11

Late Pleistocene Environmental Change in Eastern Patagonia and Tierra del Fuego – A Limnogeological Approach

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1. Introduction: Lakes and Limnogeology

Modern lakes and lacustrine sediments are ideal sites to study both ongoing and past environmental changes. Limnogeology refers to a broad approach to study lake sediments, investigating complex systems and their interactions and, thus, it is interdisciplinary by nature. This chapter summarizes geophysical, sedimentological and geochemical results from several lacustrine basins in eastern Patagonia and Tierra del Fuego. These examples illustrate the potential of a multiproxy limnogeological approach to tackle some of the standing questions dealing with the Late Quaternary environmental evolution of southernmost South America.

Lacustrine basins are ideal sites to study a wide variety of geological processes and their sediments can be used as excellent archives of past environmental changes. Hence, modern lakes and their sediments have always fascinated earth scientists and naturalists in general. Early on, lakes have been compared with oceans. In 1705 AD, an Italian naturalist, Count Marsili, in his wandering with his Swiss colleague J.J. Scheuchzer described some Swiss lakes as “small seas” with all attributes of their larger counterparts such as the Mediterranean (Kelts, 1987). At the end of the nineteenth century, F.-A. Forel was the first to recognize the enormous erosional power of the turbidity currents generated by the turbid Rhône River when entering Lake Geneva and set up the basis of the new field of limnology (Forel, 1892). Almost contemporaneously with this Swiss scientist, Gerard De Geer started to explore the potential of lacustrine sediments in Scandinavia to archive environmental information with a high temporal resolution (De Geer, 1912, 1927a). In his pioneer study of several Swedish proglacial lakes, he defined the concept of varves or annually laminated sediments. He further proposed that long- and short-term responses of glaciers to globally concurrent climatic changes could be inferred using the sedimentary record of proglacial lakes. Several of his doctoral students went to distant areas in the world searching for varved records that could then be compared to the freshly established Swedish varve chronology. Years later, De Geer concluded that glacial growth in both hemispheres inferred from these records occurred in response to a global, astronomically controlled or “cosmic”, forcing mechanism (De Geer, 1927a, b). He referred to a *Cosmic Melody* that dictated climate change – a very poetic and early version of the Milankovitch orbital theory. One of the audacious De Geer’s students was Carl Caldenius, who went to Patagonia and – as mentioned in several chapters of this book – set up the grounds of our present knowledge about glaciations in the region. He published in the Swedish journal *Geografiska Annaler* in the 1930s, the first classic papers regarding glaciations in the Southern Hemisphere (Caldenius, 1932). He further compared varved lacustrine records from Sweden with varve series from proglacial lake sediments outcropping at the Corintos River, Argentina (43°10′ S, 71°20′ W). Many marine and continental records have been obtained at both boreal and austral latitudes since this pioneer attempt of interhemispheric climate correlation.

Limnogeology, as defined by Kerry Kelts in the early 1980s, refers to a broad approach to study lake systems driven by the progress in ocean research in the context of marine geology (Kelts, 1987). Thus, it includes the study of complex systems and their interactions and is interdisciplinary by nature. At present, this approach has become widely accepted and a large number of lake studies are performed all over the world including South America (e.g. Baker *et al.*, 2001; Bradbury *et al.*, 2001; Piovano *et al.*, 2002; Brenner *et al.*, 2003 among others). There is, however, a very limited number of publications dealing with both modern lakes (e.g. Baigunand and Marinone, 1995; Cielak, 1995) and ancient lacustrine sediments in Patagonia (e.g. Iriondo, 1989; Ariztegui *et al.*, 2001; Zolitschka *et al.*, 2004). In this contribution, we would like to summarize some of the results of our research of the last 10 yrs in eastern Patagonia (Fig. 1). These examples illustrate the use of a multiproxy limnogeological approach to tackle some of the standing questions dealing with the Late Quaternary environmental evolution of southernmost South America.

2. Main Components of the Patagonia Climate System

The study of present climates indicate that only a few places on the globe are dominated by a single meteorological element as southernmost South America with the persistence and strength of westerly winds (Prohaska, 1976). As backbone of the continent, the Andean Cordillera is a major geographical barrier that generates a sharp

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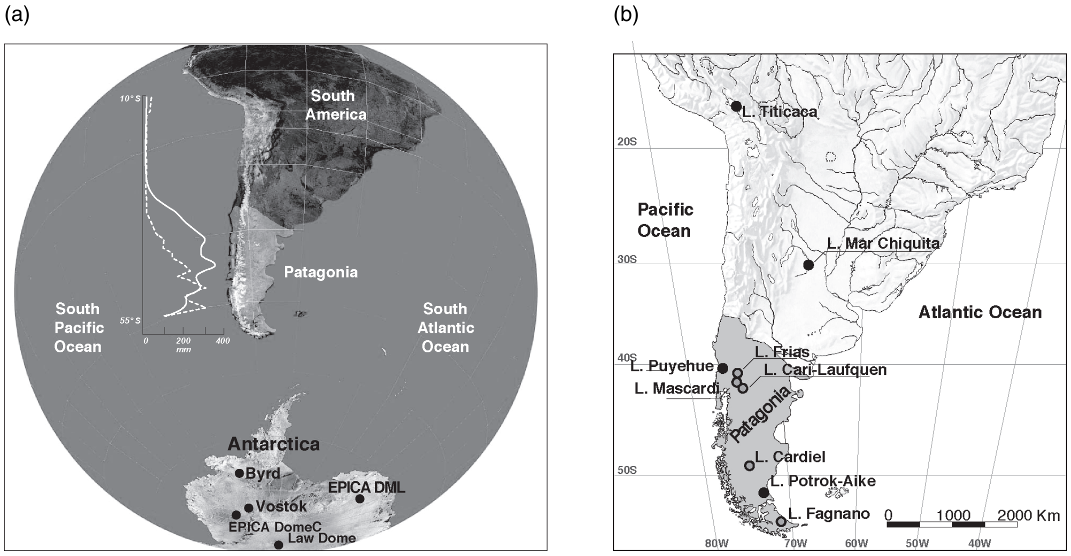

