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PALAEOLIMNOLOGY

Palaeolimnology of Lake Hess (Patagonia, Argentina): multi-proxy analyses of short sediment cores

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Abstract In contrast with the extensive palaeolimnological studies carried out in North America and Europe, relatively few studies have described the anthropogenic and/or climate impacts in Patagonian lakes. We addressed these issues by analysing geochemistry, lithology, pigments and chironomid remains from sediment cores collected from Lake Hess (41°22′20″S, 71°44′0″W) located in the Nahuel Huapi National Park in northern Patagonia. The aim of this study is to provide a palaeoenvironmental and climate reconstruction of the past ca. three centuries for this cold oligotrophic, quasi-pristine lake which receives meltwaters from the Tronador ice cap. Chronology was based on ^{137}Cs and ^{210}Pb measurements of the upper sediments, and the inferred sedimentation rate of 23.2 mg cm^{-2} y^{-1} (0.15 cm y^{-1}) was consistent with both sets of measurements. The sediment from Lake Hess was rich in tephra deposits particularly evident in the lower part of the cores. Tephras are valuable to use for core correlation and can be traced through peaks in the magnetic susceptibility (MS) profiles. Results from the multiproxy analyses in the longest core (83 cm) identify three main phases of change. From the bottom up to 42 cm (ca. AD 1800), the sediment is composed of light-grey organically rich clays. Both pigments and chironomids suggest variable trends in productivity and precipitation regime. At the end of the Little Ice Age chronozone (AD 1770–1850), pigment concentrations were very low. From 42 cm to ca. 25 cm (AD 1800–1940), the sedimentary record is composed of alternating black and dark organic-matter rich mud with variable amounts of macrophyte remains. Pigment concentrations and chironomid head capsule counts were also very low. These facies are composed of very fine plastic sediments with some faintly laminated intervals and an organic matter composition gradually decreasing towards the top of the zone. A sharp change occurs at 25 cm (ca. AD 1940) showing a strong increase in organic matter content,

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Palaeolimnological Proxies as Tools of Environmental Reconstruction in Fresh Water

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algal nutrients and plant pigments together with a change in the chironomid assemblages. This might document a change in the trophic condition of the lake associated with changes in erosion/deposition rates. Although there are records of human impact in the area studied, involving the use of fires, most of the observed chemical and biological changes in Lake Hess sediment sequence were interpreted in terms of climate changes, especially to changes in moisture balance brought about by variations in the strength of the westerlies.

Keywords Palaeolimnology · Pigments · Chironomids · Patagonia · South America

Introduction

Palaeolimnological research has shown that many remote areas (e.g., high mountain lakes) have experienced considerable biotic and sedimentary changes in the recent decades (e.g. Lami et al., 2000a; Lotter & Birks, 2003), but few studies have quantified the anthropogenic and climatic impacts in South America using Patagonian lakes (Ariztegui et al., 1997, 2007; Massaferro et al., 2005; Villarosa et al., 2006). Hydrological changes since the Last Glacial Maximum up to the Little Ice Age in Patagonia have been described from lake sediment cores on both sides of the Southern Andes in Lago Puyehue (40°S) in the Chilean Lake District (Chapron et al., 2006; Moernaut et al., 2007; Bertrand et al., 2008; Charlet et al., 2008; De Batist et al., 2008) and Laguna Frias (Ariztegui et al., 2007) in the Argentinean side. In the Patagonian Plateau, the record of Lago Cardiel (49°S; Gilli, 2003; Gilli et al., 2005; Markgraf et al., 2003) and Laguna Potrok Aike (52°S; Haberzettl et al., 2006; 2007a, b; Mayr et al., 2005) contain a detailed climate archive of the environmental variability since the late Pleistocene.

A multi-proxy approach is important in palaeolimnological studies to get an overview of the natural and anthropogenic events registered in the lake sediments. Northern Patagonia is a particularly interesting area for these studies because it is home to many different aquatic environments which are in turn controlled by regional and local climate effects (Villalba, 2007). For instance, the presence of the westerlies at the latitude of 40° S is a source of change in the atmospheric moisture coming from the Pacific Ocean (Ariztegui et al., 2007). Patagonia is particularly sensitive to seasonal atmospheric air-humidity changes driven by the Southern westerlies and the polar front position in winter (Prohaska, 1976). Temporal changes in the north–south precipitation gradient are controlled by the latitudinal position of the westerlies, which in turn is regulated by the strength and latitudinal position of the sub-tropical anticyclone in the southeast eastern Pacific and the circum-Antarctic low-pressure belt (Markgraf et al., 2000). The present-day northern limit of westerlies' influence along the Chilean Pacific coast lies at ca. 27°S. South of 38°S, the influence of westerlies is permanent resulting in high precipitations throughout the year, whereas at more northern latitudes, mean annual precipitation is comparatively low and is highest in winter (Veit, 1996).

Lake Hess is a small lake, which receives discharge from the River Manso Medio carrying meltwaters directly from the Tronador Glacier. Therefore, this lake is an interesting site, well placed to record variations in moisture regime and/or changes in the status of the glacier. Previous studies in the region have shown that the Tronador ice cap has reacted to climate change during distinct episodes such as the Late-Glacial–Holocene transition (Ariztegui et al., 1997; Hajdas et al., 2003), the Medieval Climatic Anomaly and the Little Ice Age with well-identified glacial advances between AD 1800–1850, and recent push-moraines (Rabassa & Clapperton, 1990; Villalba et al., 1997).

In this article, the issues of climate and palaeoenvironmental changes in a more recent period (the last ca. three centuries) have been addressed by analysing organic matter (by Loss on Ignition, LOI), nutrients (carbon and nitrogen), photosynthetic pigments and chironomid remains from three lithologically described sediment cores collected from Lake Hess located in the Nahuel Huapi National Park in northern Patagonia.

Records of organic matter, nutrients and fossil pigments in lake sediments reflect the environmental conditions in a lake and its catchment at the time of deposition (Guilizzoni et al., 2006). Their sedimentary chemical composition and algal abundance can record historical changes in lake trophic status, anthropogenic and natural (climate) change, adding greatly to our understanding of the development and functioning of lakes.

In addition, the use of chironomid remains (Diptera: Chironomidae) has, due to their stenotopic response to climate, productivity and water depth changes, and their high resistance to degradation, become widespread in palaeoecological studies (Brundin, 1958, 1966; Brooks & Birks, 2004).

