and Ariztegui (2013) document that microbial activity in the sediments largely depends on past climate via primary production and preservation of organic matter in the sedimentary record. This directly leads to nutrients in lacustrine sediments and their implications on microbial communities with processes of denitrification and methanogenesis being important. Meanwhile, comparable geomicrobial approaches have also been applied to investigate microbial activity from samples obtained in the framework of other ICDP deep drilling projects at Lake Van, Turkey, and at the Dead Sea, Israel.

To provide the best possible scientific output, precisely documented subsampling is the key step. This is actually the most crucial procedure as mistakes that happen during subsampling usually cannot be corrected during any further processing. Thus, decisions taken at this stage often influence the scientific output and interpretation. Therefore, it is important to maintain a certain standard agreed upon by all involved scientific parties. For the International Ocean Drilling Program (IODP) such a standard is accepted practise (Weaver and Schultheiss, 1990; Backman et al., 2006); for ICDP deep lake drilling projects this is not yet the case. Thus Ohlendorf et al. (2011) developed procedures as well as tools for PASADO that allow for a continuous subsampling of undisturbed, uncontaminated and high-quality samples of known volume from identical stratigraphic depths, especially designed for multidisciplinary studies with the demand of many samples from the same depth interval. This protocol has already been applied successfully to the sediment record from another ICDP project (Lake Elgygytgyn) and likely will become a common protocol for upcoming lake drilling projects.

4. Environment and climate of the last 51 ka

Laguna Potrok Aike developed as a volcanic crater (maar) in the Pali Aike Volcanic Field (Province of Santa Cruz, southern Patagonia, Argentina). Ross et al. (2011) investigated the regional volcanology of maar volcanoes while Coronato et al. (2013) surveyed the geomorphology of glacial and volcanological features in this very remote semiarid Patagonian steppe region and discuss their chronostratigraphic relationships based on aircraft and satellite images as well as on a digital elevation model. Glacial and fluvioglacial activity basically ceased since the Middle Pleistocene because glacial advances have not reached this region since ca 800 ka (i.e. during the last eight glacial cycles). There was no major volcanic activity during this period in the Pali Aike Volcanic Field leaving behind an almost fossilised landscape that continued to be shaped only by cryogenic processes and eolian activity, as fluvial incision plays only a minor role in this semiarid region. The survey provides background information for environmental processes that occurred and still occur in the catchment area of the maar lake. One geomorphological feature, most obvious in and around the lake, is the presence of marked lake-level terraces, typical for terminal lakes in dry environments (cf. Zolitschka et al., 2006; Anselmetti et al., 2009). In order to pin down links between their formation and causative hydrological (climatic) variations, a meteorological and limnological monitoring program was set up. The data obtained were used for hydrological balance calculations (Ohlendorf et al., 2013), which document that the lake water table decreased during periods of persistent SHW with high wind speeds and dominant evaporation while it increased when easterly winds occurred more frequently with lower wind velocities (reduced evaporation) and slight increases in precipitation.

Due to its overall cold and semi-arid climatic conditions, Laguna Potrok Aike is one of the very rare lacustrine sites globally, where the carbonate mineral ikaite was detected. It precipitates at temperatures near the freezing point of water and disintegrates rapidly if temperatures increase above +4 °C under atmospheric conditions. Modern ikaite crystals and their pseudomorphs as well as calcite crystals from the sediment record were analysed by mineralogical, scanning electron-microscopic (SEM) and isotopic methods to elucidate their (paleo-) environmental implications (Oehlerich et al., 2013).

For any climatic and environmental reconstruction based on sediment records, dating is of fundamental importance. Only if a well-constrained chronological framework is available, site-specific climatic reconstructions and inter-site correlations with other sites and archives can be developed. This places South America in an excellent position to contribute high-resolution terrestrial climatic records for the improvement of our perceptions about climate evolution in the southern hemisphere. After a detailed lithological description necessary to exclude sections with remobilised sediments from the age/depth model, Kliem et al. (2013a) develop a chronology based on 58 AMS radiocarbon ages providing a calibrated record of 51 ka for Site 2 from Laguna Potrok Aike, which is used throughout the publications of this volume. The age model is validated by geomagnetic paleointensity data and tephrochronology, as the oldest part of the record is at the limits of the radiocarbon dating technique.

To complement lithological descriptions of the sediment record, clay mineralogical analyses were carried out with authigenic, detrital and early diagenetic mineral fractions to shed light on the origin of mineral grains (Nuttin et al., 2013). In addition, for the only relatively abundant diagenetic mineral (vivianite), an attempt was undertaken to carry out U-series dating. However, the very low U fluxes in the sediment did not provide conclusive results.