Fig. 1. (a) Map of South America showing the location of Patagonia as defined in this publication. Average annual precipitation in the region displays a sharp latitudinal gradient with a strong seasonal imprint as shown on the left panel (after Lawford, 1996). Paleoenvironmental records from Patagonia are particularly suited to be compared with the growing dataset emerging from Antarctica ice cores (PAGES News, 2006); (b) Map displaying the lake sites discussed in this article (gray dots) and other records used for comparison (black dots).

longitudinal trend in precipitation. While most of the moisture is precipitated on the western (Chilean) side of the Andes, a striking gradient in precipitation characterizes the eastern (Argentinean) side that can decrease from 4000 to 200 mm×yr^{-1} in less than 200 km within a west–east transect. Meteorological data from western Patagonia show an additional sharp latitudinal gradient in precipitation with a clear seasonal behavior (Lawford, 1996; Fig. 1). This gradient mimics seasonal variations in wind intensity (i.e. westerly winds). While the westerlies migrate poleward during Austral summer (December–March), the associated storm tracks are centered around 45° S. Its northern migration during winter (July–September) to latitude of $\sim$40° S generates a well-defined rainy season. Recent instrumental data indicate that the southern westerly belt intensity and associated storm tracks are related to the strength and latitudinal position of the subtropical anticyclone in the southeastern Pacific and the circum-Antarctic low pressure belt (Pittock, 1978; Aceituno *et al.*, 1993). Due to its particular geographical location, Tierra del Fuego is affected directly not only by the westerly winds but also by the Southern Ocean circumpolar flow and the South Pacific Gyre. Markgraf (1993) suggested that the onset of the modern behavior with a seasonal latitudinal shift of the westerly winds occurred sometimes during the Middle Holocene. The past location of the southern westerlies during the Last Glacial Maximum (LGM), however, is still controversial (e.g. Heusser, 1989; Markgraf, 1989; Lamy *et al.*, 1999; Jenny *et al.*, 2001). This uncertainty is partially related to the paucity of multiproxy records with enough latitudinal coverage and comparable high time resolution.

In this chapter, we briefly review a series of case studies that combine seismic stratigraphy and multiproxy results of seismically targeted sediment cores (Fig. 1b). The combination of these results provides information essential to the interpretation of the paleoclimate evolution of southernmost eastern Patagonia for the Late Quaternary. The following examples have been selected to illustrate a range of environments:

- Northernmost Patagonia: Proglacial open lakes, Mascardi and Frias; and Laguna Cari-Laufquen (41° S), a closed-basin system.
- Central Patagonia: Lago Cardiel (49° S) illustrates a relatively large closed basin.
- Southernmost Patagonia: Lago Fagnano (54° S) is an open lake system representing the largest and southernmost non-ice covered lake in the world.

All these examples will be cross-correlated and confronted with the existing limnogeological datasets from the Patagonian region of Argentina and Chile. The main goals pursued with these case studies are (1) to check on the timing and magnitude of the observed stepwise climatic evolution of the Lateglacial–Holocene transition; (2) to identify latitudinal variations during the Early Holocene; (3) to spot changes in El Niño Southern Oscillation (ENSO) activity during the second part of the Holocene; and (4) to highlight new evidence for the Little Ice Age (LIA) at different latitudes.

3. Methodology

The different case studies discussed in this chapter utilized various types of seismic data acquisition and processing as well as diverse coring equipments. All the investigations, however, were conducted using the same limnogeological approach that includes a seismic survey prior to coring followed by a true multiproxy laboratory study.

More than 150 km of seismic profiles were collected in lakes Frías, Mascardi (1993/94) and Cari-Laufquen Grande (1998) using an ORE-geopulse 3.5 kHz single-channel pinger system with a vertical seismic resolution of ~10–20 cm (Ariztegui *et al.*, 2001). The system achieved a maximum of 40–50 m of penetration, and navigation was accomplished through conventional Global Positioning System (GPS) system. Long sediment cores were retrieved in Lago Mascardi using a Kullenberg system from a self-propelled coring platform (Ariztegui *et al.*, 1997), whereas only short gravity cores were obtained in both lakes, Frías and Cari-Laufquen (Ariztegui *et al.*, 2007). Additional vibrocores were taken in Laguna Cari-Laufquen Grande in April 2000 (Gilli, 1999).