The aims of this article are the following: (1) to provide additional paleolimnological information from northern Patagonian lake sediments during the last ca. 300 years, and (2) to establish the degree of human and climate impact within a quasi-pristine lake ecosystem.

Study area and sampling

Lake Hess (41°21′20″S; 71°44′0″W, 735 m a.s.l.) is a small, shallow (max depth 8.3 m), glacial lake located 100 km southeast of San Carlos de Bariloche. It receives meltwaters from Tronador ice cap via the Rio Manso Medio (Fig. 1). Water level fluctuations are quite common, given the small lake area and the significant water discharge by the outlet. The area is located far from urbanised regions, and no direct anthropogenic impacts on the lake are expected though records of extended fires in the region for the past 10,000 years have been reported in Kitzberger et al. (1997) and Veblen et al. (2003).

The climate of the area is predominantly cold temperate, and the vegetation is composed of mixed north Patagonian rainforest communities with mainly evergreen deciduous *Nothofagus* spp. At this latitude, the Patagonian region is dominated by air masses coming from the Pacific Ocean and strong constant west winds (westerlies) are dominant across the region.

In December 2005, using an inflatable boat, three short sediment cores named Hess 05-1 (83 cm long), Hess 05-2 (70 cm long) and Hess 05-3 (65 cm long) were sampled from the same site using a gravity corer (Ø PVC liner 6.3 cm).

Methods

In the laboratory, all cores were split lengthways, opened, photographed, visually inspected, and sub-sampled every 1 cm. Each sub-sample was freeze-dried and homogenised. Cores were correlated using organic matter, dry weight content, MS, tephra markers

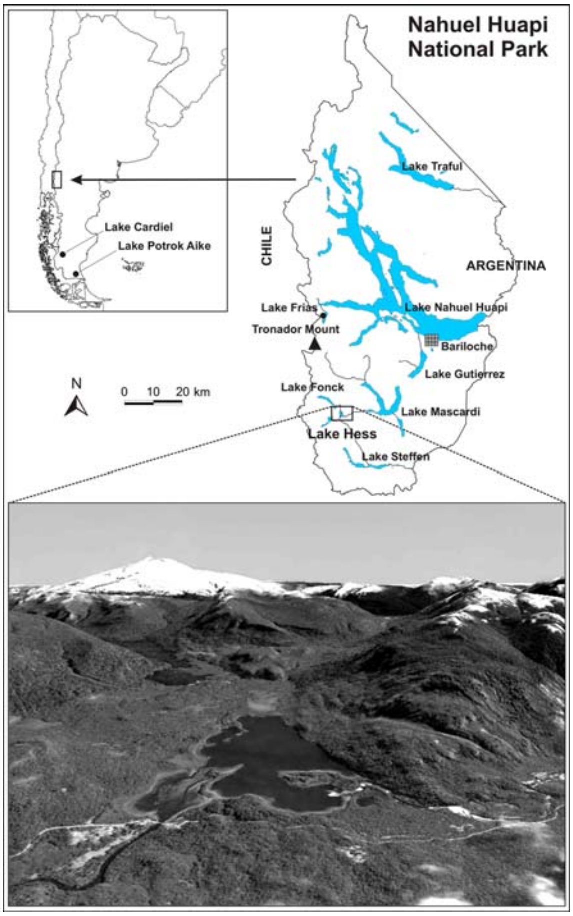

Fig. 1 Map showing the location of the study Lake Hess (Northern Patagonia, Argentina). An aerial view of Lake Hess showing the Tronador Mount and other investigated lakes mentioned in the text are also shown

and lithological features. MS was measured at 1 cm increments using a Bartington MS IB instrument prior to cutting the core. The sediment density was determined by computing the ratio between the dry weight of each sub-sampled sediment layer and its volume.

Core Hess 05-3 was used for radiometric dating at Laboratorio de Análisis por Activación Neutrónica, Comisión Nacional de Energía Atómica (LAAN CNEA), while cores Hess 05-1 and Hess 05-2 were studied for palaeolimnological indicators.

Chronology

Core dating was performed by ^{210}Pb and ^{137}Cs assay. ^{210}Pb, ^{226}Ra (in secular equilibrium with supported ^{210}Pb), and ^{137}Cs specific activity profiles were determined by high-resolution gamma ray spectrometry on core Hess 05-3. The measurements of the upper 8 cm are reported for ^{210}Pb and ^{137}Cs dating; below 8 cm, no significant radiometric values were obtained. The topmost samples (slices of 1 cm) were placed in a cylindrical plastic container (46 mm diameter and 8 mm height), sealed and counted in a close sample-detector geometry. ^{210}Pb and ^{226}Ra specific activities were obtained by measuring the 46 keV (from ^{210}Pb), 295 keV and 351.9 keV (from the decay of the ^{226}Ra short-lived daughters) emissions with a planar HPGe (LO-AX) detector. ^{137}Cs specific activity was determined by measuring the 661.7 keV emissions using an HPGe detector with 30 % relative efficiency.

The Constant Rate of Supply (CRS) model was used for ^{210}Pb dating (Joshi & Shukla, 1991; Robbins and Herche 1993). Correction of the old date error of the CRS model (Binford, 1990) was implemented by logarithmic extrapolation of the measurements to complement integration to infinite depth. For ^{137}Cs dating, the specific activity profiles were compared with the fallout sequence determined in this region, associated mainly with South Pacific nuclear tests from 1966 to 1974 (Ribeiro Guevara & Arribére, 2002).

Chemical and biological analyses

On core Hess 05-1, dry mass and organic matter were measured by LOI at 70 and 550°C, respectively. Total carbon, sulphur and total nitrogen were obtained using a Carbon Hydrogen Sulphur analyzer (NA 1500 Fisons). C/N has been based on an atomic ratio. All the chemical analyses were performed at CNR—Istituto per lo Studio degli Ecosistemi.