Luminescence dating was considered from the beginning of PASADO to shed more light especially on the chronology older than 40 ka when radiocarbon reaches its limits. For infrared stimulated luminescence (IRSL), K-feldspar extracts were analysed with a recently developed protocol. Moreover, a new criterion was established to identify and reject poorly bleached samples. Thus it was possible to set up a consistent and independent IRSL-based chronology for the sediment record from Site 1 (Buylaert et al., 2013). As Site 1 has not yet been correlated precisely with Site 2 of Laguna Potrok Aike, merging of results from both numeric dating methods is still an ongoing task and might affect the overall chronology and thus also future interpretations.

One of the best possibilities for inter-site correlation is the detection and analysis of volcanic ash layers. They provide geochemically characterised isochrones, which can be used to establish a regional tephrochronology if directly or indirectly dated. For Laguna Potrok Aike the lack of sufficient K for Ar/Ar dating excludes direct dating of volcanogenic minerals (M. Storey, 2011, pers. comm.). Moreover, dated tephras are mainly published for the Holocene and only very few exist for the Lateglacial. Archives with older ash layers are almost unknown for southern South America.

Therefore, the geochemical characterisation of 18 tephra layers from Laguna Potrok Aike (Wastegård et al., 2013) and their dating contributes to setting up a tephrochronological framework that potentially can be applied to other terrestrial, marine and ice core records to be studied in the future. All tephra layers derive from the Austral Andean Volcanic Zone (AVZ; 49–55°S). Two main groups occur, one group with K_2O contents between ca 1.5 and 2.0 wt% indicating an origin in the Mt. Burney volcano, and one group with K_2O contents between ca 2.7 and 3.9 wt%, tentatively correlated with Viedma or Lautaro and the Aguilera volcanoes in the northern part of the AVZ.

A comparable potential for a vast range of geoscientists is evident from paleomagnetic investigations providing new data to better understand the past global magnetic field variability, to adequately calibrate geomagnetic field models and to constrain the chronology of long sediment cores (Lisé-Pronovost et al., 2013). A high-resolution paleomagnetic record is presented since 51 ka cal. BP, which reveals that large secular variations were recorded during the Laschamp and the Mono Lake geomagnetic excursions in southern South America and thus support their global character. Also documented are two additional directional and intensity changes around 46 and 20 ka cal. BP, both possibly linked to features of the Earth's magnetic field. The former seems to be only observed in the Southern Hemisphere and could develop into a new regional or hemispheric chronostratigraphic marker. Magnetostratigraphy remains to be a promising tool to constrain radiocarbon-based chronologies, at least for specific time intervals (cf. Kliem et al., 2013a).

A combination of the composite sediment record from the lake centre (Kliem et al., 2013a) with seismic surveys in the lake basin (Anselmetti et al., 2009; Gebhardt et al., 2011) and outcrops located on exposed lake-level terraces, enables Kliem et al. (2013b) to develop chronological constraints for lake-level fluctuations since 51 ka and thus a hydrological reconstruction. Time control is provided by a firm tephrochronological correlation between lake-sediment cores and lake-sediment outcrops as well as by additional IRSL ages.

The development of long composite profiles, as they usually were obtained in the framework of ICDP projects, depends on at least one, but better, more data sets with high-resolution and environmental significance. More and more, core-scanning data are used for this purpose as the fastest and most efficient option. The physical property "density" is often used because this parameter integrates sediment porosity, water content, mineralogy, organic content and compaction. Moreover, it is a necessary parameter for calculating sediment flux rates and can be analysed with a variety of core scanners but also conventionally on individual subsamples. In order to investigate, which of the available methods provides the most accurate, fast, reliable and cost-efficient results, Fortin et al. (2013) carried out a study along the 106 m composite record from Site 2 to evaluate the quality of analyses conducted with four different techniques, three of which are non-destructive scanning techniques. All methods applied provide reliable stratigraphic details. However, when it comes to spatial (temporal) resolution, core-scanners operating on split core halves have clear advantages. Their resolution is up to 20 μm, not achievable with discrete sampling. Nevertheless, a spatial resolution of only several centimetres can still provide a high temporal (decadal) resolution for lake-sediment records with sedimentation rates approaching a few millimetres per year. Two constraints with subsampling at highresolution are evident: (1) technical problems with such a subsampling density in combination with a restricted amount of sediment available for multi-proxy analyses, and (2) financial limitations to analyse a large number of samples.

The use of infrared techniques for fast and cost-efficient measurements of biochemical sediment parameters has recently been advanced (Hahn et al., 2011; Rosén et al., 2011) and is now applied with high-resolution to the entire record from Laguna Potrok Aike (Hahn et al., 2013). After calibration of data obtained by Fourier transform infrared spectroscopy (FTIRS), they were interpreted in terms of paleoproductivity that relates to climatic control mechanisms during the past 51 ka. This record with decadal resolution is compared with Antarctic ice cores suggesting that hemispheric warm (Antarctic A) events are documented in our lacustrine record from Patagonia.

