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Crater lakes of the Pali Aike Volcanic Field as key sites for paleoclimatic and paleoecological reconstructions in southern Patagonia, Argentina

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Abstract

Sedimentary records from crater lakes are of major scientific interest because they provide continuous high-resolution climatic and environmental archives. From a limnogeological survey of crater lakes performed in the Pali Aike Volcanic Field (52°S, southeastern Patagonia, Santa Cruz, Argentina), two deep crater lakes have been recognized: Laguna Potrok Aike (100 m water depth) and Laguna Azul (56 m water depth). Physico-chemical analyses of these closed lake systems demonstrate that Laguna Azul has a dimictic and thermally stratified freshwater body, whereas Laguna Potrok Aike is a subsaline polymictic lake. Both have an oxygen-rich water column from top to bottom. Laguna Potrok Aike in particular is enriched in Na, P, and Cl. The morphometry suggests that Laguna Azul is of Holocene age, whereas the potential sediment infill of Laguna Potrok Aike may comprise 250 m to a mid-Pleistocene age (770 ka). Several aerial and subaquatic lake level terraces at Laguna Potrok Aike point to lake level fluctuations triggered by prior hydrological changes. Although fine-grained sediments of both lakes are not varied, they may eventually provide a detailed terrestrial record of past environmental and climatic variations for this southern mid-latitude region.

Keywords: Crater lakes; Limnology; Paleoecology; Limnogeology; Glacial advances; Patagonia; Argentina

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Resúmen

Los registros sedimentarios obtenidos en lagos volcánicos revisten gran interés científico porque proporcionan datos climáticos y ambientales continuos y de alta resolución. Análisis limnogeológicos realizados en lagos volcánicos del Campo Volcánico Pali Aike (52°S, Patagonia austral, Santa Cruz, Argentina, pusieron en evidencia dos profundos lagos volcánicos: Laguna Potrok Aike y Laguna Azul (100 my 56 m de profundidad respectivamente). Los análisis físico-chémicos de estos sistemas lacustres cerrados demuestran que Laguna Azul es un cuerpo de agua dulce dimíctico con estratificación térmica, mientras que Potrok Aike es subsalino y polimíctico. Ambos poseen una columna de agua rica en oxígeno desde la superficie hasta el fondo y especialmente Potrok Aike está enriquecida con Na, P y Cl. La morfometría sugiere que Laguna Azul es de edad Holocena, en tanto que el relleno sedimentario potencial de Potrok Aike podría abarcar 250 my alcanzar una edad Pleistocena media (770 ka). En la Laguna Potrok Aike se identificaron varias terrazas aéreas y subacuáticas que estarían señalando fluctuaciones del nivel del lago, motivadas por

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cambios hidrológicos pretéritos. A pesar de que los sedimentos de grano fino de ambos lagos no son varvados, estos pueden, eventualmente, proveer un registro terrestre detallado de las variaciones ambientales y climáticas pasadas para esta región austral.

Palabras clave: Lagos en cráteres; Limnología; Paleoecología; Limnogeología; Avances glaciarios; Patagonia; Argentina

1. Introduction

Southern South America is the only continental landmass between 38°S and the Antarctic Circle. As such, it presents a unique opportunity to reconstruct terrestrial paleoclimatic conditions in an area subject to shifts in polar and mid-latitude wind (pressure) fields and precipitation regimes, as well as to variations related to the El Niño southern oscillation (ENSO) and Antarctic oscillation (AO). Air temperatures, precipitation, and wind velocities over southern South America (Patagonia) are a direct response to the high meridional air-pressure gradient between 35° and 50°S, as well as to the sea surface temperatures of the southern oceans, sea-ice dynamics, and the ice shields of Antarctica and the Patagonian ice fields. The resulting west wind circulation that advects cold Antarctic air masses to the continent is an important factor that controls climatic conditions over southern Patagonia (Weischet, 1996). Moreover, evidence indicates the ENSO affects climate as far south as 50°S (Depetris and Pasquini, 2000; Diaz et al., 2001). Intense interaction among terrestrial, marine, and glacial environments makes southern South America one of the most interesting locations for investigating the behavior of the climate system throughout time.

The only way to explore climate system dynamics beyond instrumental records is by studying natural archives, such as sediments, ice, trees, and corals. Nearly all terrestrial climate records from southern South America have been restricted to pollen and isotope studies of peat bogs and mires to approximately 16,000 years BP (e.g. Markgraf, 1993; Heusser, 1995; Pendall et al., 2001), whereas ice core data have been available only further north (Thompson et al., 2000) or from Antarctica (e.g. EPICA community members, 2004). These sedimentary records often show low subsampling resolution, and their radiocarbon time control is restricted to a few data points. Tephra layers, important isochronous marker horizons, are present but have not been fully exploited to provide an additional, independent tephrochronological time frame. If dating problems and the factors controlling lacustrine sedimentation processes can be tackled successfully, site-specific climatic reconstructions and intersite correlations could be developed, which would place South America in an excellent position to contribute high-resolution terrestrial climatic records to improve perceptions about climate evolution in the southern hemisphere.

However, in this extremely windy and semiarid region, only lake sediments provide the opportunity to reconstruct continuous records of late Quaternary environmental changes. Lake sediments also can be used as terrestrial dust archives. Due to the common source area of dust in Patagonia (Basile et al., 1997), these archives should correlate with records of terrigenous dust reported from Antarctic ice cores (Petit et al., 1999). Moreover, a correlation with southern ocean paleotemperatures (Becquey and Gersonde, 2003) is likely. Despite their potential, long and high-resolution lacustrine records have rarely been reported from southern Patagonia. Lago Cardiel (Markgraf et al., 2003; Gilli et al., 2005) and Lago Argentino (del Valle et al., 1995) are the only recently studied lakes east of the Andes south of 45°S.

Within the interdisciplinary project ‘South Argentinean Lake Sediment Archives and Modeling’ (SALSA), long and high-resolution paleoenvironmental records are being investigated from the Pali Aike Volcanic Field (Figs. 1–3), an area with several promising deep crater lakes and dry maars. SALSA follows an integrated research strategy for a multidisciplinary study of lacustrine sediments, including monitoring of modern processes in combination with climate and ecosystem modeling. Thus, environmental and climatic conditions in space and time inferred from lacustrine proxy data will result. Such data should improve our understanding of forcing mechanisms on the climate system and help bring forward models and predictions for the future (Valdes, 2000).

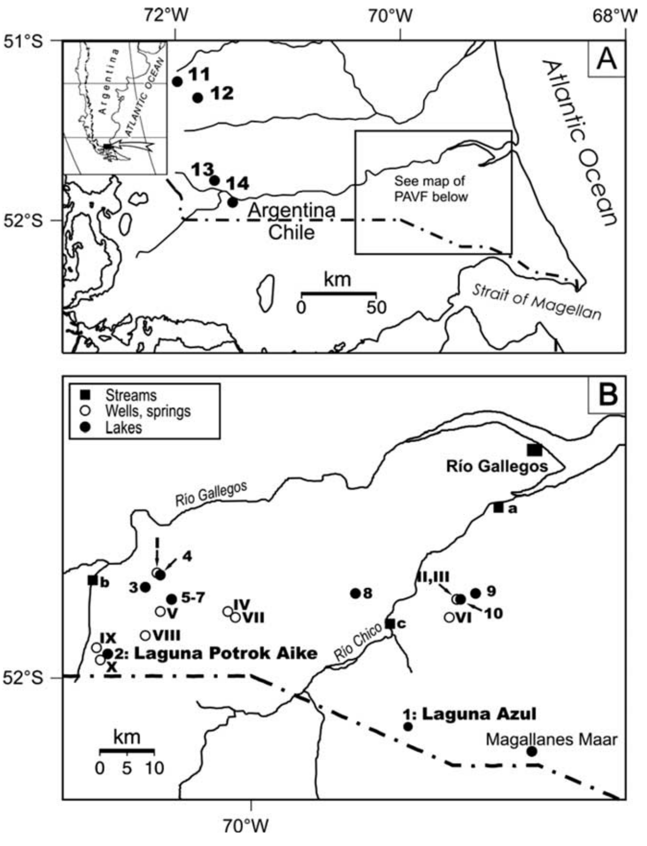

Fig. 1. Investigated area in southern Patagonia (Provincia de Santa Cruz, Argentina) with location of studied lakes; numbers refer to sites listed in Table 3. The Pali Aike Volcanic Field (PAVF) is marked by the frame of B.

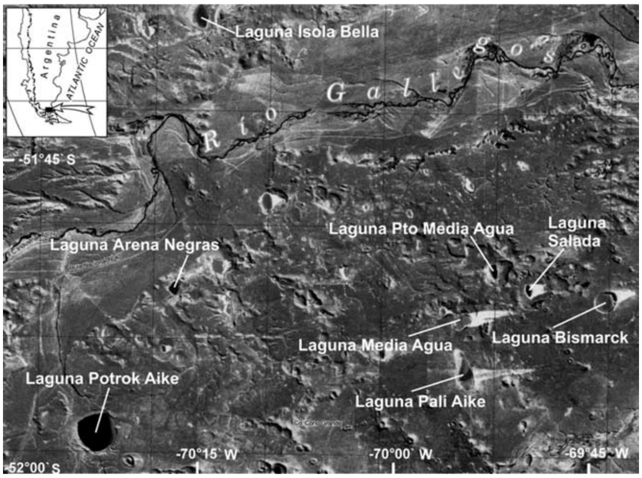

Fig. 2. Satellite image of the Pali Aike Volcanic Field demonstrating permanent and ephemeral lakes, the latter with lee-side accumulations of aeolian sand. Laguna Potrok Aike is marked; Laguna Azul is farther to the west and not on this image.