Photosynthetic pigments were extracted from ca. 1 g of wet sediment (large macrophyte remains free) in a 5 ml of 90% acetone, overnight in the dark, under nitrogen. The extract obtained was used to quantify both the chlorophylls and their derivatives (Chlorophyll Derivatives Units, CD) and total carotenoids (TC) by spectrophotometer (for details see Lami et al., 2000b). Individual carotenoids were detected by reversed phase high-performance liquid chromatography using a Dionex SUMMIT with a DAD-UV detector (Lami et al., 2000b). Carotenoid concentrations were expressed in nanomoles per gram of organic matter (nmol g^{-1} LOI; Züllig, 1986) and chlorophyll derivates in units per gram of organic matter (U g^{-1} LOI; Guilizzoni et al., 1982, 1983). Guilizzoni et al. (1992), Lami et al. (2000b), Guilizzoni & Lami (2002) and Lami et al. (2009) provide a detailed account of the spectrophotometric and chromatographic analyses of the plant pigments, their identification, quantification and interpretation.

Chironomid remains were studied in 82 samples at 1-cm intervals, throughout the core Hess 05-1. Subsamples of 3–4 g wet weight were deflocculated in 10% KOH, heated to 70°C for 20 min and subsequently sieved on a nested pair of 212- and 95-μm mesh sieves. Head capsules were picked from the wet residue in a Bogorov sorting tray under a stereo microscope at 25–40× magnification. Larval head capsules were mounted in Euparal and then identified with reference to Brundin (1966) and Cranston (1997). Chironomid and geochemical data were plotted using C2 software (Juggins, 2003). Data are expressed as percentage of relative abundance and as total concentration of heads capsules (HC) (number g d.w.$^{-1}$).

Data analysis

Profiles from each dataset were split into zones using CONISS (CONstrained Incremental Sum of Squared cluster analysis) with square root transformation to optimise the signal to noise ratio. Dendrograms are not shown to cause the self-evident large changes. Zones were constructed independently for each proxy using variables indicated in each figure. Samples with missing data values for some variables were excluded for the purposes of zonation.

Interpretation of pigment data

In low productivity lakes such as the alpine and remote sites like Lake Hess, a large proportion of the sedimentary organic matter is allochthonous, and pigments are poorly preserved in the terrestrial detritus, owing to its longer exposure to oxidation at the soil surface (Sanger, 1988). Pigments reach the surface of a lake as particulate matter from autochthonous planktonic and littoral organisms. Each population contains pigments that are distinctive and group specific that can be used in palaeoecological studies to indicate, for example, changes in the nature of the physical and chemical environments. The validity of using sedimentary pigments as an index of past events or processes such as trophic conditions and primary productivity depends mainly on the preservation of these relatively labile organic compounds, the extent of differential degradation during and after sedimentation, and the extent of allochthonous sources of sedimentary pigment products (Leavitt, 1993; Lami et al., 2000b).

Chlorophyll *a* is found in all photosynthetic aquatic organisms, with the exception of some species of autotrophic bacteria. Its degradation products (phaeophytin *a*, phaeophorbide *a*, chlorophyllide *a*) are relatively well preserved in lake sediments. Carotenoids are also widely distributed in all photosynthetic organisms. The principal carotene is β-carotene, which is present in all algal taxa. Lutein is present in Chlorophyta and macrophytes. In addition to these in Lake Hess, there are other specific xanthophylls, such as fucoxanthin and diatoxanthin, present in the diatoms, whereas echinenone and in part zeaxanthin are present in the cyanobacteria. Finally, alloxanthin is a carotenoid characteristic of strictly planktonic cryptophytes and could be used in alpine or arctic lakes to identify the degree of thaw experienced. Enhanced alloxanthin concentrations should indicate increased ice-free periods. The variation of alloxanthin (as well as diatoxanthin; Buchaca & Catalan, 2007; Lami et al. 2009) is also used to infer water level changes (Züllig, 1982; Pienitz et al., 1992; Leavitt et al., 1994). Phaeophorbide *a* is typically a pigment related to zooplankton and is produced by zooplankton during grazing (e.g., Leavitt et al., 1994; Buchaca & Catalan, 2007).

Results

Chronology

^{210}Pb-, ^{226}Ra-, and ^{137}Cs-specific activity profiles from Hess 05-3 are shown in Fig. 2. The total ^{210}Pb-specific activity (supported ^{210}Pb) was significantly higher than ^{226}Ra only in the five topmost slices. Therefore, a ^{210}Pb-based estimate of the sedimentation rate was only possible in the upper core section. Since there were few unsupported ^{210}Pb determinations, with highly associated uncertainties, the measured values of the CRS model were fitted to a logarithmic scale, and interpolated values were used. The estimation of the sedimentation rate obtained is 23.2 mg cm^{-2} y^{-1} (0.15 cm y^{-1}). Since Lake Hess is a geomorphologically active environment, approximate extrapolated age values have been calculated only for the core section 8–45 cm using the mean post 1950 sedimentation rates of 23.2 mg cm^{-2} y^{-1}. According to the extrapolation of the sedimentation rate estimated by ^{210}Pb, the sample at 5–6 cm corresponds approximately to 1965, which agrees well with the 1963 fallout peak estimated by ^{137}Cs dating (Fig. 2). From 45 cm downwards, the continuity in sedimentation rate cannot be assumed due to the strong changes in sediment density. No terrestrial plant remains suitable for ^{14}C analysis were found.

Although core Hess 05-3 was taken close to the other cores, the presence of coarser lenticular bodies interbedded in the sedimentary sequence suggests that different processes had affected normal sedimentation in the lake perhaps caused by irregularities in the bottom at the site of extraction.

Lithology and core-to-core correlation

The lithology of the cores shows a generally common pattern; the upper part is a unit composed of black silty organic matter-rich mud with a high abundance of macrophyte remains (Fig. 3). Although this unit has a variable thickness in the different cores (from 8 to 22 cm), it shows similar low values of dry weight (density is only measured in one core) (Figs. 3, 4). Below this unit, the sequence is composed of homogeneous dark grey-brownish organic-rich silty clay sediment, with some scattered macrophyte remains. The other remarkable feature is the presence of tephra layers intercalated in the sequence. Magnetic susceptibility in core 05-2, as well as density and LOI clearly identify these ash layers (Fig. 4). Based on several parameters (dry weight, LOI, tephras and lithology), used independently or in combination, a good correlation of cores Hess 05-1, Hess 05-2 and Hess 05-3 was established (Figs. 3, 4). Core Hess 05-1 is longer than cores Hess 05-2 and Hess 05-3, and shows some differences in lithology. Cores Hess 05-2 and Hess 05-3 appear to have more closely comparable lithologies.