Micropaleontological investigations are much more time consuming and thus were carried out with less temporal resolution to date and only for the upper part of the record, i.e. back to 16 ka. In their study of lacustrine biota (diatoms and chironomids), Massaferro et al. (2013) use these organic remains for reconstructing the hydrological history providing independent information about limnology as well as regional climatic and hydrological variations supporting geochemical and sedimentological evidences. Most recent research aims at developing transfer functions for chironomids (Massaferro and Larocque-Tobler, 2013) and diatoms. Once these are established, limnological and climatic parameters will be reconstructed quantitatively, like already now in the palynological study at Laguna Potrok Aike.

Based on modern pollen and climate data, transfer functions are introduced for southern South America and applied to the palynological record of the last 16 ka by Schäbitz et al. (2013). Before using these transfer functions to reconstruct quantitative climate parameters their performance with regard to temperature and precipitation is tested. Best statistical output was obtained for precipitation, while temperature variations are insignificant for the modern data set and thus have to be excluded for the past as well. The precipitation record is the first quantitative palynological approach from Laguna Potrok Aike and will be extended to the entire record once the pollen study is completed.

Two high-resolution contributions focus on the Pleistocene-to-Holocene transition. They refine our understanding of hydro-climatic conditions especially during the Antarctic Cold Reversal (ACR) and the Younger Dryas (YD), i.e. time periods with probably most intense climatic and related environmental changes during the entire time span covered by the PASADO sediment cores. Combining μ-XRF profiles with thin sections and SEM analyses, Jouve et al. (2013) develop ideas about the intensity of water-column mixing that relate to water depth and temperature and confirm that the ACR was colder than the YD on the southern hemisphere.

A similar but slightly extended time interval was analysed by Zhu et al. (2013) for stable isotopes and the composition of bulk organic matter to provide insights into environmental responses at the transition from glacial to interglacial conditions. The environmental instability during this transitional period, as expressed in sedimentary isotope variations, can be linked to the overall warming trend and is modulated by the availability of nutrients and changes in wind stress on the aquatic environment. Since the YD productivity decreased and continued to be low at the onset of the Holocene.

In a modelling approach Pollock and Bush (2013) investigate present and past climatic conditions over southern South America using a mesoscale model nested in a global atmosphere-ocean model. This approach shows that the SHW were shifted northward since the LGM until the onset of the Holocene, which is consistent with reconstructions based on the sediment record from Laguna Potrok Aike if the Lateglacial warming with related calcite precipitation is not linked to intensified SHW. However, as detected by, for example, isotope and FTIRS studies, at least an intensification of the SHW might be interpreted for the early Lateglacial. Also Toggweiler (2009) argues that the SHW moved southward as soon as the warming started after the LGM. Further studies are necessary to better understand the underlying processes.

Altogether, the high-resolution record from Laguna Potrok Aike with its interdisciplinary suite of data provided by the ICDP project PASADO allows developing environmental and climatic reconstructions for this continental region in the southern hemisphere. Southern Patagonia is very susceptible to hydrological fluctuations mainly controlled by precipitation (Ohlendorf et al., 2013; Kliem et al., 2013b; Schäbitz et al., 2013). But there are additional factors that influence the water balance: groundwater (not well explored so far), permafrost (increased runoff) and wind stress (increased evaporation). Especially the factor wind is closely linked to the position and intensity of the SHW, which is currently one of the most important control mechanisms discussed on the interhemispheric climatic asymmetry observed during the late Pleistocene (e.g. Fletcher and Moreno, 2012). Moreover, intensity changes of the SHW are suspected to be one of the major triggers for increased upwelling of deep ocean water, which in turn releases large amounts of CO_2 into the atmosphere during deglaciation (Anderson et al., 2009; Moreno et al., 2010; Toggweiler and Lea, 2010). Therefore, temporal variability of the SHW is an important component of the atmospheric circulation pattern contributing not only to the understanding of past atmospheric composition, but also improves our possibilities to develop more reliable scenarios for the future.

5. Lake level changes since 51 ka

In general, environmental records of closed lakes like Laguna Potrok Aike carry a signature of past variations in the regional hydrological balance (Piovano et al., 2009) and the lake level mirrors the water balance until overflow conditions are reached. Evidences for lake-level fluctuations are outstanding at Laguna Potrok Aike and documented by a sequence of subaerial as well as submerged lake-level terraces (Anselmetti et al., 2009; Gebhardt et al., 2012; Kliem et al., 2013b). Additionally, the observed range (60 m) of lake-level fluctuations for the last 51 ka caused drastic changes in the lake's water body, from a freshwater lake with an outflow in which solutes were diluted to a subsaline lake where dissolved loads built up over time. Increasing salinity as well as a higher pH initiates the formation of chemical precipitates. Such distinct changes are to be reflected in the chemical composition of the sediments.