Over 240 km of seismic profiles and ~90 m of sediment cores were recovered in the Lago Cardiel Basin during two-field campaigns in 1999 and 2002 in the framework of the multidisciplinary, international Patagonian coring project (Ariztegui *et al.*, 1998; Gilli *et al.*, 2001). Seismic surveys were conducted using three different systems (3.5 kHz pinger, 1–12 kHz boomer and 1 in^3 airgun) to optimize resolution and acoustic penetration of the imaged sections (Gilli *et al.*, 2005a, Beres *et al.*, 2008).

In March 2005, >800 km of geophysical data were acquired in Lago Fagnano, combining simultaneous single-channel 3.5 kHz (pinger) with 1 in^3 (airgun) multichannel systems. A preliminary set of short gravity cores were recovered at selected locations (Waldmann *et al.*, 2008).

All retrieved cores were stored in a dark cold room at 4°C and scanned prior to opening at the ETH-Zürich with a GEOTEK^{TM} multisensor core logger to obtain the petrophysical properties (P-wave velocity, gamma-ray attenuation bulk density and magnetic susceptibility). After opening, the cores were photographed and described in detail.

Element mapping in selected samples at ca. 50 μm resolution was carried out at the University of Geneva with a Röntgenanalytik Eagle II Micro X-ray Fluorescence system using a Rh tube at 40 kV and 800 mA.

Chronology was resolved through accelerator mass spectrometry (AMS) radiocarbon dating and further combined with ^{137}Cs fallout and tephrochronology for lakes Frías and Cardiel, respectively.

4. Limnogeological Case Studies from Northeastern Patagonia

4.1. Lago Mascardi

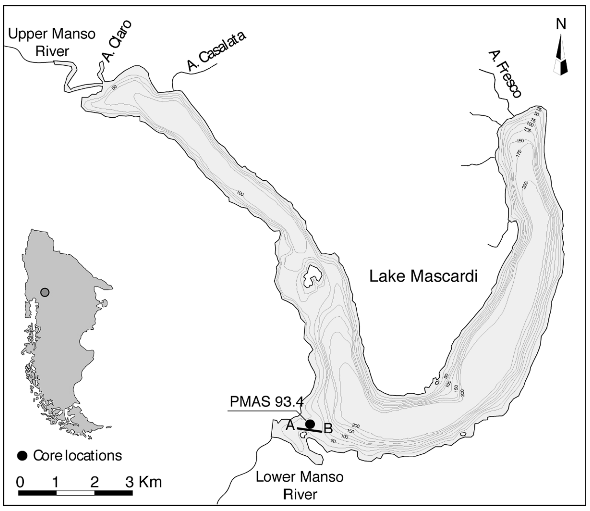

Fig. 2. Bathymetric map of Lago Mascardi showing the location of seismic profile AB close to the lake's outlet and the position of core PMAS 93.4 discussed in this chapter.

Proglacial Lago Mascardi is located ~15 km east of the Tronador ice cap (41°10′ S, 71°53′ W; 3554 m a.s.l.), at an altitude of ~800 m a.s.l. This horseshoe-shaped lake has a surface area of 38 km^2 and a maximum water depth of ~200 m (Fig. 2). The western branch of the lake is directly fed by glacial meltwater through the Upper Manso River. Previous work showed that the extent of the Tronador ice cap is sensitive to both winter precipitation, derived from the Southern Pacific Westerlies, and mean summer temperatures (Villalba *et al.*, 1990). Thus, Lago Mascardi sediments record fluctuations in glacial meltwater activity providing evidence of the Southern Hemisphere postglacial climate variability (Ariztegui *et al.*, 1997 and references therein).

The bathymetry of this lacustrine basin was reconstructed using ~60 km of 3.5 kHz seismic profiles that further allowed the identification of the dominant sedimentary geometries as well as the effects of climate and neotectonics on lake sedimentation. The latter is critical since the lake is located in an area of significant Holocene volcanic activity associated with earthquakes of variable magnitude (Chapron *et al.*, 2006). Seismic profiles image the sediments up to 50 m below the lake floor, representing approximately the last 15,000 yrs of infill history. Sedimentation is characterized by a relatively simple stratigraphy with sporadic thin, up to a few centimeter thick packages of chaotic debris (Fig. 3). Bedrock surface and overlying thick proglacial sediments reflect glacial erosion and the impact of proglacial meltwater influxes to the basin. Although the predominant pattern of sedimentation comprises simple and continuous basin infilling, variable sedimentation rates as well as hiatuses were identified in certain areas of the lake (Ariztegui *et al.*, 2001).