We chose the longest core (Hess 05-1) for a detailed lithological description. This sedimentary sequence consists of three different lithological units: (I) light grey muds with tephra layers at the top; (II) dark grey muds which occur cyclically in the upper part of core and in the bottom of core; (III) black

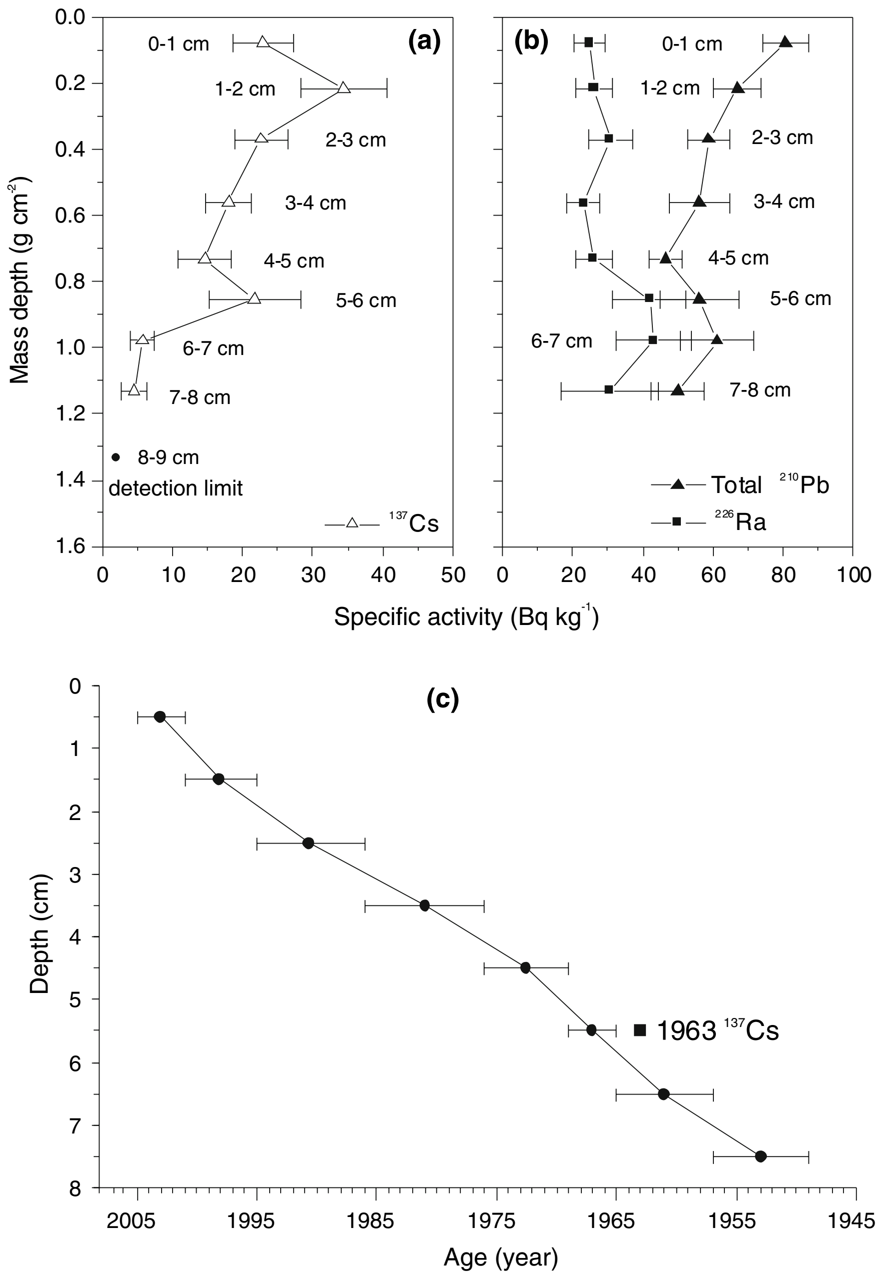

Fig. 2 Profiles of ^{137}Cs-specific activity (**a**); **b** ^{210}Pb and ^{226}Ra (in secular equilibrium with supported ^{210}Pb) specific activity versus cumulative dry mass (g cm^{-2}) in core Hess 05-3; **c** the plot of ages versus sediment depth is based on calculations using the CRS model applied to excess ^{210}Pb data; the depth of the 1963 ^{137}Cs peak is also shown

massive muds with abundant macrophyte remains (Fig. 3).

Abundant remains of macrophytes (mosses) are present between 0 and 6 cm, 12 and 15.5 cm, and 18 and 22 cm. The grey muds are composed of very fine, plastic sediment with faint laminations. This lithological feature is present below 22 cm and includes reworked tephra layers at 25–26 cm, 32–38 cm, 55–56 cm and 58–59 cm.

Tephra layers are located at different depths in the three cores (Fig. 3). The one located at 24–26 cm depth in core Hess 05-1 is characterised by brownish glassy shards, dark and grey fragments (scoria and rock fragments), plant remains and diatom frustules, among other organic materials, included in a silty clay matrix. This layer was related to the tephra located below 19–21 cm in core Hess 05-3 (Fig. 3). According to this characterisation, this ash could be