A good example for the interplay between climate forcing and water balance changes is the Pleistocene-to-Holocene changeover at Laguna Potrok Aike, when sediment facies are characterized by transitions between clastic-dominated (i.e. high-inflow lake conditions, perhaps with an outflow) and carbonate-rich (i.e. terminal lake) conditions:

(1) A clastic system dominates prior to 13.5 ka cal. BP;
(2) Minerogenic sediments are replaced by carbonaceous sediments with chemically and biogeochemically (*Phacotus*) precipitated calcite during the late Pleistocene (13.5–11.5 ka cal. BP);
(3) At the transition from the Lateglacial to the Holocene (11.5 ka cal. BP until 9.3 ka cal. BP) clastic sediments regain dominance (Haberzettl et al., 2007; Kliem et al., 2013a);
(4) Starting at 9.3 ka cal. BP, intense carbonate precipitation (up to 35% calcite) is recorded until 6.9 ka cal. BP. Since then, carbonates continue to be present until modern times but with reduced amounts. There is only one marked interruption recorded by carbonate-free deposits during the neoglacial "Little Ice Age" (LIA; Haberzettl et al., 2005).

Geomorphological observations corroborate these sedimentological and geochemical data with dated lake levels: a high lake level during the LIA, a low lake level during the mid Holocene and highest lake levels with overflow conditions prior to 17 ka cal. BP (Kliem et al., 2013b). These data form the backbone of the lake-level history developed for Laguna Potrok Aike (Fig. 3C) which is complemented by sedimentological and geochemical evidence obtained from the composite stratigraphic record of the lake centre. It also suggests additional lake-level low-stands around 40 ka cal. BP and during the YD, both of which are discussed.

Highest lake levels are documented for 49–44 and 34–17 ka cal. BP by dated outcrops of lacustrine sediments in an elevation linked to the potential outflow (Fig. 3C). The lake-level drop around 40 ka is based on an erosional hiatus between the OSL ages 7 (44 ± 2 ka) and 6 (34 ± 2 ka) which are located in a vertical distance of only 10 cm on top of each other (cf. Table 1 in Kliem et al., 2013b). The assumed lake-level lowering (Fig. 3C) causing the discontinuity between both ages coincides with changes in lacustrine productivity inferred from biogenic silica concentrations (Hahn et al., 2013) as well as with diatom data (Recasens et al., 2012). This indicates a more productive lake related to hydrological changes in the catchment area caused by either shifts to less precipitation or warmer temperatures with increased evaporation linked to Antarctic warm events A1 and/or A2 or a combination of both. Based on the lack of more detailed information, the degree of lake-level lowering in Fig. 3C is only a first assumption. However, its duration is based on exposed and dated lacustrine sediments related to overflow conditions at 34 and 44 ka cal. BP.

The onset of deglaciation in Patagonia around 17 ka cal. BP (Kaplan et al., 2008) is marked in the sediment record of Laguna Potrok Aike by increasing lacustrine productivity evidenced by higher values for organic matter, diatoms and C/N ratios (Hahn et al., 2013) which reflect higher contributions of alloch-thonous organic matter with nutrients from the catchment area probably related to more runoff. Moreover, an abrupt and distinct shift in isotopic values is recognised by Zhu et al. (2013) for the time window 17.3–13.0 ka cal. BP linked to increased lake primary productivity and caused as well by deglacial warming and an elevated nutrient influx. Based on the availability of an only 16,000-year long record prior to 2008, Haberzettl et al. (2007) argue that the lake level was high with overflow conditions from 16 ka cal. BP until the onset of carbonaceous sediments at the beginning of the YD. As the occurrence of *Phacotus* depends on the degree of calcium supersaturation (Schlegel et al., 2000), this was interpreted as the result of a lake-level lowering (Haberzettl et al., 2007). With the longer perspective we have now, the potential lake-level drop culminating in the precipitation of calcite and *Phacotus lenticularis* between 13.5 and 11.5 ka cal. BP that covers the entire YD (a warmer period of the Southern Hemisphere), more likely started with deglaciation at 17 ka cal. BP (Fig. 3C – option 1 and less pronounced also with option 2).

The prominent Lateglacial lake-level lowering as presented with option 1 (Fig. 3C) would require a considerable increase in strength of the SHW in response to deglacial warming. Physically-controlled calcite precipitation would then have occurred during the early Holocene lake-level low-stand. However, diatoms indicate no change towards higher salinity as they do for low lake-level conditions after 9.6 ka cal. BP. Instead, freshwater input is documented by these algae from 16.6 until 9.4 ka cal. BP (Recasens et al., 2012; Massaferro et al., 2013). Moreover, as the SHW are assumed to arrive in southern Patagonia during the early Holocene (e.g. Gilli