The combination of seismic profiles with results of multiproxy analyses from a set of sediment cores allowed to establish a well-dated lithostratigraphy (Ariztegui *et al.*, 1997) that was further refined for the last glacial transition using a high-resolution AMS ^{14}C dating approach (Hajdas *et al.*, 2003). A non-interpreted seismic profile at 30 m water depth is shown in Fig. 3 (see Fig. 2 for profile location). Different gray shades in the zoomed rectangle indicate the interpreted seismic sequences mapped by tracing reflection terminations abutting unconformities. Radiocarbon ages in core PMAS 93.4 were assigned to sediment layers equivalent to prominent seismic

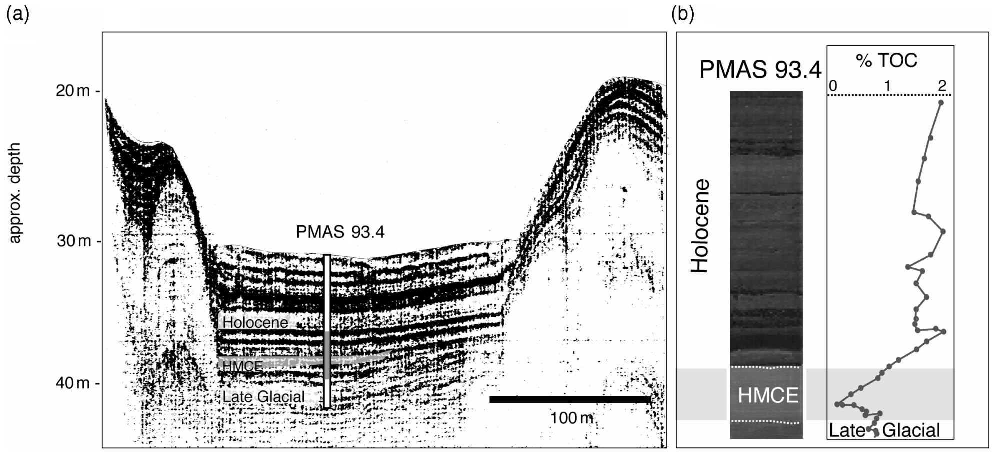

Fig. 3. Seismic profile showing distinctive seismic facies for both Lateglacial and Holocene sediments. The light gray zone indicates the Huelmo-Mascardi Cold Event that is visualized in core PMAS 93.4 (located in this seismic section) by both increasing quality of the lamination and total organic carbon content.

reflections (Ariztegui *et al.*, 1997; Hajdas *et al.*, 2003). Coherent high-amplitude reflections characterize the Holocene, whereas low amplitude to transparent facies distinguishes lateglacial deposits. These different seismic facies are caused by differences in physical properties. Mapping of reflection patterns that define seismic unconformities indicate two major environmental events probably representing lake-level changes (Fig. 3). The first of these unconformities corresponds to the Lateglacial–Holocene transition, also noticed by a distinct onlap surface. The sedimentation at this relatively shallow site is very sensitive to changes in water depth recorded in the sediments not only as a change in lithology, but also as a change in sediment geometry as documented by the onlapping reflections. The multiproxy analyses of a sediment core retrieved in this part of the lake show further changes in the percentage of total organic carbon throughout time. Hence, combined acoustic, lithological and geochemical features indicate an abrupt rather than a smooth change in the depositional environment related to climate change (Ariztegui *et al.*, 1997). The excellent chronology of these changes and their synchronism with the equivalent Huelmo site on the western side of the Andean Cordillera (Moreno *et al.*, 2001) allowed to define the Huelmo-Mascardi Cold Event (HMCE) interpreted as a cool event encompassing the European Younger Dryas chronozone, the Gerzensee/Killarney Oscillation and intervening warm spell (Hajdas *et al.*, 2003). The second and youngest unconformity seems to be associated with an event in the Middle Holocene (~6.0 ka) showing a less prominent impedance contrast than the Holocene boundary and, thus, may reflect a less abrupt change in environmental conditions.

4.2. *Lago Frías*

Like the Lago Mascardi system, Lago Frías (40° S, 71° N, 790 m a.s.l.) is a proglacial lake located ~7.5 km north of the Frías Glacier that is one of the seven Argentinean tongues of the Tronador ice cap with well-identified glacial advances between 1800 and 1850 AD and recent push moraines (Rabassa *et al.*, 1979; Villalba *et al.*, 1990). We carried out the first bathymetric survey in 1994 documenting a maximum water depth of 75 m for this 4.1 km long and 1.1 km wide lacustrine basin (Fig. 4).

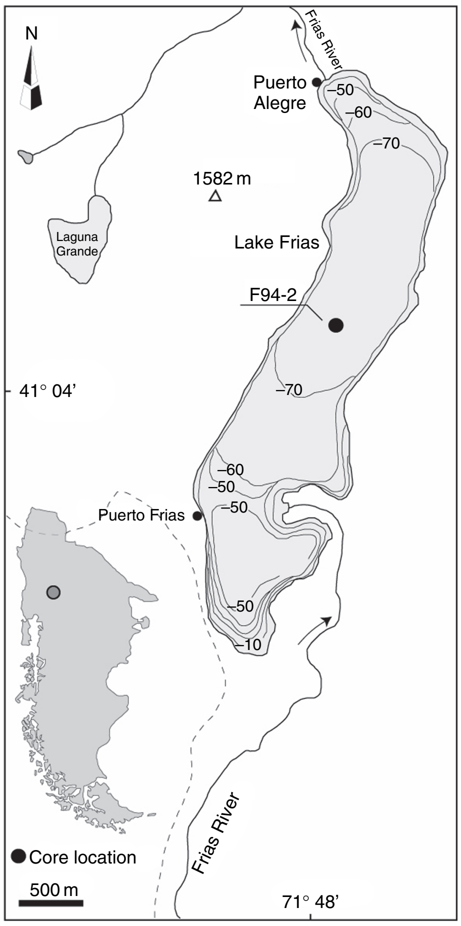

Fig. 4. Bathymetric map of Lago Frías displaying the location of sediment core F94.2 discussed in this chapter. This proglacial lake is located much closer to the Tronador ice cap than Lago Mascardi.