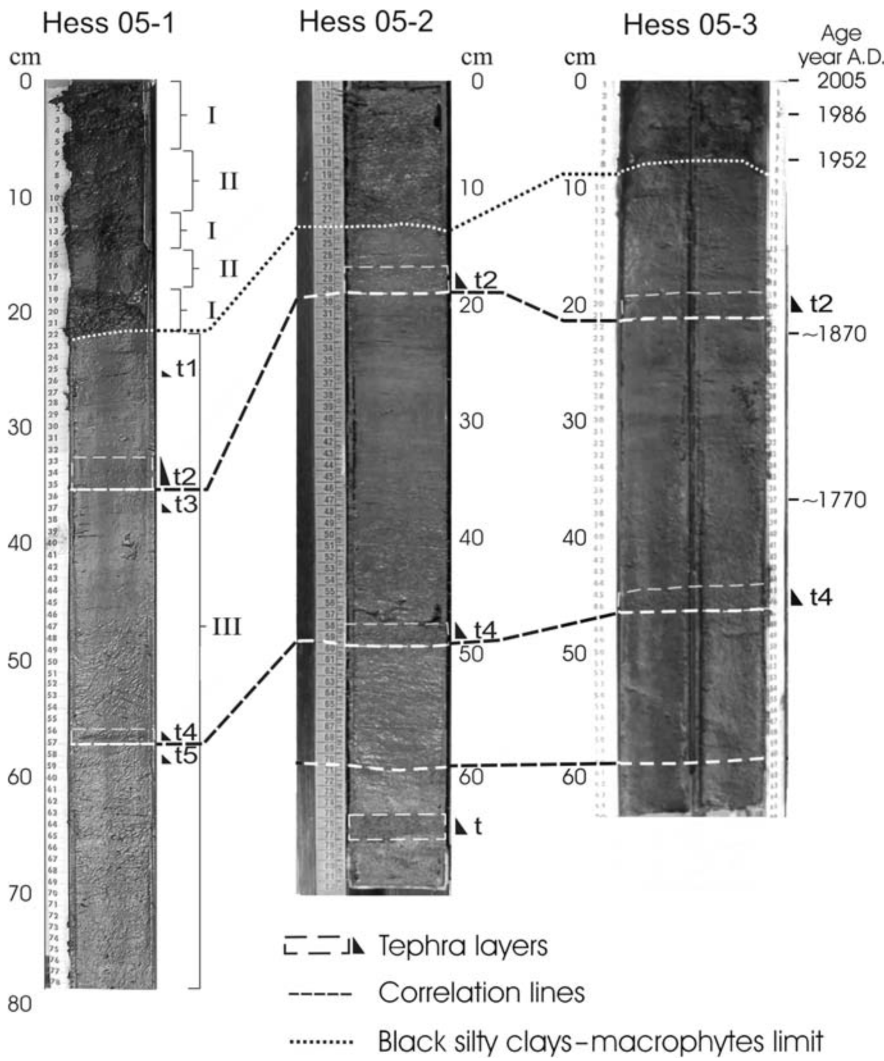

Fig. 3 Core correlations based on lithology and tephra layers (t) from Lake Hess. *Dotted line* correlates the top layer rich in macrophytes. *Dashed lines* indicate both the correlation of the main tephra layers and the thickness of the tephras (cf., the legend). Thickness of the tephras is also indicated by a *triangle*. Sedimentological units (I–III) are also indicated. *Note*: the top of core 05-2 starts at 10 cm (equivalent to 0 cm) because the photograph included the 'green foam' material used to store the sediment core after collection

correlated among cores, and associated with the same volcanic event (Fig. 3). A detailed microscopic and geochemical characterisation of the material is needed to achieve a better understanding of these events. Regarding the tephra layer identified at 16–17 cm in Hess 05-2 (located at 13–14 cm in Hess 05-3), additional analyses would be necessary before we could confidently conclude that they reflect the same event.

Additional tephra layers were identified in Hess 05-1 at the time of sub-sampling at 32–35 cm, 36.5–38 cm and 58–59 cm depths. These were not identifiable in core Hess-05-3. Instead in core Hess 05-3, a coarse tephra was visible at 46–47 cm depth (Fig. 3). In core Hess 05-2, four strong peaks of MS, between 60 and 70 cm, could indicate different volcanic events (Fig. 4).

Magnetic susceptibility and geochemistry

Magnetic susceptibility and dry weight profiles are often indicative of the presence of tephra layers or clastic materials derived, e.g. from episodes of high soil erosion or floods (Thompson & Oldfield, 1986). In our case, dry weight fluctuations are strongly related to tephra layers: three high peaks in core Hess 05-1 are shown at ca. 57, 43 and 25 cm core depth (Fig. 4). Dry weight is negatively correlated with organic matter (LOI). The upper 10–20 cm layer is rich in plant remains.

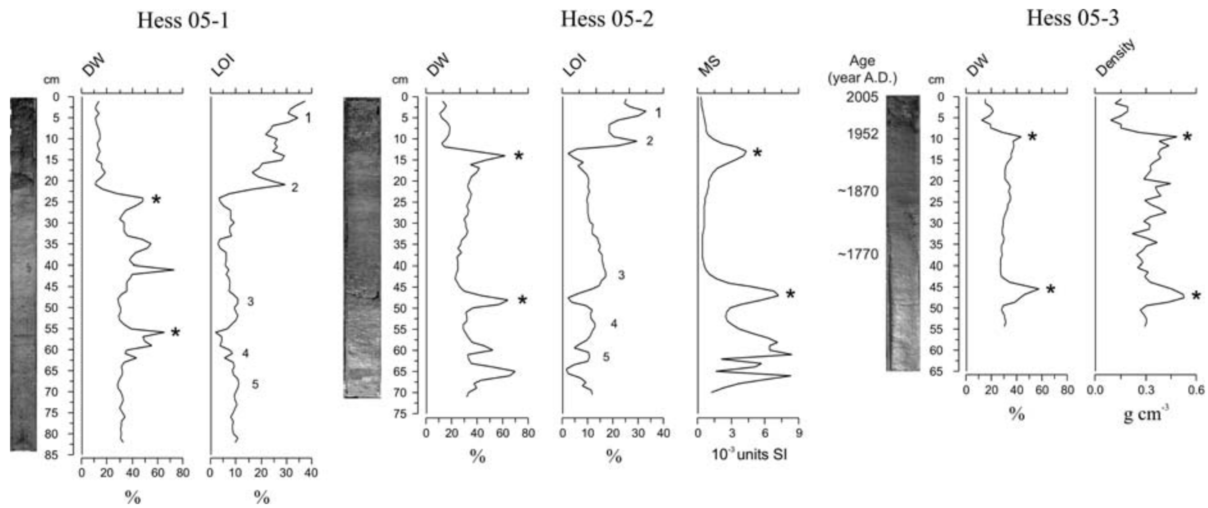

Fig. 4 Lake Hess, cores 05-1, 05-2 and 05-3. Depth distribution of dry weight (DW, % w.w.), density (g m^{-3}), magnetic susceptibility (MS, in SI 10^{-3}) and organic matter content (LOI, % d.w.). Core correlation between cores Hess 05-1 and Hess 05-2, based on LOI, is shown by *numbers*. *Asterisks* show the correlation between cores Hess 05-3 and Hess 05-2, also based on dry weight (d.w.). Additional information from the three cores and their correlation based on lithology and tephra layers is also shown in Fig. 3

Figures 3 and 4 summarise the data for core-to-core correlation and effects of the tephra deposits on organic matter. The same effect of tephra and the sharp increase in LOI in the upper part is also seen in core Hess 05-2 (Fig. 4).