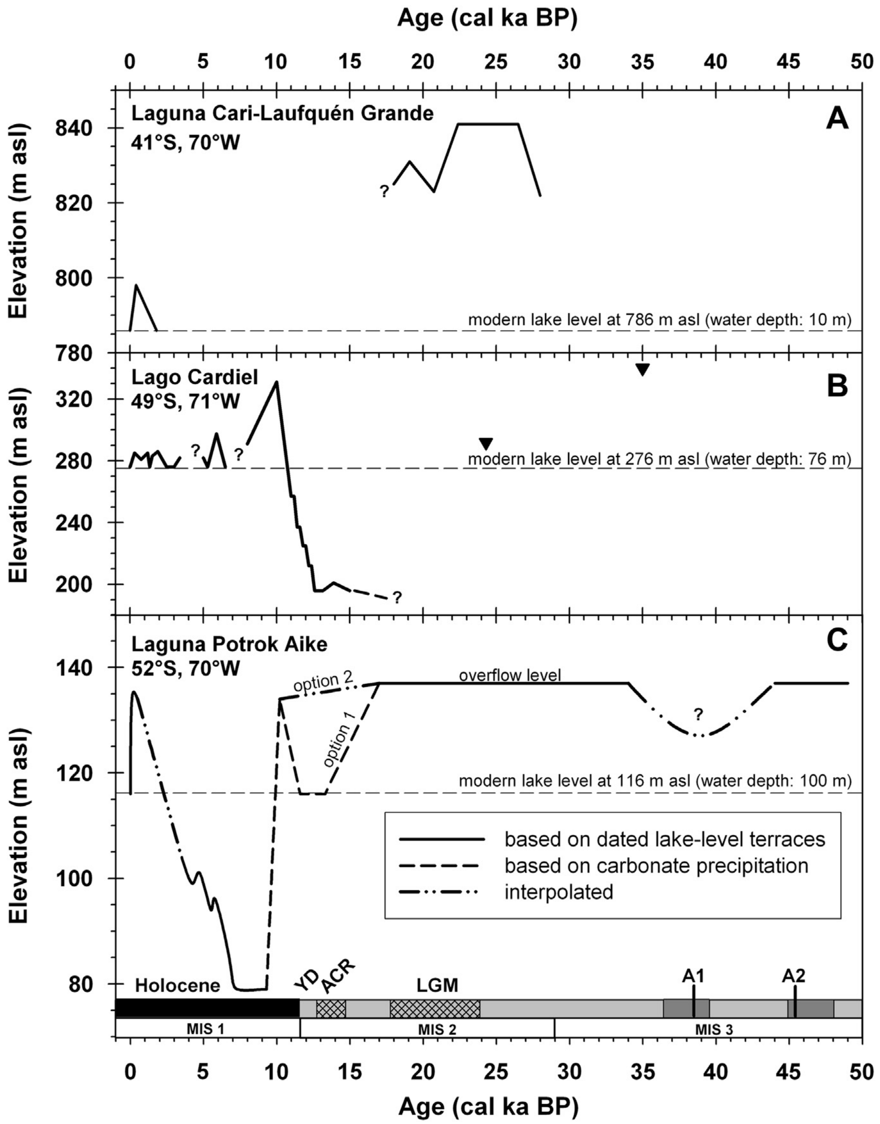

Fig. 3. Discontinuous lake-level histories from A) Laguna Cari-Laufquén (41°S; data from Cartwright et al., 2011) and B) Lago Cardiel (49°S; data from Ariztegui et al., 2010; Gilli et al., 2001) with two Last Glacial lake level high stands (exposed transgressive units) indicated by black triangles (data from Stine and Stine, 1990) compared with the lake-level history for C) Laguna Potrok Aike (52°S; data from Anselmetti et al., 2009; Kliem et al., 2013b). For Laguna Potrok Aike two alternative options for the lake level record are shown for the time interval 17–10.5 ka cal. BP (for explanations: see text). Younger Dryas (YD), Antarctic Cold Reversal (ACR), Last Glacial Maximum (LGM) and peak warmth of Antarctic Warm Events (A1 and A2) are marked as well as marine isotope stages (MIS) according to Lisiecki and Raymo (2005). Two periods with increased productivity as determined by Hahn et al. (2013) are coloured in dark grey.

et al., 2001; Pollock and Bush, 2013) other explanations have to be considered. According to option 2 (Fig. 3C), a more or less constant but only slightly decreasing lake level is suggested for the Lateglacial and calcite precipitation would be of biochemical origin without any necessity of a lake-level lowering. Instead, this would be linked to a lack in strong winds (no SHW) without any constant mixing (polymixis) of the water column during the Lateglacial. Thus the lake became stratified with significantly warmer surface-water temperatures during summer compared with today, when polymictic conditions prevail and cause colder temperatures in the epilimnion throughout the year that rarely exceed 10 °C (Zolitschka et al., 2006). Thus, favourable temperatures in conjunction with a higher availability of nutrients enable an increased lacustrine productivity which in turn causes a higher consumption of CO_2. This is supported by geochemical data (Hahn et al., 2013) as well as by diatoms (Recasens et al., 2012; Massaferro et al., 2013) indicating highest lacustrine productivity during the Lateglacial. Such a productivity-controlled shift of the CO_2 equilibrium in the lake water column caused the precipitation of calcites as well as the formation of calcified organic remains such as *Phacotus*. Comparable processes are well-known and frequently observed elsewhere in modern lake systems (e.g. Bluszcz et al., 2008) but also in early Lateglacial lacustrine settings (e.g. Zolitschka et al., 2000).