These investigations are of not only scientific but also economic interest, as the major form of land use in eastern Patagonia is based on extensive sheep farming without hay stocks (Aagesen, 2000). This drought-sensitive economy is extremely vulnerable to short-term climate changes and therefore can benefit from improved climate predictions.

Results from fieldwork in the Pali Aike Volcanic Field carried out in the austral summers of 2002–2005 are presented herein. Following a regional survey, two deep crater lakes, Laguna Azul and Laguna Potrok Aike (Figs. 1–3), were selected for bathymetric, limnological, and initial sedimentological investigations, as well as for monitoring studies. These lakes differ in age, morphometry, and limnology and thus provide an ideal subject for comparative (paleo)limnological studies, similar to those carried out for crater lakes in Ethiopia (Prosser et al., 1968) and Germany (Scharf and Menn, 1992).

2. Area of investigation

The Pali Aike Volcanic Field (52°S, 70°W), located in the Argentine province of Santa Cruz (Figs. 1–3), is comparable in age and the presence of maars to European volcanic fields (Negendank and Zolitschka, 1993). These volcanic provinces, especially the West Eifel Volcanic Field in Germany (e.g. Zolitschka et al., 2000) and the Campanian Volcanic Field in southern Italy (e.g. Zolitschka and Negendank, 1996; Allen et al., 1999), contain long, high-resolution sedimentary records. Therefore, Patagonia should contain deep lakes with a high potential for continuous sedimentary records that cover much more time than the Late- and Postglacial eras. The only sediment record recovered in the Pali Aike Volcanic Field before the start of SALSA was from Magallanes Maar (Fig. 1; Corbella et al., 2000). This 59 m long sediment core from a dry maar covers the last approximately 30,000 years and has a low-resolution diatom and pollen record, indicating distinct fluctuations in water depth and salinity that have been interpreted in terms of summer temperature variations (Maidana and Corbella, 1997; Corbella et al., 2000). Records from permanently water-filled deep crater lakes of this region were lacking and have started to appear only recently in the framework of

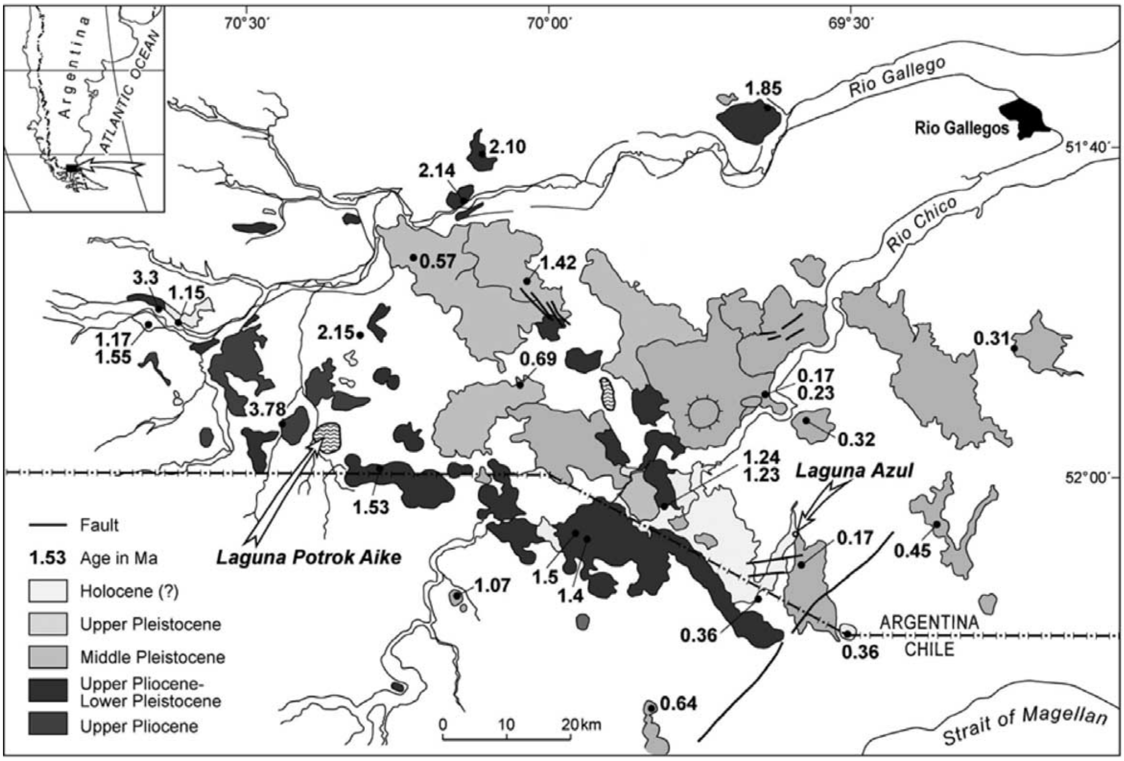

Fig. 3. Volcanic map of the Pali Aike Volcanic Field with radiometric ages of the Pliocene to late Quaternary volcanic backarc (Corbella et al., 2002).

the SALSA project (Zolitschka et al., 2004; Haberzettl et al., 2005, 2006a,b; Mayr et al., 2005).

2.1. Climate and vegetation

The modern climatic conditions of southern Patagonia are very peculiar. Its small landmass does not warm up during the austral summer like continents in the northern hemisphere at comparable latitudes. In addition to the unique distribution of land and sea, this characteristic is mainly due to the relative proximity of the Antarctic continent, which acts as a 'freezer' during the whole year (Weischet, 1996). Large amounts of incoming solar radiation are required to melt the extensive ice shelves in the southern summer. Moreover, cold ocean currents, the Humboldt Current along the west coast and the Falkland Current along the east coast of South America–transport cold water to Patagonian coasts, reducing atmospheric heating further. Thus, the advection of cold air masses to the continent causes cool summers, but the proximity to the oceans promotes mild winters. Moreover, occasional catabatic winds leave Antarctica and add cold air masses to more northerly locations. The temperature decrease related to these so-called polar outbreaks mainly affects more subtropical and tropical regions like Brazil (Marengo and Rogers, 2001). However, polar outbreaks may be of hydrological importance further south if they cause advection of moist air masses from the east to southern Patagonia.

The eastern part of southern Patagonia is a semiarid and cool semi-desert that lacks any well-defined rainy season (Weischet, 1996). A strong precipitation gradient exists between the west and east coasts of South America, caused by the topography of the continent. The southern westerlies transport humid air from the Pacific Ocean to the Andes, leading to annual precipitation of 4000–6000 mm along the west coast (Weischet, 1996). In the rain shadow east of the mountain chain, precipitation decreases to less than 400 mm and, in the Pali Aike Volcanic Field, to less than 300 mm (McCulloch et al., 2000; Gonzalez and Rial, 2004); at the Potrok Aike meteorological station, values of only 150 mm have been observed. In addition to the rainout effect of the Andes, precipitation east of the Andes is influenced by the adiabatic increase of mean annual temperature and, hence, decreased relative humidity. Other processes cannot compensate for this lack of moisture because additional sources of water vapor are absent, and evaporation by xeric plants remains low (Weischet, 1996).

The southern westerlies across Patagonia are characterized by high wind speeds with mean annual values of 7.4 ms^{-1} at Río Gallegos and maxima during the summer (Baruth et al., 1998). Wind direction is primarily from the west, shifting occasionally to NW and SW (Weischet, 1996; Baruth et al., 1998). The instrumental meteorological record of the Río Gallegos weather station exists since 1931 (75 years) but is rather fragmentary. It shows an annual mean precipitation of 251 ± 62 mm (missing values: 11) and a mean annual temperature of 7.4 ± 0.7 °C (missing values: 57), with a July (winter) minimum of $+1.0 \pm 1.5$ °C (missing values: 20) and a January (summer) maximum of 13.0 ± 1.2 °C (missing values: 17). Both mean annual temperature and annual precipitation for the Potrok Aike meteorological station are 30–40% lower than the weather station in the coastal city of Río Gallegos. Although the differences in temperature can be explained by the different degree of continentality, the discrepancy in precipitation may point to an eastern source region for rainfall events that may be related to polar outbreaks.

The strong trans-Andean precipitation gradient determines the vegetation patterns in southern Patagonia. However, positive atmosphere-vegetation feedbacks may play an additional role in increasing the west-east moisture gradient under modern conditions. Five major vegetation zones are distinguishable in southern South America (Hueck and Seibert, 1981; Moore, 1983; Roig, 1998): the Magellanic moorland and evergreen Magellanic rain forest thrives west of the Andes, Andean tundra dominates above the tree line, and deciduous *Nothofagus* forest grows near the tree line in the Andes, as well as at lower elevations east of the Andes where precipitation is in excess of 400 mm. In the more arid regions further to the east, Magellanic steppe occurs.