During the twentieth century, the ENSO and ENSO-like phenomena have dominated climatic variations in the Americas on interannual as well as decadal time scales (Dettinger *et al.*, 2001). The ENSO impact on local climate has been well determined using meteorological, historical and dendrochronological approaches at the Frías valley (Villalba *et al.*, 1990, 1998). More recently, a sediment trap study in Lago Mascardi covering the 1992–1998 interval combined with meteorological data has shown changes in sedimentation rates that can be linked to ENSO climatic events (Villarosa *et al.*, 1999). Since proglacial Lago Frías, like Lago Mascardi, is fed by the Tronador ice cap, the laminated sequence of Lago Frías can provide a continuous record of ENSO and ENSO-like variations through time.

Similar to Lago Mascardi, Lago Frias is located in a tectonic and volcanic sensitive region. The latter combined with the abrupt margins of the basin are both propitious features to generate mass wasting events, precluding the accumulation of undisturbed sediments in all areas. Non-perturbated areas of the lake bottom were spotted in the field using high-resolution seismic profiling that further allowed to target core sites containing well-laminated sequences (Ariztegui *et al.*, 2007).

The combination of instrumental and historical information as well as event stratigraphy and radioisotopic data permitted the calibration of the sedimentary model in core F94-2 (Fig. 4), generating a robust chronology that confirms the annual character of the lamination (Fig. 5). Variations in the thickness of the clay lamina of a continuous laminated sequence have been related to changes in winter precipitation covering the last ~200 yrs. Statistical analyses of this dataset indicate a dominant ENSO signal that has been previously identified in the Frías valley using tree rings (Villalba *et al.*, 1990; 1998), and more recently in the sedimentary sequence of Lago Puyehue on the Chilean side of the Andes (Boës and Fagel, 2008; see Fig. 1 for lake location). Conversely, these lacustrine records indicative of variable cold and rainy conditions during the LIA seem to be out of phase with the contemporary record of Laguna Mar Chiquita in subtropical Argentina (Piovano *et al.*, 2002, 2004; refer to Fig. 1 for site location). Furthermore, the Lago Frías laminated sequence shows additional frequencies superimposed on the decadal ENSO variations that can be related to both the 11 yrs solar cycles and the Tropical Atlantic Dipole (TAD) (Ariztegui *et al.*, 2007).

4.3. Laguna Cari-Laufquen

Laguna Cari-Laufquen Grande and its small tributary Laguna Cari-Laufquen Chica (Fig. 6) are two closed basins located in a tectonic depression surrounded by basalt plateaus or "mesetas" of Mesozoic to Tertiary age (Coira, 1979). In contrast to lakes Mascardi and Frías, this region was not affected by the last glaciation of the Andes Cordillera. At an elevation of 800 m a.s.l., lakes Cari-Laufquen Grande and Chica are ephemeral, brackish water bodies with an average water depth of ~3 m during the rainy season. Although high precipitation rates characterize the Andean region at the same latitude (e.g. lakes Frías and Mascardi), the mean annual precipitation in Laguna Cari-Laufquen is only about 200 mm/yr, occurring primarily in the winter months (May–August). Mean annual temperature is 4°C with prevailing winds from the west. Paleoshorelines have been observed and mapped at elevations up to 68 m above the present lake level (Coira, 1979), and even older shorelines up to 100 m above today's level have been previously described (Galloway *et al.*, 1988). During these lake-level highstands, both lakes merged forming a large paleolake. Today, they are two separate basins but connected through the Río Maquinchao (Fig. 6). Dated paleoshorelines indicate higher lake levels than nowadays occurring ca. 19 ka (Galloway *et al.*, 1988) and also between 14 ka and 10–8 ka (Bradbury *et al.*, 2001). Finegrained lacustrine deposits underlying the uppermost two shorelines contain high amount of diatoms and ostracods suggesting deposition in a deeper, saline and alkaline lake (Cusminsky and Whatley, 1996).