The early Holocene is characterised by a change from carbonaceous to clastic sediments between 11.6 and 9.6 ka cal. BP which implies less supersaturation of calcium and thus a more positive water balance. Datable lake-level terraces for these episodes have not yet been detected. Thus, elevations given in Fig. 3C are estimates and remain tentative in their range and duration.

During the early mid-Holocene, starting at 9.6/9.3 ka cal. BP, there is evidence for a considerable decrease of the lake water volume (Anselmetti et al., 2009) which caused a two millennia-long period of above average calcite precipitation. This coincides with reactions of several sediment proxies: (1) appearance of diatoms that indicate a higher degree of salinity (Massaferro et al., 2013), (2) less precipitation reconstructed by pollen transfer-functions (Schäbitz et al., 2013) and (3) increased redeposition of littoral sediments as indicated by higher C/N ratios (Hahn et al., 2013). All these lacustrine data agree with the assumption that the SHW arrived with high wind speeds and increased evaporative power at the latitude of Laguna Potrok Aike causing a negative water balance and the lake level to recede by around 35 m compared with present day. After ca 7 ka cal. BP the lake level increased in a step-wise mode as documented by the 3.5 kHz seismic survey (Anselmetti et al., 2009) until it reached the LIA maximum when overflow conditions are probably reached (Kliem et al., 2013b). Although the carbonate content shows a response to the LIA (no calcite precipitation), there is no clear calcite signal that would allow to infer a rising lake level during the late Holocene. Subsequent to the LIA calcite and documented lake level data indicate drier conditions with a negative water balance for the second half of the 20th century.

6. Causes of water balance changes and the role of Southern Hemispheric Westerlies

Geochemical changes of the sediment record and related hydrological variability (i.e. water balance and lake-level changes) are interconnected and caused by:

(1) Changes in intensity and position of the SHW linked to variations in precipitation;
(2) Temperature and wind-speed control on evaporation;
(3) Changes in runoff due to permafrost sealing of the frozen ground during the Last Glacial;
(4) Lacustrine productivity controlled by temperature and nutrient influx variations;
(5) Seepage of groundwater.

Groundwater is currently an unknown factor, although groundwater recharge was completely different during glacial periods with permafrost-sealed soils compared to interglacials with dominating infiltration. Moreover, the sea-level drop during glacials and its deglacial rise should have modified groundwater flow-dynamics. For the current state of knowledge, however, we have to assume equilibrium between groundwater yields and losses.

During the Last Glacial period, temperatures have generally been lower and the SHW were weaker and shifted northward (Toggweiler, 2009) as modelled by Pollock and Bush (2013). As there is evidence for permafrost in the catchment area of Laguna Potrok Aike (Coronato et al., 2013; Kliem et al., 2013), we assume that sealed ground conditions prevailed at least for some periods of the Last Glacial. These conditions increased surface runoff during snowmelt and decreased infiltration in general. Thus, more surface water was directed into the lake explaining the high lake level while rainfall did not increase considerably (cf. Schäbitz et al., 2013). Such high lake-level conditions are maintained as lower temperatures combined with a more northern position of the SHW decrease evaporation from the lake surface. Additionally, a positive feedback mechanism is related to decreasing temperatures and wind speeds during winter causing the development of an ice cover on the currently ice-free lake which reduced evaporation even further.

The erosional hiatus prior to the LGM at 40 ka cal. BP most likely was formed by a decrease of the lake level and related wave erosion along the shoreline like the dated hiatus observed on the submerged lake-level terrace during the early Holocene (Anselmetti et al., 2009; Haberzettl et al., 2008, 2009). However, the causes were different. The pre-LGM lake-level lowering was not very substantial because there is no indication of carbonate precipitation. As the SHW were too far north to have any influence on southern Patagonia at that time, a change in water balance not related to precipitation is the likely cause for this lake-level lowering. If temperature increased slightly, as indicated by the coincidence of the 40 ka cal. BP lake-level low stand with Antarctic warm events A1/A2 and with an increase in lacustrine productivity (Fig. 3C; Recasens et al., 2012; Hahn et al., 2013), this could have caused a reduced duration of ice cover with increased evaporation. Whether less surface runoff due to an increase in infiltration in response to waning permafrost supported this process is debatable as subsurface permafrost most likely remained during interstadials and thus also increased runoff into the lake.