The Pali Aike Volcanic Field is located in the lowland between the Andes and the Atlantic coast amid the Magellanic steppe formation, which is characterized by grassland with occasional shrubs. It can be divided into a moister (mesic) type located closer to the Andes in the west with *Festuca pallescens* as the dominant species and a dryer (xeric) type located in the east with *Festuca gracillima* as the dominant species (Pisano, 1985; Roig, 1998). Since the early European settlers reached this part of the continent in the last decades of the nineteenth century, vegetation has been altered by sheep farming (Liss, 1979; Aagesen, 2000). As a consequence, overgrazing and soil erosion is widespread. In addition, the flora has been modified by the introduction of European weeds (Huber and Markgraf, 2003). Despite this human influence on lowland vegetation, there is a close correlation between modern pollen rain and vegetation zones (D'Antoni, 1991; Mancini, 1993), which offers the possibility to apply modern pollen analog techniques to fossil pollen records (Paez et al., 2001).

2.2. Geology

The study area is located in the Pliocene to late Quaternary Pali Aike Volcanic Field (Figs. 1–3) a northwest–southeast-oriented tectonovolcanic belt about 50 km wide and more than 150 km long. This backarc volcanic area (Mazzarini and D'Orazio, 2003) is situated in the Magellan Basin, 80 km west of the city of Río Gallegos, immediately north of the Strait of Magellan, and approximately 300 km east of the active Andean volcanic arc. Petrologically, the Pali Aike Volcanic Field consists of alkali–olivine basalts with an age range of 3.8 Ma (Pliocene) in the western part to 0.01 Ma (Holocene) closer to the Atlantic Ocean (Fig. 3; Corbella, 2002). Along fissure-related eruptions, cinder cones, lava domes, and about 100 maars (500–4000 m in diameter) have been formed.

The oldest outcropping geological strata in the immediate study area are Oligocene marine sediments (sandstones, shales) related to a Tertiary marine transgression (Patagonia

Table 1
Compilation of names and related dates for the two last glaciations in the Pali Aike Volcanic Field (PAVF), the coastal area of the Atlantic Ocean, and the Lago Buenos Aires Basin

Region	Initioglacial[a] or Greatest Patagonian Glaciation[b]	Max. age	Min. age	Last Extensive Glaciation	Max. age	Min. age
PAVF	Bella Vista Glaciation[c]	<1.17 Ma[b] <1.168 Ma[d,e]		Río Ciaike Glaciation		>0.77 Ma[f]
Atlantic coast	Sierra de los Frailes Glaciation[c]	<1.19 Ma[f]		Cabo Vírgenes Glaciation[c]	<1.07 Ma[c]	>0.41 Ma[c]
Lago Buenos Aires	Telken VII moraines[e]		>1.016 Ma[e]	Telken VI–I moraines[e]	<1.016 Ma[e]	>0.76 Ma[e]

[a] Caldenius, (1932).
[b] Mercer, (1976).
[c] Meglioli, (1992).
[d] Thon-That et al., (1999).
[e] Singer et al., (2004).
[f] this study.

Formation). In the course of the Lower Miocene tectonic uplift of the Andes, fine-grained molasse–type fluvial sediments (Santa Cruz Formation) were deposited until 14 Ma and exceed 1000 m in thickness (Uliana and Biddle, 1988; Blisniuk et al., 2005). During the Pliocene and Pleistocene, the investigated area south of the Río Gallegos (Figs. 1–3) was covered by glaciers that came from the south, originating from the Magellan Strait, Seno Skyring, and Seno Otway. Fluvioglacial deposits (Patagonian Gravel Formation) form the surface of the southern Patagonian Plains today. These so-called Rodados Patagónicos make up the Patagonian Plains (Mesetas Patagónicas), which dip slightly east toward the coast of the South Atlantic Ocean. In southern Patagonia, they are regarded as glacial outwash deposited during Pliocene and early to mid-Pleistocene glaciations that stretched out to the east, beyond the present Atlantic coastline and onto the shelf. Glaciations occurred roughly between 3.5 and 1.0 Ma, but evidence and dating are poor (Table 1, Mercer, 1976; Rabassa and Clapperton, 1990; Meglioli, 1992). The most extensive glacial advance was termed Initioglacial (Caldenius, 1932) or Greatest Patagonian Glaciation (Mercer, 1976). For the same event, Meglioli (1992) introduced regionally different terms: Bella Vista Glaciation for the Río Gallegos Valley and Sierra de los Frailes Glaciation for Cabo Vírgenes. In the Lago Buenos Aires Basin, where at least 19 moraines document glacial advances from the Miocene to the Holocene (Mercer, 1976; Singer et al., 2004; Kaplan et al., 2005), the same glacial advance is related to the Telken VII moraine (Singer et al., 2004).

On the basis of the stratigraphic position of Initioglacial deposits overlying basaltic lava flows in southern Patagonia, it is possible to determine the maximum age for these glacial deposits by K/Ar- and Ar/Ar-dating of the underlying Bella Vista basalts as 1.17±0.05 Ma (Mercer, 1976) and 1.168±0.007 Ma (Ton-That et al., 1999). Stratigraphic evidence from the glacial basin of Lago Argentino points to a minimum age of 1.0 Ma (Wenzens et al., 1997), which gives an age range for the Initioglacial of 1.2–1.0 Ma. Redating of the Bella Vista basalt flow in the Río Gallegos Valley supports the Ar/Ar age of 1.168±0.014 Ma (Singer et al., 2004). In combination with the dating of the Arroyo Telken basalt flow in the Lago Buenos Aires Basin (1.016±0.01 Ma), which post-dates the Telken VII moraine, Singer et al. (2004) constrain the timing of this vast Patagonian glaciation to 1.17–1.02 Ma.

Following this largest eastward extent of glaciations in the Lago Buenos Aires Basin, there is a complex of at least six moraines that formed between 1.016±0.01 and 0.76±0.014 Ma, according to Ar/Ar dating of the under- and overlying basalt flows. They mark the second-largest ice extent related to the Telken VI–I advances (Singer et al., 2004). South of Río Gallegos, a glacial advance reached a maximum eastward position at the coast of the South Atlantic during the middle Pleistocene (Table 1). This Cabo Vírgenes Glaciation deposited on top of the Sierra de los Frailes Glaciation and has been framed by dating the under- and overlying basalt flows to 1.07–0.41 Ma (Meglioli, 1992). Geomorphologically contemporaneous but hitherto undated, the Río Ciaike Glaciation, which is related to the Seno Otway lobe, ended in a huge arc of terminal moraines approximately 10 km south of Laguna Potrok Aike. According to new and more precise data (Singer et al., 2004), the Cabo Vírgenes and Río Ciaike Glaciations likely coincide with the Telken VI–I moraines and thus terminated before 0.76 Ma.

During the late Pleistocene, the studied area was not glaciated. The Llanquihue Glaciation, South America's equivalent to the European Weichselian and North American Wisconsin Glaciations (Rabassa and Clapperton, 1990), did not extend far enough east to reach the Pali Aike Volcanic Field.

3. Methods

During the field survey, two deep lakes and several shallow ephemeral lakes (Fig. 1) were chosen for further studies. Paleoenvironmental investigations, however, concentrated on the deep crater lakes of Laguna Azul and Laguna Potrok Aike. To create bathymetric maps, as a basic prerequisite for limnogeological studies, systematic measurements of water depths were recorded with an echo sounder combined with a global positioning system (GPS) to obtain geographical coordinates simultaneously. A total of 7428 and 3494 depth measurements were interpolated for Laguna Potrok Aike and Laguna Azul, respectively, to produce detailed bathymetric maps.

To characterize the modern physical limnology of Laguna Azul and Laguna Potrok Aike and improve the interpretation of paleorecords derived from their sediments, physico-chemical parameters, such as temperature, pH, dissolved oxygen, and electric conductivity, were determined along depth profiles and for surface samples with a Universal Pocket Meter (Multi 340i, WTW) in the field. In addition, standard laboratory analyses of water chemistry were carried out on surface and water profile samples from both lakes, as well as from water samples of shallow lakes, wells, springs, and streams (Fig. 1). Cation concentrations were determined by ICP-MS techniques, whereas anion concentrations were measured by ion chromatography.

In addition to lake- and sediment-related studies, geological, geomorphological, and biological observations were carried out in the catchment areas. Furthermore, an extended sampling of (1) sediments from the catchment for mineralogical analyses; (2) topsoils for isotopic, geochemical, and pollen analyses; and (3) aquatic macrophytes, terrestrial plants, and groundwater from wells for geochemical and isotopic analyses was performed. The monitoring of modern processes was completed by moorings installed in the center of the lakes that house several sediment traps and 6–7 thermistors (Vemco Minilog) at various depths. The latter record water temperatures continuously with a resolution of 2–6 h.

First-sediment short cores were recovered with a modified ETH-gravity corer (Kelts et al., 1986) in 2002. In 2003, piston coring with the UWITEC system extended the sedimentary record into the past. Dated sediments were analyzed with high-resolution following a multiproxy approach. Detailed results and applied methods for the short cores have been published for Laguna Azul (Mayr et al., 2005) and Laguna Potrok Aike (Haberzettl et al., 2005, 2006a). Analyses of the long piston cores are ongoing.