In Lake Hess from ca. 25 cm upwards (zone III), a remarkable increase in LOI (from ca. 8–9% d.w. to ca. 40% d.w.) and plant pigments (see below) document a change in the trophic condition of the lake (Fig. 5). Those levels with LOI higher than the 20% correspond to gyttja. However, this term has been misused so frequently as to have been rendered meaningless (Schnurrenberger et al., 2003). Total carbon and nitrogen contents concentrations show the same recent increase. Sulphur, after a similar increase, decreases in the most recent sediments.

From core bottom to 25 cm (zones I and II), C and N concentrations (Fig. 5) are relatively constant with a few fluctuations, in part related to the impact of volcanic tephra deposits. From the C:N ratio, we infer that the proportion of allochthonous/autochthonous input of organic matter changed over time with a sharp increase from 25 cm onwards associated with the evident input of allochthonous materials (C:N > 10; Meyers & Ishiwatari, 1995). The core section between 50 and 25 cm points to a more autochthonous origin for the organic matter (C:N values around 9–10; Wetzel, 1983).

Fossil pigments

From the total and specific pigment profiles (Figs. 5, 6) we can recognise three main zones in core Hess 05-1: zone I (85–42 cm), zone II (42–25 cm) and zone III (25–0 cm).

The oldest part of the core (zone I) has relatively high algal pigment concentrations, which suggests a period of relatively high algal biomass (Fig. 5) (concentrations of β-carotene are also high). Pigments deceased at the end of this zone. According to the specific pigments (Fig. 6), the phytoplankton composition in zone I consisted mainly of cyanobacteria (echinenone), Chlorophyta (lutein) and siliceous algae (fucoxanthin and diatoxanthin). During this period, there was also a short phase (45–55 cm) where alloxanthin, a pigment specific to cryptophytes, showed relatively high values. Concentrations of phaeophorbides are low.

In zone II (42–25 cm), total and specific pigments (Figs. 5, 6) were barely detectable and indicate a phase of very low algal productivity probably associated to high flux of meltwater since this coincides with the low-productive phase observed among the chironomid remains. Inputs of clastic materials may dilute the pigment concentrations although the dry weight profiles generally do not change markedly except at the level of the tephra layers (cf. Fig. 4).

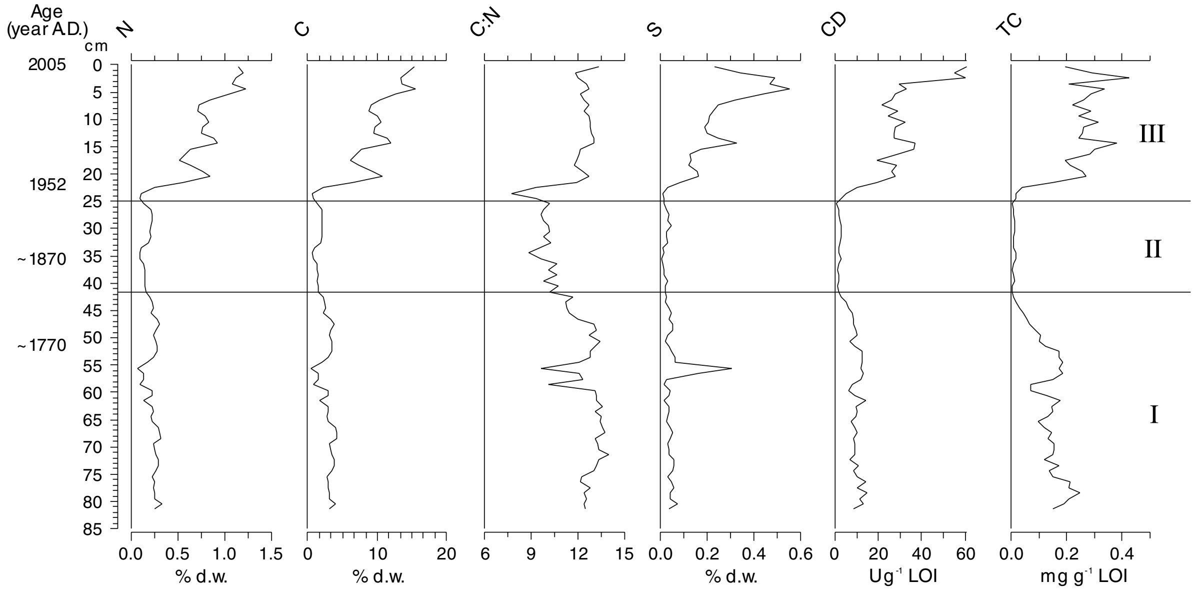

Fig. 5 Total nitrogen (N), total carbon (C), C:N ratio, sulphur (S) in per cent dry weight, total chlorophyll derivatives (CD, Units g^{-1} LOI), total carotenoids (TC; mg g^{-1} LOI) in core Hess 05-1 from Lake Hess. Zones I–III are also indicated

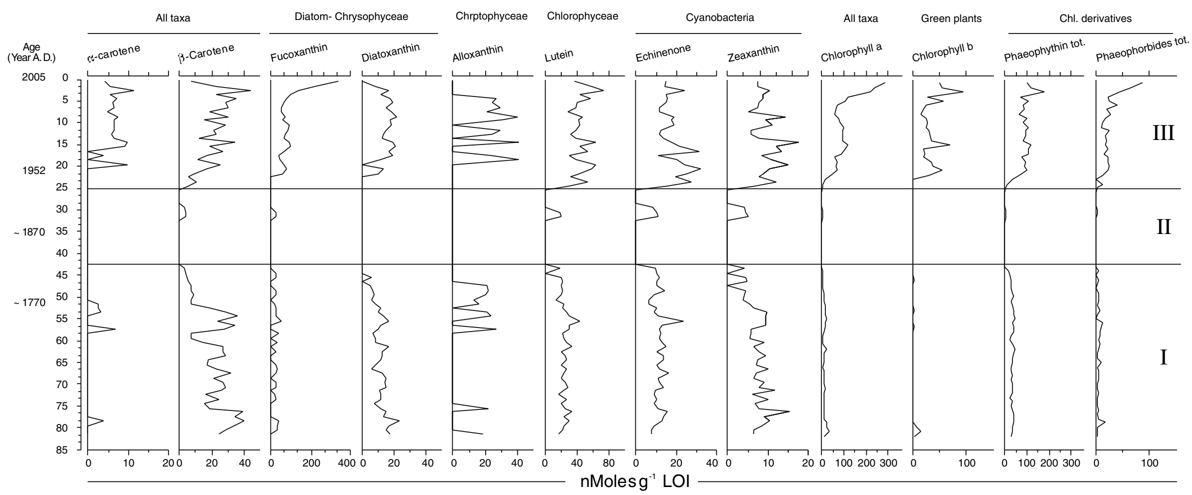

Fig. 6 Selected specific carotenoids and chlorophylls in core Hess 05-1 of Lake Hess. Zones I–III are also indicated

Among the specific carotenoids, the only distinctive episode was a very short-lived event around ca. 30 cm dominated by the presence of green algae and terrestrial vegetation (lutein) and cyanobacteria (echinenone and zeaxanthin).