After 34 ka cal. BP and for the entire LGM until the start of deglaciation at 17 ka cal. BP the lake level seemed to stay at a maximum level (i.e. at or close to overflow; Fig. 3C). At the start of deglaciation around 17 ka cal. BP the lake experienced a drastic reorganisation, which is reflected first by stable isotopes of organic matter and a few centuries later by lacustrine productivity (Hahn et al., 2013; Zhu et al., 2013). The processes responsible could have been similar to those around 40 ka. However, at this stage the lake could have reached a lower level which initiated calcite precipitation during the YD (13–11.5 ka cal. BP) and a lake level comparable to today is assumed (option 1 of Fig. 3C). The ACR cannot be discriminated sedimentologically, while the YD leaves a distinct signal in stable isotopes and geochemistry (Hahn et al., 2013; Zhu et al., 2013). As mentioned earlier, the more realistic option 2 for the lake level history is a less pronounced lake level lowering while the lacustrine ecosystem reached a maximum in productivity causing calcite to precipitate.

At the onset of the Holocene, calcite disappears from the record indicating either a higher lake level (option 1) or no reaction with regard to the lake level at all (option 2). We assume a lake level similar to the LIA for this time (Fig. 3C). Permafrost has disappeared and temperatures increased, making higher runoff and less evaporation unlikely. An increase in precipitation remains as a possible cause, which is also shown in the reconstruction of precipitation based on pollen transfer-functions (Schäbitz et al., 2013). Major precipitation events in the region around Laguna Potrok Aike are related to less intense SHW and cyclones entering the continent from the South Atlantic as easterly winds (Wagner et al., 2007; Mayr et al., 2007a). As the SHW are still situated further north (Pollock and Bush, 2013) and the South Atlantic is losing its sea-ice cover in response to the Holocene warming, more open water is available for evaporation and thus moist air masses eventually found their way onto the continent. For the time between 11.5 and 10.5 ka cal. BP we assume the same stepwise lake-level increase as observed between 7 and 3.5 ka cal. BP (Anselmetti et al., 2009). Similarly, a stepwise lake-level decrease can be assumed for 17–13.5 and for 10.5 until at least 9.3 ka cal. BP.

At 9.3 ka cal. BP the lake level has dropped several tens of metres within less than one millennium and the deposition of endogenic carbonates recommenced. We relate this to the southward migration of the SHW reaching 52°S after the Glacial. Additionally, the insolation maximum was reached around 9 ka cal. BP in the southern hemisphere. The importance of the SHW is also documented by long-distance transport of *Nothofagus* pollen grains from the Andean mountain ranges to the catchment of Laguna Potrok Aike (Mayr et al., 2007a; Wille et al., 2007; Schäbitz et al., 2013). After this pronounced lake-level low-stand that caused the erosional hiatus along the submerged lake-level terrace (Haberzettl et al., 2008, 2009), the lake level experienced a stepwise increase (Anselmetti et al., 2009) after 7 and until ca 3.5 ka cal. BP when the lake level signal at Laguna Potrok Aike started to become uncertain (Fig. 3C).

The mid-Holocene period generally is characterised by cooler and moister climatic conditions for Patagonia from 41°S (Lago Condorito: 7.6–4.1 ka cal. BP; Moreno, 2004) via Laguna Potrok Aike at 52°S to Isla de los Estados at 55°S (8.5–4.5 ka cal. BP; Fernández et al., 2012). The lake-level at Laguna Potrok Aike finally culminates in the LIA high stand (Haberzettl et al., 2005, 2007; Kliem et al., 2013b; Vuillemin and Ariztegui 2013; and many other records from Patagonia cited therein). This was followed by a moderate lake level decrease towards modern conditions.

Regional comparison of the lake-level record from Laguna Potrok Aike (52°S) with two other sites with lake-level records from more northern latitudes of south-eastern Patagonia, i.e. Lago Cardiel (49°S; Ariztegui et al., 2010; Gilli et al., 2001) and Laguna Cari-Laufquén Grande (41°S; Cartwright et al., 2011) provides a framework for a regional synthesis (Fig. 3A–C). Although highest lake levels occurred during the LGM only for Lagunas Cari-Laufquén and Potrok Aike (Fig. 3A, C), in an earlier publication of Stine and Stine (1990) the oldest exposed transgressive units were dated to minimum ages of 35 and 24.3 ka cal. BP for Lago Cardiel (Fig. 3B). A more negative water balance followed until the end of the Lateglacial for the then desiccated Lago Cardiel and Laguna Cari-Laufquén Grande and – if considering option 1 – for the low lake level at Laguna Potrok Aike. The more realistic option 2 for Laguna Potrok Aike indicates a positive water balance until 9.6 ka cal. BP.

The first two millennia of the Holocene for Lago Cardiel and Laguna Potrok Aike are marked by a high lake level followed by a distinct change towards a negative water balance for two millennia (Fig. 3B–C). Since 7 ka cal. BP the lake level at Laguna Potrok Aike rose until the LIA maximum by ca 55 m, while at Lago Cardiel the lake level oscillated between present level and 10 m above current lake level and shows weak responses to the mid-Holocene cool and wet period.