4. Results and interpretation

4.1. Morphology and formation of lakes

Many lakes are visible on a satellite image of the Pali Aike Volcanic Field (Fig. 2). Aerial photographs show that not all lakes are volcanic crater or maar lakes in origin. A second type, as exemplified by the shallow Lagunas Uno, Dos, and Tres (names are provisional; no official names have been assigned), presumably were formed by deflation. A third group of lakes probably is of glacial origin (e.g. Laguna Esperanza, Laguna Travesía, both located outside the Pali Aike Volcanic Field ~180 km to the northwest) (Fig. 1). The comparison of satellite images taken at different seasons reveals that many of these lakes desiccate toward the end of the austral summer, especially shallow lakes or lakes in exposed topographic positions. Their sediments dry up seasonally and are deflated by the prevailing westerly wind. Supported by tussock grasses, such as the psamofile *Stipa chrysophylla*, and dwarf-shrubs, such as *Senecio filaginoides*, deposition occurs on the lee side of depressions in several kilometers-long sand sheets with small-scaled dunes (nebkhas or lunettes). This phenomenon is frequently observed in satellite images (Fig. 2). Consequently, the sedimentary record related to such shallow lakes is discontinuous, with hiatuses formed during erosional periods and reworking of older sediments occurring during periods with infilling water. Although young sediments may be eroded in seasonally dry lakes, such as Laguna Bismarck (Figs. 1 and 2), these lakes still may contain a complete sediment sequence of older sediments from wetter periods, as is demonstrated for several dry lakes in northern Patagonia (Schäbitz, 1999). To avoid such erosional unconformities as much as possible, the currently deep and permanently water-filled lakes of the Pali Aike Volcanic Field (Laguna Azul and Laguna Potrok Aike) are the sole focus of this study; the others have been analyzed only limnologically for comparison, in that they may serve as a modern analog for drier conditions in the history of permanently water-filled lakes.

4.1.1. Laguna Azul

Laguna Azul is situated at the side of a scoria cone and located in a crater with an almost complete and up to 30 m thick ring wall consisting of pyroclastic ashes and lapilli. The inner crater slopes, covered with scoria, ashes, and lapilli, are steep, with approximately 60 m altitudinal difference between the surrounding Patagonian plain and the present lake level. The lake itself has neither an inlet nor an outlet. The elliptical lake has a maximum water depth of 56 m (Fig. 4, Table 2). Rugged bottom morphology of the lake and the presence of the 10–30 m high, not yet eroded pyroclastic ring wall point to a rather young Holocene age of the volcanic structure. The bathymetric map (Fig. 4) reveals three subbasins that, together with the shape of the crater, indicate that the volcano was formed by at least three volcanic vents.

The crater of Laguna Azul exhibits a complex eruptive history of explosive and effusive activities. First, a cinder cone was formed by strombolian activity, followed by the formation of a lava lake. The latter was partly overflowing through a narrow channel to the north, creating a small lava flow with proximal pahoehoe and distal aa lava. Second, the lava lake collapsed, and the partly solidified lava lake surface partly covered the pyroclastic material of the inner crater walls and led to the formation of lava caves. This process stabilized the crater slopes, as is especially evident in the very steep southeastern part of the crater. Third, strombolian activities were responsible for the formation of the pyroclastic ring wall.

The lake that formed after the volcanic eruptions is rather circular (shoreline development: 1.2), has a very small catchment area in relation to the lake surface (*z*-ratio: 1.6), and has a theoretical mixing depth of 20 m (Table 2). First-sediment short cores provide a basal age of 1010 cal. BP at 1.25 m sediment depth (Mayr et al., 2005). The maximum sediment thickness (6.5 m) recovered with a piston core reached bedrock that consists of graded scoria lapilli. The grading points to a slump of pyroclastic material into an already existing water body during an early stage of the crater lake. The sediments yield a preliminary basal age of 3400 cal. BP that confirms a late Holocene origin of Laguna Azul.

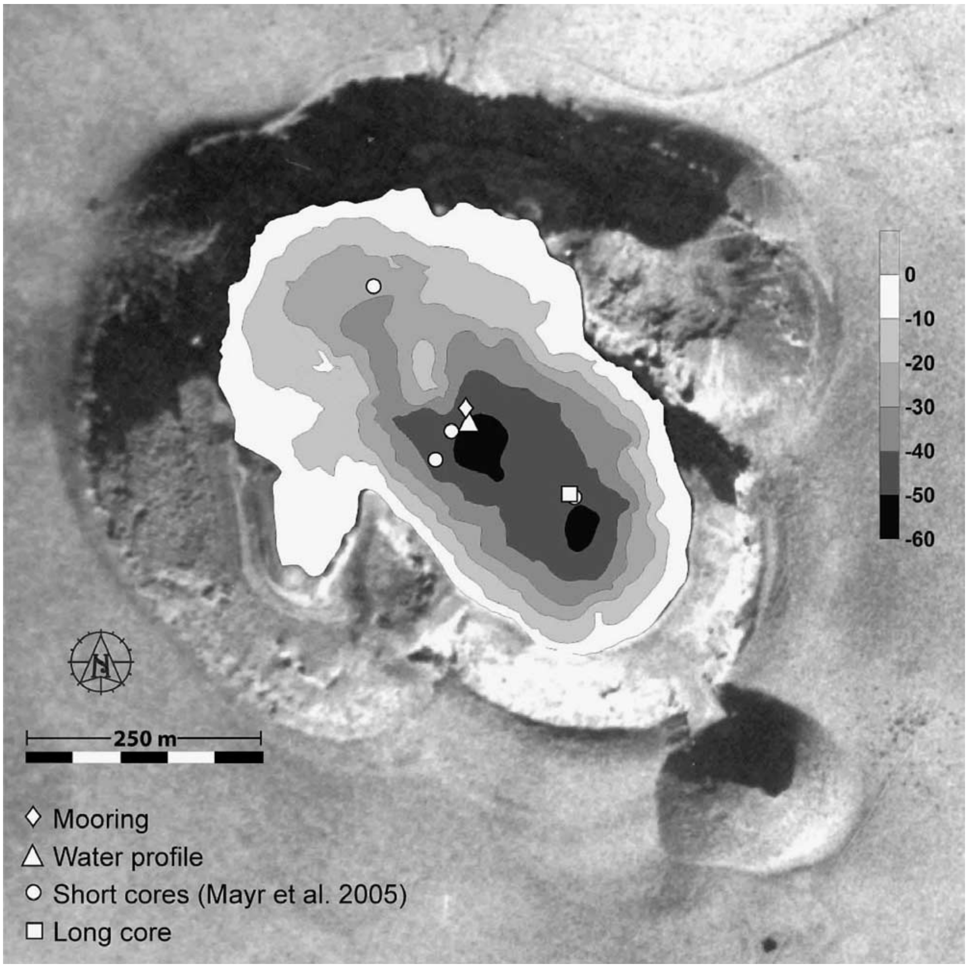

Fig. 4. Bathymetric map of Laguna Azul with positions of obtained sediment short and long cores, water profile (cf. Fig. 6), and installed thermistor chain (cf. Fig. 7) with sediment traps (mooring); depth intervals in meters.

4.1.2. *Laguna Potrok Aike*

Laguna Potrok Aike is a completely different lacustrine system than Laguna Azul. The lake surface area is 50 times larger, with a lake diameter of almost 3.5 km (Fig. 5, Table 2). The crater itself has a diameter of approximately 5 km. The inner crater walls are not very steep. The difference in elevation between the present-day lake level and the Patagonian plain is 50 m, with about half of that difference being occupied by several lake-level terraces. At the southwestern crater rim, there is a cinder cone with a well-developed basaltic lava flow, and Patagonian gravel covers both. The lava flow never entered the lake and probably was not related to the formation of the crater lake. There is no ring wall preserved in the catchment. However, remnants of a hyaloclastic tephra layer have been detected and point to a phreatomagmatic origin. Therefore, a maar explosion is assumed, also on the basis of the low relief of this crater. A maar generally is a shallow explosive eruption caused by the contact of rising magma with groundwater that forms craters with a diameter of 50–2000 m. Preferably, larger maars develop in valleys that provide a higher amount of groundwater (Lorenz, 1973), as is the case for Laguna Potrok Aike.

Table 2
Summary of geographic and morphometric data for Laguna Azul and Laguna Potrok Aike (Pali Aike Volcanic Field, Argentina).

	Laguna Azul	Laguna Potrok Aike
Longitude	52°04.526′ S	51°57.337′ S
Latitude	69°34.881′ W	70°22.688′ W
Elevation of lake level	100 m a.s.l.	113 m a.s.l.
Max. elevation in the catchment area	190 m a.s.l.	227 m a.s.l.
Relative relief	90 m	114 m
Maximum lake diameter	560 m	3470 m
Minimum lake diameter	240 m	2740 m
Maximum water depth	56 m	100 m
Mean water depth	19 m	44 m
Theoretical mixing depth	20 m	52 m
Water volume	0.01 km^3	0.41 km^3
Lake surface area (L)	0.15 km^2	7.58 km^2
Catchment area (C)	0.24 km^2	ca. 200 km^2
z-ratio (C/L)	1.6	>26
Length of shoreline	1.7 km	11 km
Shoreline development	1.2	1.1
Secchi depth	4.0 m	6.9 m
Trophic state[a]	Eutrophic	Eutrophic

[a] Trophic classification according to OECD (1982).