Zone III (25 cm-top). The recent phytoplankton biomass, as detected by the pigment analysis (Fig. 5, 6), shows higher concentration values compared with the older periods (80–25 cm) and is dominated by siliceous algae (high concentrations of fucoxanthin, diatoxanthin). The carotenoid composition of this zone is also characterised by the presence of planktonic algae (alloxanthin), particularly abundant between 5 and 20 cm, and lutein that show the highest value in this zone. Lutein, as well as chlorophyll *b*, are specific pigments not only in algae, but they are also present in terrestrial vegetation and aquatic macrophytes (mosses remains in our cores). Therefore, their concentration peaks are also very likely associated with the presence of these organisms. Grazing on algae leads to the production of high concentrations of phaeophorbides, suggesting that grazing is an important factor in this zone.

Chironomids

The Lake Hess chironomid record (Fig. 7) is represented by a blend of profundal and littoral/lotic taxa (Brundin, 1958; Saether, 1979). Profundal taxa such as the Tribe Tanytarsini are poorly represented throughout the sequence. A CONISS cluster analysis (not shown) allowed us to divide the assemblages into three distinct zones described and interpreted as follows.

Zone I (from 85 to ∼40 cm) is characterised by the coexistence of upper-littoral, littoral and lotic elements with profundal taxa. Although profundal taxa are present in high abundance (between 20 and 40%), the presence of littoral *Eukiefferiella* and *Demicryptochironomus*, a predator not only found in bottom sediments but also associated with upper littoral zones (Brodersen et al., 1998) together with other littoral elements, generally indicates low water levels. The occurrence of a mixed littoral/profundal chironomid assemblage could thus be related to a decrease in precipitation. As a consequence, as the lake dries, it develops a more fluvial character more strongly influenced by the melting waters of the Tronador ice cap. The presence of *Eukieferiella* and upper littoral chironomid remains could be linked to this fluvial system (Fig. 7).

In Zone II (from 40 to 25 cm), the abundance of head capsules drops sharply. The dominant and almost sole taxa present in this zone are *Ablabesmyia* and *Parapsectrocladius* showing abundance values close to 80%. Littoral and lotic elements disappear. A long period of low productivity (zone II) may correlate in part with a generally cold and wet period. During this period, chironomid assemblages are represented by profundal taxa, indicating an increase in precipitation, an increase in the lake water level and therefore, a more lotic regime. Another notable aspect of zone II is the decrease in the concentration of head capsules (total HC; Fig. 7) just after the tephra deposition, coinciding with the decrease in all biotic parameters studied (Figs. 5, 6). Three tephra layers were identified in this section, recording volcanic events that may strongly affect lake dynamics. Only *Ablabesmyia* and *Parapsectrocladius* relative abundance increased in zone II, while other taxa decreased drastically, revealing of the way in which these two genera are favoured by this kind of sediment, as observed by Urrutia et al. (2007) in Lake Galletué (Chilean Andes).

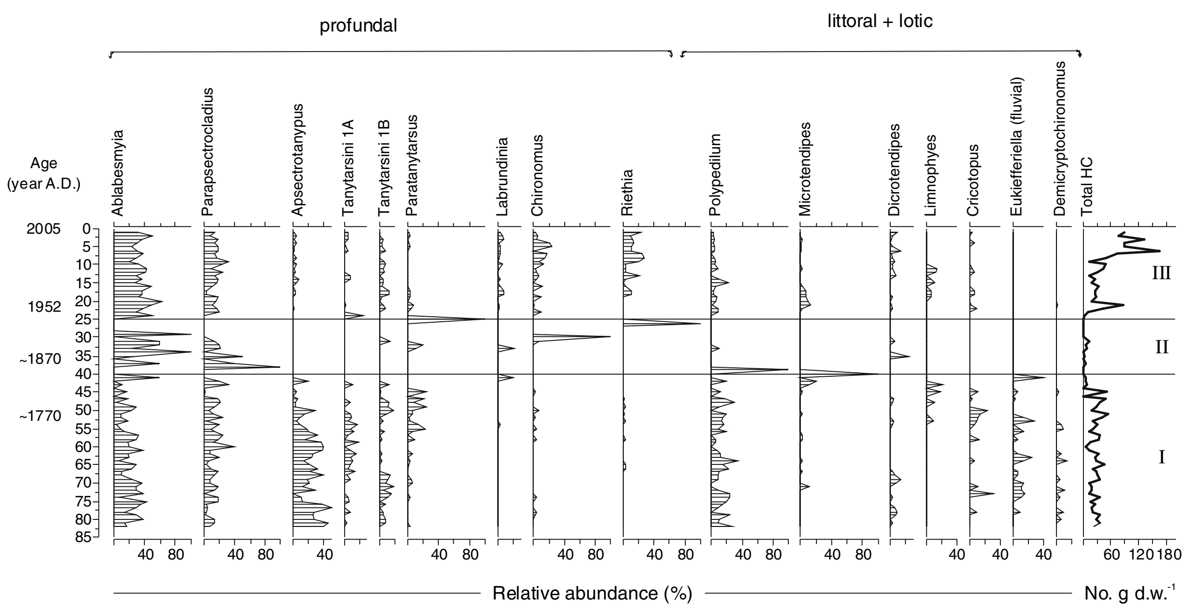

Fig. 7 Chironomid percentage diagram showing the most abundant taxa found in the Lake Hess sediment core (Hess 05-1). The taxa are grouped according to profundal and littoral plus lotic habitats. Zones I–III are also indicated. HC = head capsules

The uppermost zone III (25–0 cm) is characterised by the increase in profundal *Chironomus* and *Riethia* (Massaferro et al., 2008) and the appearance of littoral taxa such as *Limnophyes* and *Cricotopus*. It is interesting to note the total disappearance of *Apsectrotanypus* and *Eukiefferiella* which were very well represented in zone I.