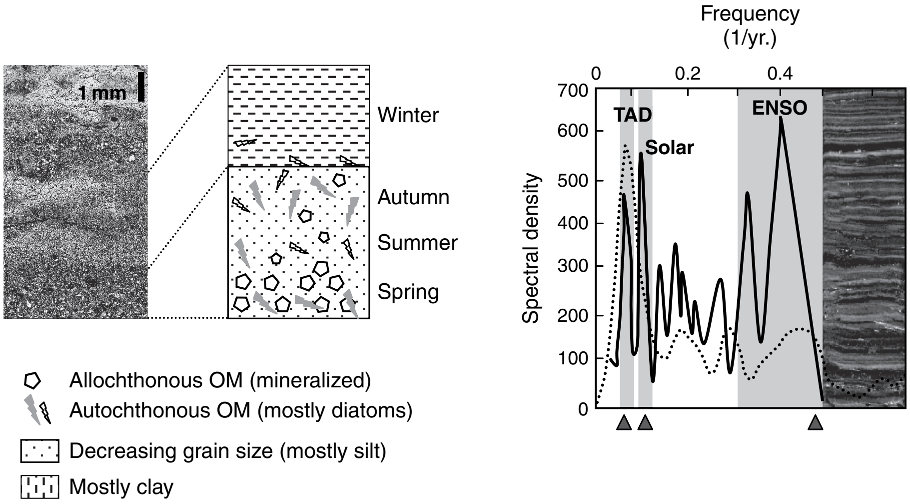

Fig. 5. SEM backscattering microphotograph of a representative section of Lago Frías varves as shown in the interpreted sketch on its right. The statistical analyses of these annually deposited sediments indicate a dominant but not exclusive ENSO signal (see text for discussion).

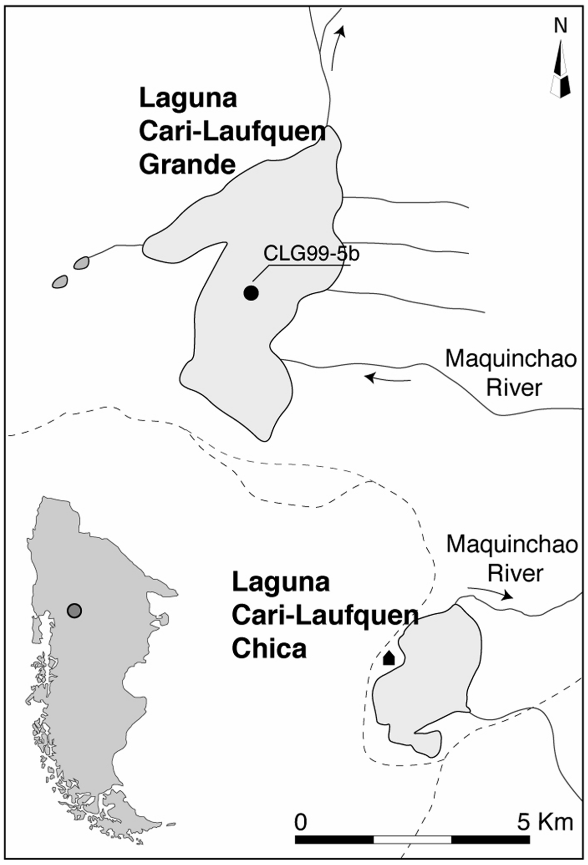

Fig. 6. Location map for lakes Cari-Laufquen Grande and Cari-Laufquen Chica presently joined by Río Maquinchao. The black dot in Laguna Cari-Laufquen Grande indicates the location of sediment core CLG99-5b.

A seismic survey using a 3.5 kHz pinger system was undertaken in both lakes (Anselmetti *et al.*, 1998). The dominant organic-rich sediments of Laguna Cari-Laufquen Chica prevent the acquisition of any subsurface images. Conversely, seismic sections obtained in Laguna Cari-Laufquen Grande yielded good acoustic stratigraphy in the central area of the lake. A very weak waterbottom multiple allowed imaging subsurface geometries in great detail to a depth of over 15 m documenting major structures related to paleo-lakelevel variations (Ariztegui *et al.*, 2001).

These geophysical data were used for choosing optimal coring sites. Sediment cores were retrieved using a short core and a vibrocoring system (see Fig. 6 for core location). Figure 7 shows results from multiproxy analyses of core CLG99-5b. Sharp differences in sediment color and fabric are accompanied by concurrent changes in both physical properties and geochemical character of the sediments. Increasing values of density and magnetic susceptibility may indicate lowstand and even desiccation intervals. Conversely, sediments holding relatively higher organic carbon and carbonate contents have been most probably deposited during periods of comparatively higher lake levels than today. Two range finding AMS ^{14}C dates indicate very variable sedimentation rates that support the hypothesis of alternating erosional or constructional processes at or near desiccation levels in the lake during the Late Quaternary (Ariztegui *et al.*, 2001). As a result, the sedimentary record is fragmented containing several hiatuses that, if well-dated, can provide a unique record of dramatic changes in the hydrological balance. A dataset combining modern ostracod assemblages and stable isotopes from the region indicates that biological remains