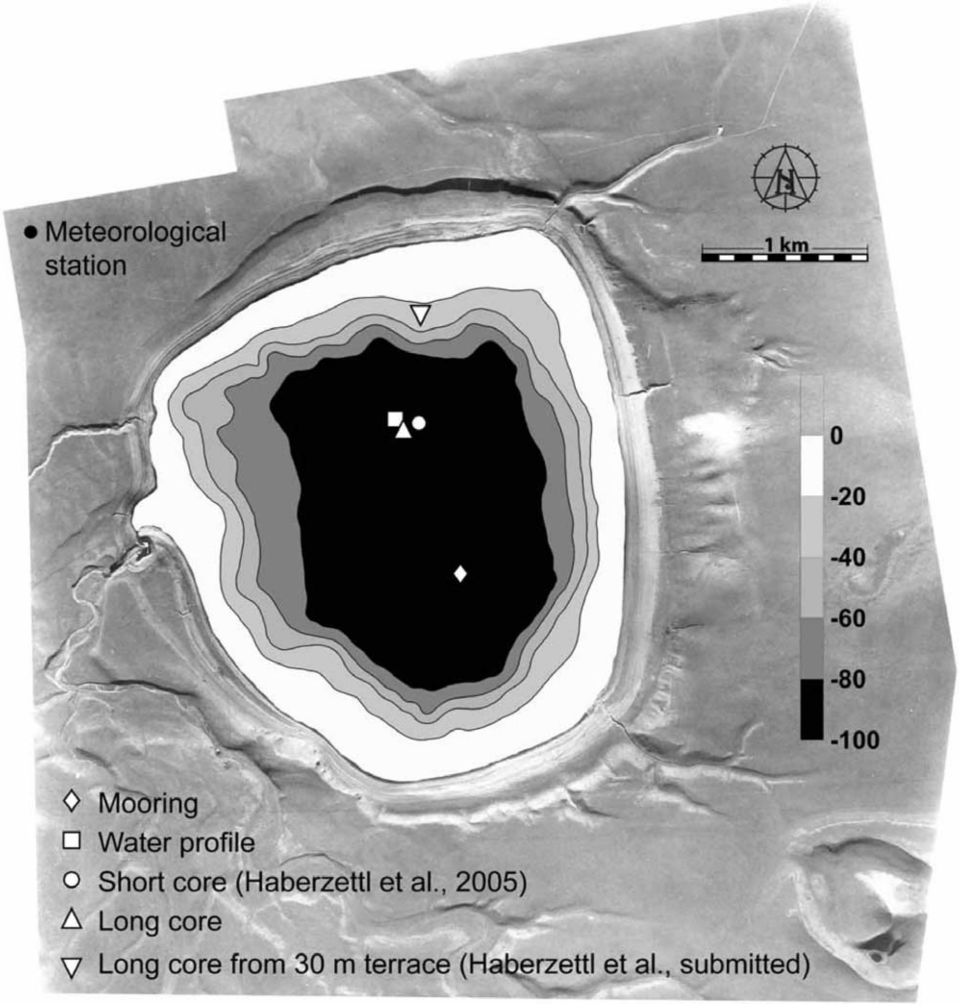

Fig. 5. Bathymetric map of Laguna Potrok Aike with positions of obtained sediment short and long cores, water profile (cf. Fig. 6), and installed thermistor chain (cf. Fig. 8) with sediment traps (mooring); depth intervals in meters.

Morphometric data (Table 2) reveal an almost circular shape of the lake (shoreline development: 1.1), whereas the topography suggests a significant influence of the catchment area on the lake system (*z*-ratio: >26). Therefore, a substantial supply of sediment and a thick sedimentary infill must be expected. Although the catchment area is rather large ($\sim 200\ \mathrm{km}^2$) and extends far south into Chile, the maximum water depth is 100 m, which points to an enormous initial size and depth of the crater. The bathymetry of the lake (Fig. 5) reveals an almost flat and pot-shaped morphology of the lake floor, as is typical for maar lakes. The theoretical mixing water depth of Laguna Potrok Aike is 52 m. Thus, there is the potential for seasonal anoxic or even meromictic conditions in the hypolimnion below this depth. However, water profile data reveal that under modern conditions, there is almost no stratification of the water column (Fig. 6) due to the strong winds that enforce polymictic conditions and hardly allow for the formation of a thermally stratified water body during southern summers.

Concerning the age of the maar, two new radiometric dates obtained in the Noble Gas Mass Spectrometry Laboratory (Oregon State University) confirm that this sedimentary archive existed for a long time and thus demonstrates enormous potential for paleolimnological and paleoclimatological studies. A whole-rock sample at the tip of the lava flow from the cinder cone was Ar/Ar dated to 1.19 ± 0.02 Ma. Because glacial sediments cover the lava flow as well as the cinder cone, the last glaciers reaching this site must have been younger than the lava flow. Most likely, the related glacial advance was part of the Sierra de los Frailes ice lobe from the south rather than the Bella Vista ice lobe from the west (Table 1). This proposition agrees in timing with the age for the Initioglacial, dated between 1.17 and 1.02 Ma (Singer et al., 2004). The second newly available Ar/Ar date provides an age of 0.77 ± 0.24 Ma for a basaltic clast from the phreatomagmatic tephra related to the maar explosion. These dates show that the formation of the cinder cone with the lava flow was not related to the maar eruption but occurred approximately 400 ka earlier. Furthermore, the Río Ciaike Glaciation, with its terminal moraines approximately 10 km south of Laguna Potrok Aike, must be older than 0.77 Ma. If the maar lake had existed during this glacial advance, the lake basin probably

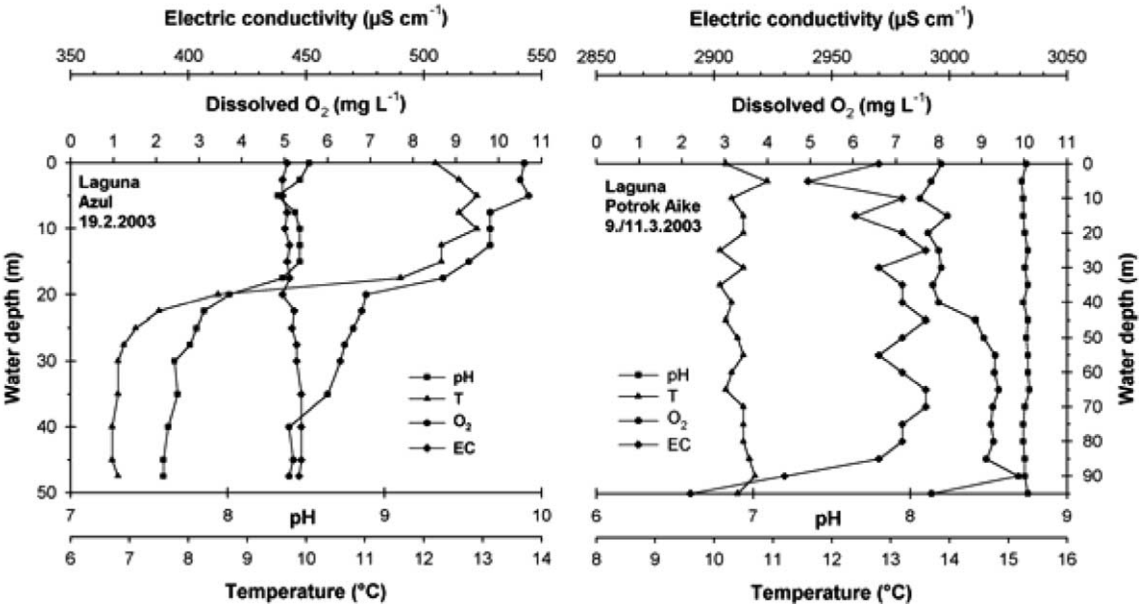

Fig. 6. Depth profiles of electric conductivity, dissolved oxygen, pH, and temperature of Laguna Azul (56 m max. water depth) and Laguna Potrok Aike (100 m max. water depth) from 2003. Positions of water profiles are indicated in Figs. 4 and 5.

would have been silted-up rapidly by proglacial and fluvioglacial sediments originating from this last glacial advance. Geomorphologically, the ice advance from Seno Otway is considered synchronous with the Cabo Vírgenes Glaciation, dated to a minimum age of 0.45 ± 0.1 Ma (Meglioli, 1992; Corbella, 2002). With the now available Ar/Ar age for the formation of Laguna Potrok Aike (0.77 Ma), it is possible to render this age more precisely, because the formation of the maar post-dates the glaciation (Table 1). Therefore, a new tentative minimum age for the Río Ciaike Glaciation (Cabo Vírgenes Glaciation) of 0.77 Ma is suggested. Assuming that the second-largest glacial advance in the Magallanes region is synchronous with the second-largest glaciation in the Lago Buenos Aires area (the Telken VI–I moraines), the dating of the latter (1.02–0.76 Ma) strongly supports this interpretation (Table 1).

Sediment cores obtained thus far agree with this general time frame. A 19 m long piston core from the center of Laguna Potrok Aike at 100 m water depth provides a calibrated basal radiocarbon age of 16,000 cal. BP. A 10 m long piston core from a submerged lake level terrace at 30 m water depth has a basal ^{14}C age of 44,500 BP. This age, however, includes an erosional unconformity with a hiatus of unknown duration (Haberzettl et al., 2006b). In addition, preliminary data of an airgun seismic survey carried out in March 2005 indicate a thickness of approximately 250 m for the lacustrine sediments (Niessen and Gebhardt, 2006).

On the basis of a combination of these data, it is possible to estimate (1) a linear sedimentation rate of 0.3 mm yr^{-1}, assuming 250 m of lacustrine sediments and an onset of lacustrine deposition at 770 ka, and (2) the beginning of sedimentation by extrapolating the linear sedimentation rate for the last 16,000 years (1.05 mm yr^{-1}) to the entire 250 m, yielding a basal age of approximately 240 ka. As compaction has not been taken into consideration for this calculation, the latter age must be regarded as a minimum age. Together, these estimates demonstrate that the sedimentary record from Laguna Potrok Aike covers at least two and up to seven glacial to interglacial cycles, perhaps back to the Brunhes/Matuyama boundary.