Discussion

Multi-cores, multi-proxy analyses at Lake Hess show a number of palaeolimnological changes which, according to our extrapolated sedimentation rates, should represent ca. three centuries of lake and catchment history.

The ^{137}Cs fallout sequence in the sediments of some lakes from the Nahuel Huapi National Park area has been determined previously (Ribeiro Guevara & Arribére, 2002; Ribeiro Guevara et al., 2003). The most intense fallout peaks were registered in 1964–1966, as a consequence of the combination of stratospheric and tropospheric fallout, with the tropospheric contributions coming from the South Pacific nuclear tests. Another ^{137}Cs peak, associated mainly with tropospheric fallout, was detected in 1970–1972, with a secondary peak in 1974. No other relevant ^{137}Cs fallout was evident—not even the 1986 Chernobyl nuclear power plant accident that produced little stratospheric ^{137}Cs fallout in 1987 and 1988 and was not relevant here for dating purposes. The ^{137}Cs specific activity profile for the topmost 8 cm of our core did not follow the fallout sequence, and the reasons could be caesium mobilisation after deposition and/or sediment mixing.

Lake Hess sediments are represented by a dominance of organic matter-rich clay and are rich in tephra deposits particularly in the lower part of the cores. The lithology, tephras and geochemical parameters have been used for core correlation (Figs. 3, 4). Previous studies performed on sedimentary sequences from water bodies from Nahuel Huapi National Park demonstrated that the region was impacted by frequent volcanic eruptions from the Calbuco volcano and Puyehue-Cordón Caulle volcanic system with the Calbuco volcano eruptions being the most important affecting the south of the park (Daga et al., 2006, 2008a). However, it is not possible to assign dates to the eruptions without a better geochemical characterisation of the tephras providing a basis for correlation with potential source eruptions (Daga et al., 2008a). For the present, the sequence of tephras in the lower part of the cores cannot be used to strengthen the age model suggested here.

Although tephra layers from volcanic eruption events deposited in the lake may have had an impact on the biota, the main biological changes may have been in response to hydrological-related environmental changes in the catchment area.

Based on algal biomass (as inferred from the photosynthetic pigments), nutrient and chironomid assemblage analyses, three main intervals were evident along core Hess 05-1: at 85–40 cm (zone I; pre-AD 1800), 42–25 cm (zone II; ca. AD 1800–1940) and 25- top (zone III; last 50 years).

Zone I is characterised by low water level and low precipitation. In fact, the phaeophorbides (a marker carotenoid of zooplankton), as well as alloxanthin, are associated with a more lentic conditions (Buchaca & Catalan, 2007). In this zone, the sporadic presence of alloxanthin (cryptophytes, a truly planktonic algal group) is usually associated with high lake water levels (Pienitz et al., 1992). In general, however, zone I is characterised by a low water level and lower grazing pressure as shown by the generally low concentrations of phaeophorbides (Leavitt et al., 1994) compared with the rest of the core (Fig. 6).

Zone II shows intermediate environmental conditions, likely associated with relatively cold temperatures. From the organic matter, pigment contents and chironomid profiles, a long period of very low productivity is inferred. This is in agreement with a palaeoenvironmental study of the nearby Lake Frias (Ariztegui et al., 2007).

In zone III, the littoral/profundal chironomid fauna again indicates a lentic environment and a decrease in precipitation. From pigment (Fig. 6) and chironomid total abundance profiles (Fig. 7), it is possible to distinguish further trophic and hydrological changes in the topmost 10 cm which could be linked to the temperature increase in the recent times. A strong increase in nutrient (C, N) and sulphur concentrations (Fig. 5) occurs synchronously with these biotic changes. Also, the presence of macrophyte remains in the topmost 10 cm can be related to a decrease of water level and dry periods which, in turn, might suggest an increase in productivity. We cannot exclude the possibility that these changes during the last century are caused by an increased flux of inorganic sediments via the meltwater input. We believe that these changes are strongly affected by the physical environment such as water level fluctuations and the lotic/lentic regime of the lake, associated with dry/wet periods and incoming water from the glaciers. Chironomid assemblages, showing changes in profundal/littoral and lotic elements, confirm these repeated dry/wet alternations.

Another study based on a sedimentary sequence collected in Lake Toncek (1,700 m a.s.l.) from Nahuel Huapi National Park shows that both natural and anthropogenic events (long-range atmospheric transport of pollutants) occurred in the region during the last 900 years (Rizzo et al., 2007; Daga et al., 2008b; Ribeiro Guevara et al., 2009). The study of sub-fossil chironomid assemblages showed the predominance of *Pseudosmittia* and cold-stenothermic Podonominae from eleventh to seventeenth centuries, which decrease in the upper layers (eighteenth century to present) being replaced by the warm-adapted Tanypodinae. These observations together with a continuous increase of abundance and diversity indices during the twentieth century (Rizzo et al., 2007) are consistent with the observations in the sediment record from Lake Hess.

In summary, remote oligotrophic lakes Hess and Toncek both show biological and geological changes mainly related to climate and regional environmental variations. In contrast, at Lake Morenito (a small closed basin close to Lake Hess), located in an anthropogenically disturbed environment, the changes recorded were mainly related to productivity change due to human impact over the last 100 years (Massaferro et al., 2005).

Biological and geochemical profiles from Lake Hess sediment cores confirm a varying pattern of climate change. Chironomid assemblages show profundal, littoral, sub-littoral, terrestrial and fluvial elements, which may indicate alternating dry/wet periods. Whether the environmental variations are the result of the varying dominance of moisture and/or temperature controlling the Tronador Glacier mass balance remain an elusive question (Ariztegui et al. 2007).

In conclusion, owing to the remote location of this lake, this high-resolution short-core multiproxy study has added some valuable information on changes probably related to the westerlies influence and possibly ENSO-related variability (Jenny et al., 2002), and the occurrence of volcanic events in the area. Further research is needed in Patagonia, particularly to asses the extent to which climate changes over the last millennium have occurred in response to the El Niño Southern Oscillation (ENSO), Little Ice Age (LIA) and other short-term climate events in southern South America.

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