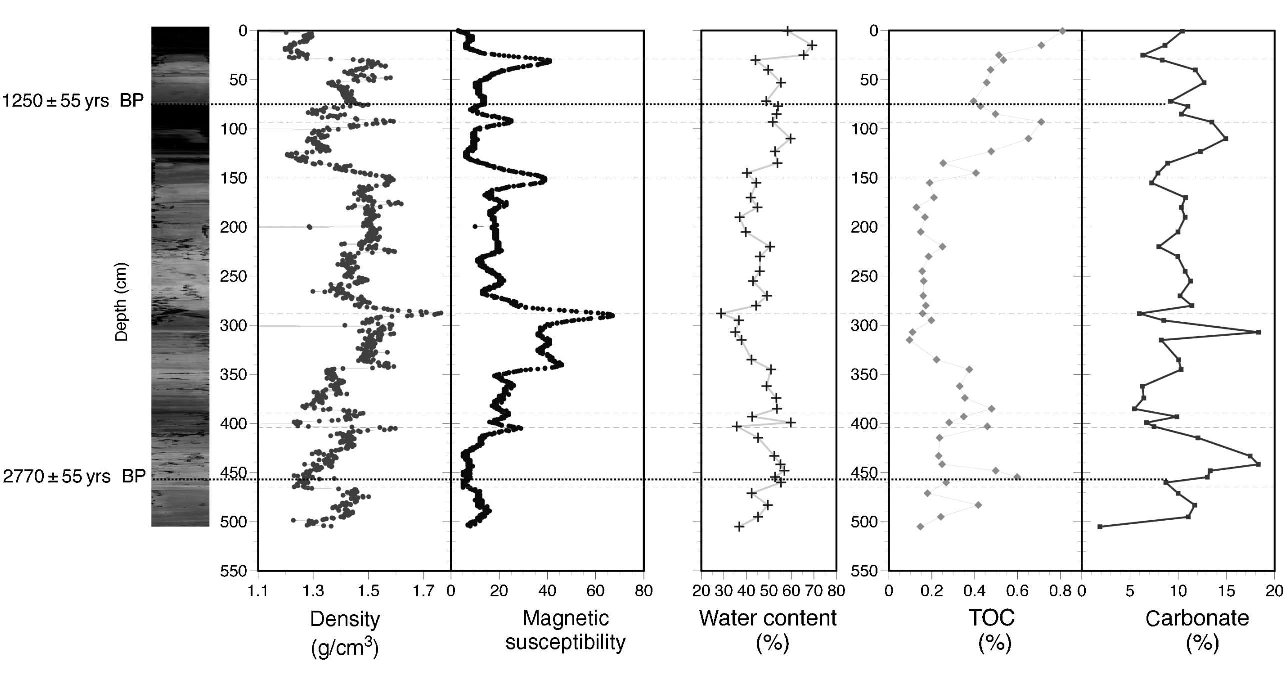

Fig. 7. Sedimentological, petrophysical and geochemical data for core CLG99-5b from Laguna Cari-Laufquen Grande. Concurrent changes in these various parameters are indicative of lake-level changes (see text for explanation).

may provide an additional approach to identify and calibrate these former variations in moisture budgets using lake cores (Schwalb *et al.*, 2002).

5. Limnogeological Case Studies from Central Eastern Patagonia

5.1. Lago Cardiel

Lago Cardiel (49° S) is a closed lake system on the Patagonian plateau about 200 km east of the Andes mountain chain. The lake is situated in a tectonic depression covering a modern surface area of about 370 km^2 and has a maximum water depth of 76 m (Fig. 8). Mean annual precipitation in the area of the lake is relatively low (~150 mm) due to the orographic rain shadow effect on the southern westerlies (Stern and Blisniuk, 2002). But as the lake's catchment area is mostly located to the west, it is characterized by a steep precipitation gradient receiving an annual precipitation of up to 500 mm. This geographical setting within a precipitation gradient makes the lake a sensitive recorder of past changes in the regional climate as shown by a series of paleoshorelines indicating past lake-level changes. Galloway *et al.* (1988) and, in greater detail, Stine and Stine (1990) dated these paleoshorelines using bulk radiocarbon analysis and proposed a major lake-level highstand of +55 m above the modern level around 10.8 ka BP, an intermediate highstand (+21.5 m) around 5.9 ka BP and four minor lake-level fluctuations in the last 2500 yrs. But a complete record of lake-level fluctuations can only be acquired in the deepest part of the lake, where the sedimentation can be expected to be continuous. A combined approach of seismic surveying and analyzing sediment cores permitted to identify, map the extent and date past lake-level fluctuations. The excellent acoustic subsurface penetration up to 70 m allowed the mapping of the acoustic basement and the subsequent sedimentary infill almost throughout the entire basin. By applying the concept of seismic sequence stratigraphy, the imaged subsurface geology was divided into six major seismic sequences, which are labeled in roman numbers (Fig. 9). Sequence VI represents the acoustic basement of the basin consisting of Cretaceous–Tertiary claystones that make up the bedrock surrounding the basin (Beres *et al.*, 2008). Sequence V overlays Sequence VI in a restricted area on the western side of the basin and is interpreted as a former alluvial fan unit. The Pleistocene and Holocene climate history is recorded in the four youngest seismic sequences (Fig. 10). The restricted occurrence of Sequence IV in the central basin indicates a low lake level during the Late Pleistocene that is out of phase with the tropical South America record from Lago Titicaca in the Bolivian altiplano (Baker *et al.*, 2001; see Fig. 1 for lake location). On the basis of the onlap geometries of the seismic reflections in Sequence IV, the lake's water depth was only a few meters. A desiccation period of a few