4.2. Limnology and surface sediments

To improve the understanding of limnological processes at Laguna Azul and Laguna Potrok Aike, the surface water chemistry of several other lakes, as well as of springs, wells, and streams, in the Pali Aike Volcanic Field has been studied (Fig. 1, Table 3). On the basis of electric conductivity, the salinity for investigated lakes was calculated to range between 0.03 and 42.4 ppt, equivalent to grams per litre or ‰ (Table 3). For comparison, the mean salinity of world surface waters is 0.12 ppt (Wetzel, 2001). Because these values are strongly related to bedrock geochemistry and climate, they are expected to be elevated in areas glaciated during the Pleistocene without intensive chemical weathering and areas with a low precipitation/evaporation ratio. These characteristics apply to southernmost Patagonia, which therefore should yield comparatively high values, as is the case according to surface water data from Río Chico (0.26–0.28 ppt; Table 3). Consequently, investigated lakes should have salinities around or above this value, because most are closed lake basins with enrichments of soluble elements in the prevailing semiarid climatic conditions. Only Lago Argentino, Lago Nahuel Huapi, and Laguna Arenas Negras have markedly lower salinities (Table 3). The first two water bodies are open glacial lake systems from the foothills of the Andes, north of the Pali Aike Volcanic Field, and the latter is a groundwater-fed closed lake with an assumed high seepage rate. Most of the other

Table 3

pH, electric conductivity (EC), salinity (calculated from EC according to http://ioc.unesco.org), and water chemistry (anions, cations) of surface water from lakes, streams, springs, and wells from the Pali Aike Volcanic Field (La., Laguna; Ea., Estancia; for locations, see Fig. 1)

Number in Fig. 1	Site	pH	EC (μS cm^{-1})	Salinity (g L^{-1})	Cl$^-$ (mg L^{-1})	NO^{3-} (mg L^{-1})	SO$_4^{2-}$ (mg L^{-1})	TP (μ g L^{-1})	Fe (μg L^{-1})	Na (mg L^{-1})	Mg (mg L^{-1})	Si (mg L^{-1})	K (mg L^{-1})	Ca (mg L^{-1})	Mn (μg L^{-1})	Al (μg L^{-1})
Lakes																
1	La. Azul	9.0	450	0.31	23.8	<0.05	12.4	51	121.0[a]	51.0	12.4	0.20	4.8	36.0	7.0[a]	43.0[a]
1	La. Azul	8.5	442	0.30	22.1	<0.05	11.4	67	4.7	34.2	12.0	0.31	8.1	28.7	<0.3	<5
1	La. Azul	8.8	438	0.30	20.0	0.23	8.9	31	37.3[a]	38.3	8.4	1.03	22.9	33.2	2.2[a]	83[a]
1	La. Azul	9.0	440	0.30												
2	La. Potrok Aike	8.9	3110	2.53	586.0	<0.05	27.1	2247	142.0[a]	502.0	73.0	1.20	43	32.0	7.4[a]	50[a]
2	La. Potrok Aike	8.7	2970	2.22	644.0	1.73	26.3	3609	10.9	476.0	72.0	0.69	31.8	34.2	2.5	<5
2	La. Potrok Aike	8.8	2980	2.23	666.0	3.07	27.2	1297	21.8	528.0	59.0	0.78	57.0	27.8	2.3	16
2	La. Potrok Aike	9.0	3020	2.26												
3	La. Arenas Negras	7.8	90	0.06	4.3	0.87	1.5	166	358.0	3.9	2.9	2.60	9.2	4.3	5.6	304
4	La. Carolina	–	–		74.3	0.42	16.5	2220	506.0	218.0	8.1	5.90	13.7	18.6	24.9	<5
5	La. Uno	8.5	175	0.12	12.7	2.97	1.5	14	–	–	–	–	–	–	–	–
6	La. Dos	8.2	204	0.14	15.5	4.13	3.6	43	–	–	–	–	–	–	–	–
7	La. Tres	8.6	873	0.61	–	–	–	–	–	–	–	–	–	–	–	–
8	La. Bismarck	9.4	40600	37.60	5708.0	23.60	2137.0	43	26.3	8330.0	44.2	3.80	2020.0	19.7	29.8	91
9	La. Maar Tito	8.5	319	0.22	28.0	<0.05	5.3	461	5139.0	27.6	9.2	14.60	17.2	15.9	48.8	4080
10	La. Tres de Enero	7.4	163	0.11	7.6	3.77	0.5	605	1032.0	11.9	6.0	3.10	12.0	7.4	56.5	706
11	La. Esperanza	8.4	191	0.13	7.0	0.28	2.8	<1	–	–	–	–	–	–	–	–
12	La. Travesía	8.6	355	0.24	24.6	< 0.05	1.2	13	–	–	–	–	–	–	–	–
13	La. Condor	7.6	271	0.18	–	–	–	–	–	–	–	–	–	–	–	–
14	La. Rincón de los Morros	7.6	45200	42.40	15060.0	68.30	281.0	1	31.5	7920.0	515.0	1.73	573.0	50.5	4.3	38
	Lago Nahuel Huapi	7.5	39	0.03	0.5	4.20	1.2	9	–	1.8	0.9	<0.02	0.5	3.3	–	–
	Lago Argentino	7.3	43	0.03	–	1.00	6.0	7	–	0.4	0.1	<0.01	0.2	4.0	–	–
	Lago Carrilaufquen Grande	8.8	2240	1.65	25.4	1.30	528.0	298	–	744.7	30.0	0.07	17.2	26.8	–	–
Wells, springs																
I	Spring at La. Carolina	–	–		32.0	0.13	12.8	1713	8.3	38.2	16.9	7.30	5.8	29.7	1.0	<5
X	Spring at La. Potrok Aike	–	–		39.6	0.10	10.0	29	406.0	17.2	12.7	7.50	6.1	27.4	237.0	26
IX	Well INTA Potrok Aike	–	–		24.9	2.71	3.6	23	52.6	20.7	6.6	6.70	1.7	17.3	6.5	<5
VI	Well near Ruta 3	8.0	1191	0.85	–	–	–	–	–	–	–	–	–	–	–	–
II	Well Ea. 3 Enero (80 m)	7.7	1128	0.80	–	–	–	–	–	–	–	–	–	–	–	–
III	Well Ea. 3 Enero (20 m)	7.3	3010	2.25	–	–	–	–	–	–	–	–	–	–	–	–
VII	Well 1	8.3	526	0.36	63.6	3.88	6.50	<1	–	–	–	–	–	–	–	–
V	Well 2	8.1	501	0.34	58.9	4.80	8.96	<1	–	–	–	–	–	–	–	–
VIII	Well 3	8.1	446	0.31	47.4	4.37	7.95	<1	–	–	–	–	–	–	–	–
IV	Well Ea. La Argentina	8.2	558	0.38	66.6	7.61	10.90	<1	–	–	–	–	–	–	–	–
Streams																
A	Río Chico	8.0	381	0.26	–	–	–	–	–	–	–	–	–	–	–	–
B	Arroyo del Roble	–	–		35.9	0.00	11.3	2421	27.1	25.0	13.0	6.00	3.6	29.2	4.6	<5
C	Río Chico. Ea. Marka. Aike	7.8	404	0.28	45.4	0.10	11.8	45	189[a]	26.0	11.8	3.30	8.7	20.8	13.2[a]	141[a]

Three sites are added for comparison: Lago Argentino near El Calafate, Lago Carrilaufquen Grande near Ingeniero Jacobacci, and Lago Nahuel Huapi near San Carlos de Bariloche (Diaz et al., 2000).

[a] Water not filtered prior to analyses, resulting in overly high values for Fe, Mn, and Al related to suspended minerogenic matter.

investigated lakes fall in the range of the mean surface water salinity or slightly above (0.11–0.31 ppt) and should be regarded as freshwater lakes (Hammer, 1986). Three of the closed lakes (Laguna Potrok Aike, Laguna Tres, Lago Carrilaufquen Grande) fall in the group of subsaline lakes, with salinities ranging from 0.61 to 2.53 ppt, whereas Laguna Bismarck (37.6 ppt) and Laguna Rincón de los Morros (42.4 ppt) are mesosaline and thus the only salt lakes analyzed in this study.

With regard to the amount of ionic constituents (chloride, sulphate, total phosphorus, Na, K, and Mg), the investigated deep Laguna Potrok Aike has the highest values, outpaced only by the salt lakes of Laguna Maar Bismarck and Laguna Rincón de los Morros (Table 3). This finding is supported by high electric conductivities between 2970 and 3110 μS cm^{-1} for the years 2002–2005. Such values by far exceed those for all other examined lakes with conductivities $\ll$1000 μS cm^{-1}. The two mentioned salt lakes are characterized by more than 10 times higher values for electric conductivity, chloride, nitrate, and sulfate, as well as for Na and K, compared with the already enriched Laguna Potrok Aike. With respect to dissolved nutrients, nitrate (NO^{3-}) and total phosphorus (TP) were determined in the lake water. Nitrate concentrations for Laguna Potrok Aike (measured in 2002) and Laguna Azul (measured in 2002 and 2003) were below detection limits (i.e. $<$0.05 mg L^{-1}). In 2004, nitrate concentration was 0.23 mg L^{-1} for Laguna Azul. In 2003 and 2004, increased values of 1.73 and 3.07 mg L^{-1} for NO^{3-} were detected for Laguna Potrok Aike, respectively. The highest NO^{3-} concentrations of investigated freshwater lakes were observed for Laguna Dos (4.13 mg L^{-1}). Remarkable are the extremely high TP concentrations in the surface water of Laguna Potrok Aike: 2247 μg L^{-1} in 2002, 3609 μg L^{-1} in 2003, and 1297 μg L^{-1} in 2004. According to the OECD classification scheme, these concentrations characterize Laguna Potrok Aike as a hypertrophic lake (OECD, 1982). However, because phosphorous is obviously not the limiting factor for lacustrine productivity in this lake, the OECD classification cannot be applied. The high concentration of chlorides may inhibit a higher planktonic productivity in Laguna Potrok Aike and lead to less productivity compared with Laguna Azul, as is supported by the differences in secchi depths in the lakes (Table 2). The elevated TP values in Laguna Potrok Aike are difficult to explain but may be related to groundwater and regional geology; Laguna Potrok Aike and Arroyo del Roble, as well as Laguna Carolina and a nearby spring, all are located in the same area and show comparatively high TP values beyond 1700 μg L^{-1} (Table 3).