A general mechanical link between the observed hydrological variations and the SHW as the major driving factor is suggested by Garreaud (2007) who determined a covariability of precipitation and westerly circulation. For modern climatic conditions both seem to be highly correlated for the windward western Andes and anticorrelated for the rain shadow east of the Andes. This results in less precipitation for our study area in south-eastern Patagonia during periods with intense westerly winds causing a strong rain shadow effect and vice versa. Thus the positive water balance during the last glacial period can be explained by an equator-ward shift of the SHW in response to the global ice sheet growth (cf. Toggweiler, 2009; Cartwright et al., 2011; Fletcher and Moreno, 2012) which is supported by an increased runoff due to permafrost-sealed soils.

7. Conclusions

Considering this interpretation we suggest a SHW history based on the lake-level record of Laguna Potrok Aike. For this we prefer option 2 for Lateglacial lake-level variations (no lake-level lowstand during the Lateglacial), as this is more plausible than option 1 and supported by diatom-inferred salinity data with no indication of a low lake level and by climate modelling documenting that the SHW were not yet present in south-eastern Patagonia.

During the LGM (and before) lake levels of Laguna Cari-Laufquén Grande (1250 km north of Laguna Potrok Aike), of Lago Cardiel (400 km north of Laguna Potrok Aike) according to Stine and Stine (1990) and of Laguna Potrok Aike were high. Less evaporation resulting from decreased wind intensities due to the northward-shifted SHW (in consequence of lower global temperatures) and increased surface runoff caused by the presence of permafrost are responsible for this positive shift in lake water balance. Support comes from general climatological observations suggesting that rainfall and temperature in arid environments are inversely correlated (Held and Soden, 2006).

With the start of deglaciation around 17 ka cal. BP and continuing until 11.5 ka cal. BP, the lake level of Laguna Potrok Aike stayed high while the two more northern sites became desiccated. This could be interpreted as the result of a southward shift of the SHW not yet reaching the site of Laguna Potrok Aike but present as far south as 49°S. However, the early Holocene lake-level increase at Lago Cardiel could only be explained by easterly winds which require little or weak SHW. There is also a contradiction with modelling results documenting the arrival of SHW as late as during the early Holocene. A more likely explanation would be the prolonged presence of permafrost at the southernmost site (Laguna Potrok Aike) causing more runoff to reach the lake. This is consistent with the transfer of nutrients as evidenced by an elevated lacustrine productivity during the Lateglacial at Laguna Potrok Aike. Precipitation of carbonates during the warmest period of the Lateglacial, the YD, is not the result of a lower lake level but of thermal stratification of the lake water column resulting in higher surface-water temperatures than today. Thus, higher temperature and nutrient levels not only caused an increase in lacustrine productivity but also the biochemical precipitation of calcite during the YD.

At the beginning of the Holocene, precipitation from easterly directions increased for Lago Cardiel and remained stable for Laguna Potrok Aike until the SHW reached southern Patagonia around 9.3 ka cal. BP. This initiated the driest period of the record at Laguna Potrok Aike which continues until 7 ka cal. BP. For Lago Cardiel it is assumed that SHW intensity increased only at 6.8 ka cal. BP (Gilli et al., 2005). However, this discrepancy could be the result of chronological uncertainties, as the entire Holocene at Lago Cardiel is covered by only two radiocarbon ages. Thereafter, SHW progressively lost their strength until the end of the LIA. The latter seems to be the period with weakest SHW since the LGM. It is remarkable to note that high lake levels at Laguna Potrok Aike coincide with high lake levels at Laguna Cari-Laufquén (Fig. 3A, C) which would not be consistent with the assumption that the SHW belt is controlling climatic conditions in southern Patagonia by changing its latitudinal position. In modern times the SHW regained strength.

These data confirm that the anti-phased behaviour between the strength of the SHW and rainfall as observed for modern conditions by Garreaud (2007) also applies for the paleo-record. Moreover, our record matches reasonably well with reconstructions for south-western Patagonia (Moreno et al., 2012) and for the southern hemisphere (Fletcher and Moreno, 2012), if error margins as well as unavoidable dating inaccuracies for all chronologies are considered. However, all interpretations are still premature, as there are no high-resolution chronologies available for any of the discussed records. Moreover, interpretation of the large variety of proxy parameters assumed to represent intensity and/or position of the SHW (here we used agglomerated information to establish a lake-level record), provide a first-order record. It seems that the SHW shifted northward during the Last Glacial and re-established in southern Patagonia during the early Holocene at 9.3 ka cal. BP according to the chronology of Laguna Potrok Aike. Regional mid to late Holocene climate fluctuations in Patagonia, however, appear to have occurred synchronously and thus seem to be related to intensity variations of the SHW (cf. Fletcher and Moreno, 2012).

To achieve the necessary progress in climatic interpretation further effort on well-dated continental climate archives is required to better understand SHW variability and how it causally determined past climate conditions. Elevation data for the lake level reconstruction at Laguna Potrok Aike are accessible via the PANGAEA data archiving and publication system at http://doi.pangaea.de/10.1594/PANGAEA.801641.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2012.11.024.

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