In a comparative study of temperate steppe and mountain lakes in Patagonia, enrichment of TP (steppe lakes: 69–298 μg L^{-1}, mountain lakes: 1.8–11 μg L^{-1}) is regarded as characteristic for steppe lakes (Diaz et al., 2000). The same is valid for electric conductivity (steppe lakes: 1346–2240 μS cm^{-1}, mountain lakes: 23.9–92 μS cm^{-1}). This finding is interpreted as a result of a negative water balance and the shallowness of most steppe lakes. These factors do not apply to Laguna Potrok Aike however.

The marked differences in electric conductivity (salinity) of the two investigated deep lakes indicate age differences, different runoff hydrology or catchment geology, or a combination thereof. On the basis of the morphometric data obtained for the lakes and their catchment areas (Table 2) and the largely similar geological setting, it seems likely that all three reasons probably are important. The age difference of more than 0.75 Ma between Laguna Azul and Laguna Potrok Aike could have caused the formation of brackish water in Laguna Potrok Aike, due to long-lasting evaporation with a related concentration of soluble elements in the water body of this closed basin. This process is not as pronounced in the rather young, freshwater lake Laguna Azul, which is of probably Holocene age. Nevertheless, TP is slightly increased compared with mountain lakes (cf. Diaz et al., 2000), which points to a similar trend typical for steppe lakes. Surface runoff at Laguna Azul is almost non-existent. Rain seeps immediately into the tephra and scoria of the crater walls. Laguna Potrok Aike, in contrast, has a much larger catchment area (Table 2) with a periodic and snowmelt-fed inflow and episodic gullies (arroyos) that drain the surrounding areas of the Patagonian plain. In addition, a different chemical composition of groundwater seepage cannot be ruled out and might be responsible for the different TP concentrations.

No significant changes in conductivity were observed in depth profiles of the lakes. Temperature, dissolved oxygen, and pH show that these lakes have different water circulation (mixing) patterns (Figs. 6–8). Summer surface temperatures are similar (10–12 °C) for both lakes, but Laguna Potrok Aike shows almost no changes in temperature with depth (temperatures stay between 10–11 °C; Fig. 8), whereas Laguna Azul is thermally stratified—temperatures decrease from $>$12 °C near surface to 6–7 °C near the bottom—with a well-established metalimnion between 17 and 25 m water depth (Fig. 6). Temperatures (12.5 °C), dissolved oxygen (10 mg L^{-1}), and pH (8.5) remain stable in the epilimnion (uppermost 17 m). All parameters decline in the metalimnion. In the hypolimnion (below 25 m of water depth), temperature (6–7 °C), dissolved oxygen (5–7 mg L^{-1}), and pH (7.7) are relatively stable again (Fig. 6).

In contrast, the water column of Laguna Potrok Aike has stable values for pH (8.7) and temperature (10.4 °C) throughout the entire depth profile of 100 m. The absence of any pronounced summer stratification or anoxic hypolimnion in the water column of Laguna Potrok Aike (Figs. 6 and 8) can be explained only by the pronounced exposure of the lake to the extremely strong wind, which causes frequent mixing events during the whole year.

Due to its stratified water body (Figs. 6 and 7), Laguna Azul is slightly oxygen depleted in the hypolimnion and therefore has the highest potential for preservation of organic matter. Investigations of surface sediment samples and sediment short cores reveal a considerable higher content of total organic carbon (mean value: 14.7% TOC, $n=128$) for Laguna Azul, indicative of a high primary lacustrine production and little decomposition. In contrast, the total organic carbon content (mean value: 1.8% TOC, $n=97$) in the surface sediments of Laguna Potrok Aike

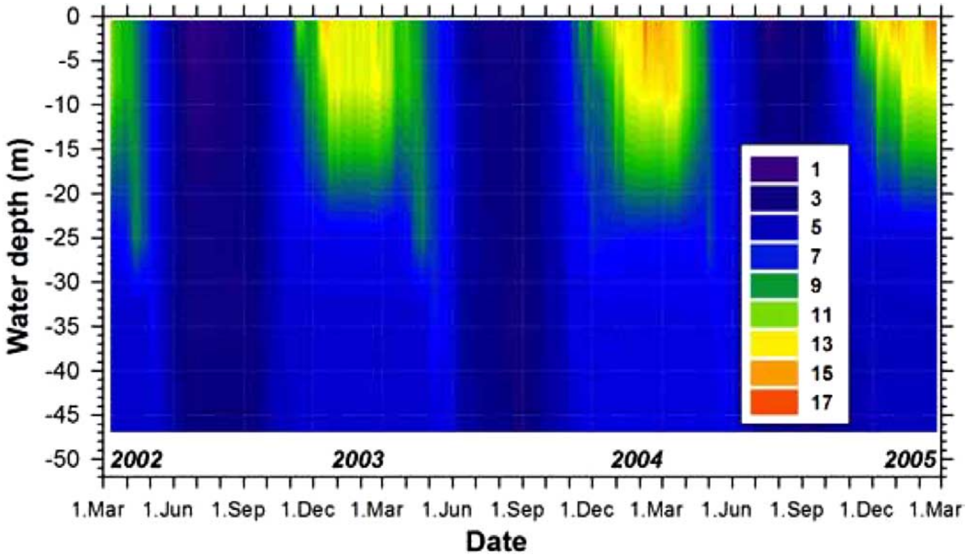

Fig. 7. High-resolution water temperature data (thermo-isopleths) recorded with 2–6 h resolution by six thermistors attached to a mooring string at the deepest part of Laguna Azul (cf. Fig. 4 for position of the mooring).

differ markedly from those of Laguna Azul and point to less primary productivity, rapid decomposition and recycling of these compounds, and/or dilution by inorganic particles at Laguna Potrok Aike. Because of the outlined differences between the lakes regarding age, surface runoff, sediment infill, physical limnology, and responding ecosystems, they bear huge potential for comparative investigations of their respective environmental and climatic histories.

4.3. Lake-level fluctuations

Geomorphological observations along the shore of Laguna Potrok Aike indicate several pronounced lake-level terraces. These levels exhibit different states of soil development and evidence lake-level fluctuations on the order of 20 m (Fig. 9). Because the lake can be regarded as a closed basin for the Holocene, it necessarily relates to changing hydrological conditions.

According to our own observations, seasonal lake-level fluctuations can be in the range of a few meters (Fig. 9: Late Holocene level A). Beyond this modern range, two distinct lake-level terraces without vegetation and soil development are distinguishable 10 and 15 m above the present lake surface. Both are separated by a step and probably can be attributed to a decrease in the amount of effective moisture during the last several centuries (Fig. 9: Late Holocene levels B and C), which might be seen in conjunction with the end of a ‘Little Ice Age’-style climate variation in the late nineteenth

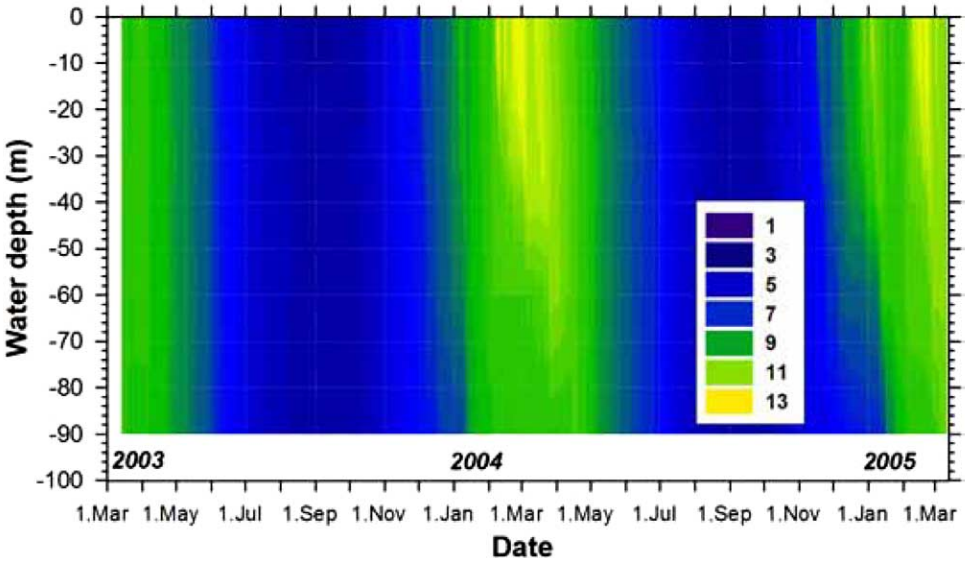

Fig. 8. High-resolution water temperature data (thermo-isopleths) recorded with 6 h resolution by seven thermistors attached to a mooring string at the deepest part of Laguna Potrok Aike (cf. Fig. 5 for position of the mooring).

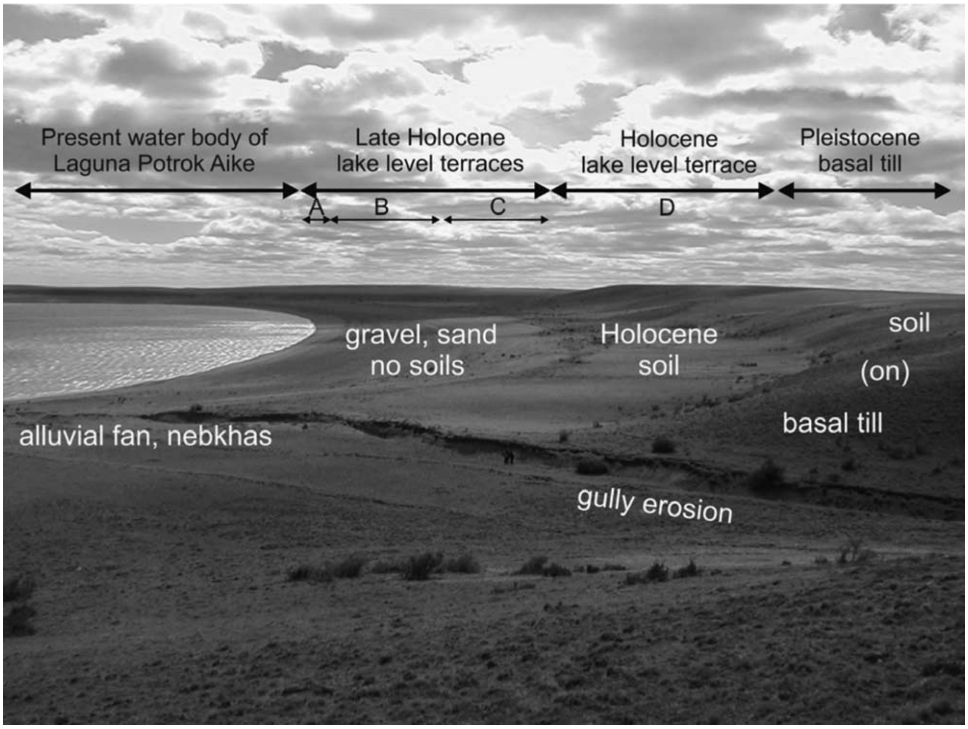

Fig. 9. Lake-level fluctuations as recorded by morphology indicating lake-level terraces along the eastern shore of Laguna Potrok Aike. Holocene lake-level terraces are subdivided into four stages: modern (A), last centuries or late Holocene without soil cover (B, C), and Holocene with soil cover (D).

century (Haberzettl et al., 2005). Such a natural cause for the drop in lake level can also be inferred from the Fitzroy Valley, north of Lago Viedma (400 km northwest of Pali Aike Volcanic Field), where the formation of sand dunes and a retreat of glaciers have been interpreted as the result of a temperature increase and a decrease in precipitation since the late 19th century (Wenzens et al., 1997).

Less precipitation in semiarid environments always means an increase in rainfall variability, which leads to episodic runoff events. If soils and vegetation are degraded, as is the case in southern Patagonia due to the introduction of sheep farming in 1890 (Aagesen, 2000), episodic rains cause severe damage through soil erosion. This damage is evident at the crater rim and the upper terrace levels, which are deeply incised by gully erosion with alluvial fans close to the current lake shore (Fig. 9). On a smaller scale, sandy and silty grain sizes of the alluvial fan deposits are exposed to deflation and form small sand dunes (nebkhas) in the lee side of the alluvial fans. On a much larger scale, a similar phenomenon is observed when lakes dry out completely and wind erosion blows out lacustrine deposits (Goergen et al., 1998), as is demonstrated for many episodically or periodically dry lakes of the Pali Aike Volcanic Field (Fig. 2).

Finally, the highest lake-level terrace D, approximately 20 m above the lake (Fig. 9), is covered by steppe vegetation and a steppe-type soil (Aridisol). The timing of this upper terrace level D is uncertain, but it may be related to a comparable period with very high lake levels that occurred at Lago Cardiel (~350 km north of Laguna Potrok Aike) during the early Holocene between 10,000 and 9000 uncalibrated radiocarbon years BP (Stine and Stine, 1990; Bradbury et al., 2001; Fritz et al., 2001; Markgraf et al., 2003; Gilli et al., 2005). In addition, a submersed lake-level terrace was detected by 3.5 kHz seismic at 30 m water depth (Zolitschka et al., 2004; Haberzettl et al., 2006b), indicating a total range of lake-level fluctuations of at least 50 m since the onset of the Holocene.

Recent lake-level fluctuations for Laguna Azul have hardly been recognized during field trips in the austral summers of 2002–2005. Although 2002 was a much drier year, the lake level did not rise more than a few centimeters in the following, wetter years. The reason for this minimal response is the small *z*-ratio in combination with the lack of surface inflow. Thus, the lake level is almost entirely related to the groundwater table, which operates as a buffer and does not react immediately to annual rainfall variations. However, a marked lake level lowering seems to have occurred since the mid-20th century, as documented by photographic evidence (Mayr et al., 2005). Whether this lowering is related to a draw down of the groundwater table due to a decrease in precipitation over a longer period of time or to human groundwater exploitation remains unclear.

5. Conclusion and perspectives

Lakes in closed basins of semiarid regions, as in southern Patagonia, generally respond much more to environmental and climatic changes than do lakes in more humid conditions. This trend is evident, for example, in documented lake-level fluctuations at Laguna Potrok Aike. However, such geomorphological evidence gives only a few tie-points back in time, which are generally difficult to date and bear little additional information. Sedimentary records from these lakes, however, can be dated and investigated with a multitude of paleolimnological methods, which, in combination, provide an excellent way to decipher the regional environmental history with regard to natural climatic and hydrological changes (Haberzettl et al., 2005, 2006b; Mayr et al., 2005) or anthropogenic influences (Haberzettl et al., 2005).

For a better understanding of lake system dynamics, a mooring with thermistors and sediment traps offers insights into stratification and mixing processes, as well as particle flux mechanisms. These data, in combination with general information about geology, soils, hydrology, and vegetation in the catchment areas, allow a profound interpretation of prior environmental conditions preserved in the sediment records. Moreover, a comparative study of the reactions of different lakes from the same area to natural forcing factors will offer the potential to infer regional climatic conditions.

The two deep lakes of the Pali Aike Volcanic Field examined for the first time in this study indicate a great potential for paleoenvironmental and paleoclimatic reconstructions. Both lakes contain continuous sediment sequences, with Laguna Potrok Aike potentially spanning several glacial/interglacial cycles, whereas Laguna Azul is an environmental archive restricted to the late Holocene. They have proved to be excellently suited for detailed geochemical, stable isotopic, diatomological, and palynological studies that aim at environmental reconstruction (Zolitschka et al., 2004; Haberzettl et al., 2005; Mayr et al., 2005). In addition, the present relation between modern pollen rain and zonal vegetation provides a means to interpret the sedimentary pollen assemblages in terms of climate, using the modern pollen analog approach (Paez et al., 2001). Marked differences between the physical and biological states of investigated lakes imply differences in the reactions of ecosystems on common climate forcing, which makes available a means to differentiate among lake internal, hydrological, and anthropogenic reactions of the lake system to the overall climatic forcing and human impact.

Investigations of sediment short cores with sedimentology, geochemistry, stable isotopes, diatoms, and pollen are published elsewhere and give a detailed record of environmental changes for the last two millennia (Haberzettl et al., 2005, 2006a; Mayr et al., 2005). In 2003, a piston corer was applied to recover long sediment records: 19 m of overlapping cores with a basal age of 16,000 cal. BP for Laguna Potrok Aike and 6.5 m with a preliminary basal age of 3400 cal. BP for Laguna Azul. The latter core penetrated into volcanoclastics, which probably are related to the formation of the crater. Laguna Potrok Aike in particular has the potential to contain a record of the last 770,000 years, unique for the higher to mid-latitudes of the southern hemisphere. A preliminary interpretation of airgun seismic data reveals a 250 m thick lacustrine sediment sequence (Niessen and Gebhardt, 2006). We envisage recovering this 250 m long sediment record in the framework of the International Continental Scientific Drilling Program (ICDP) using the GLAD 800 coring platform as an operational system. Environmental and climatic data obtained from such a record would enable interarchive correlations with marine sediment records from the South Atlantic and Antarctic ice cores and thereby provide new insights into glacial–interglacial variabilities of the climate system on the southern hemisphere.

Dating of the volcanogenic structure of Laguna Potrok Aike also makes available new age constraints for the timing of the last large Río Ciaike Glaciation, synchronous with the Sierra de los Frailes Glaciation in the Magallanes region (1.0–0.77 Ma) and probably experienced throughout Patagonia, comparable to the Telken VII moraines in the Lago Argentino Basin (Table 1). Such a narrowing of the time range for this event is not only of regional importance but also improves understanding of the timing and causes of hemispheric glacial advances and thus of major climatic changes. The study of crater lakes in the Pali Aike Volcanic Field thus provides a wealth of information that improves our knowledge of environmental and climatic conditions and processes on the southern tip of Patagonia.

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