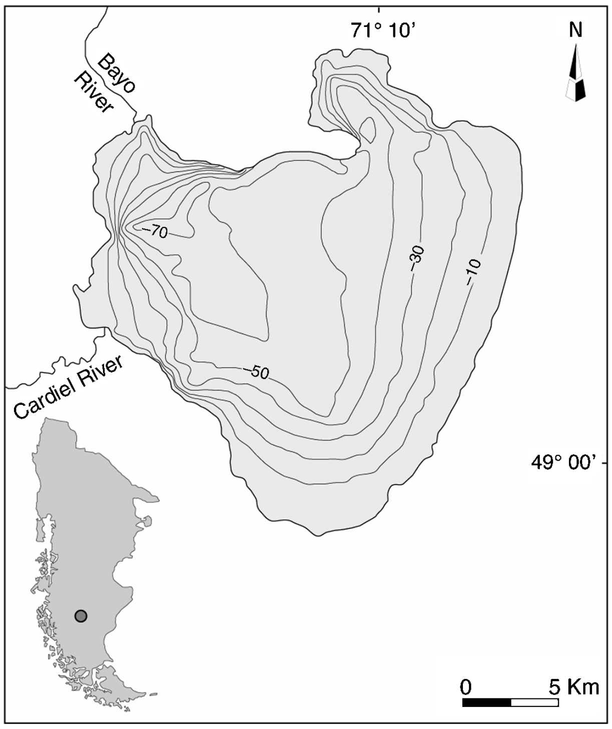

Fig. 8. Bathymetric map of Lago Cardiel in Santa Cruz Province (Argentina).

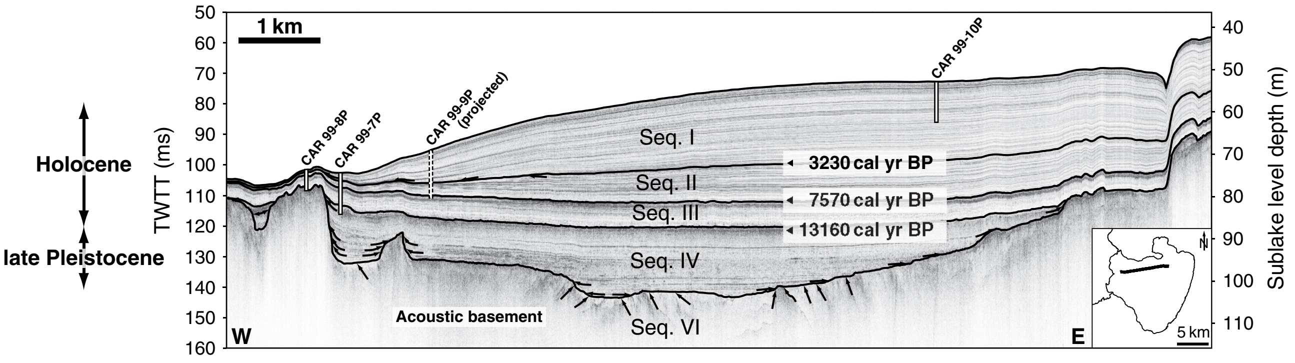

Fig. 9. Lago Cardiel selected seismic profiles and sequence stratigraphic units of the composite profiles shown on the lowermost left insert. Ages of these sequences were obtained by dating different material from targeted core sites also displayed in the figure.

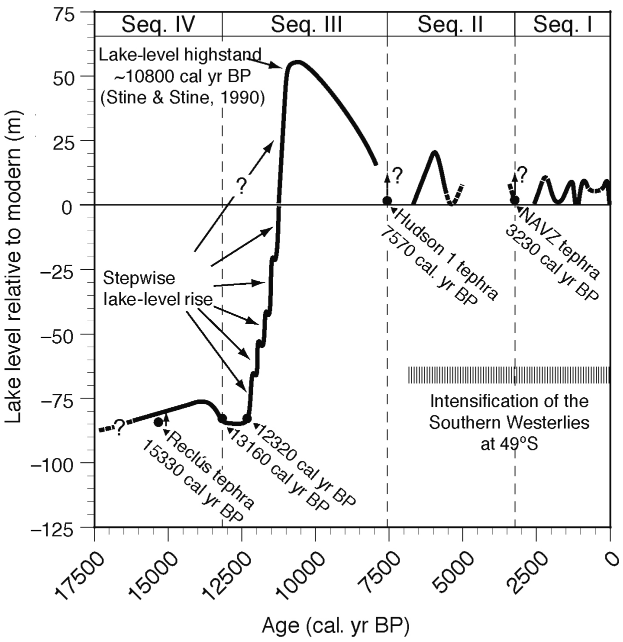

Fig. 10. Reconstructed lake-level curve for Lago Cardiel using a limnogeological approach.

hundred years occurred after 13.16 ka BP resulting in a peaty, gravelly layer deposited at the Sequence IV–III boundary. This was followed by a large change in the hydrological balance at the base of Sequence III. This sequence is found throughout the entire basin implying a large lake-level rise after ~12.6 ka BP up to at least the modern lake level. This fast transgression of almost 80 m occurred within a few hundred years but it was not constant. The occurrence of buried beach ridges during this transgression points toward a stepwise character of the lake-level rise, because only such a mechanism would allow their preservation preventing their erosion by wave action. This transgression exceeded modern lake level and reached an Early Holocene highstand of 55 m (Stine and Stine, 1990).

Subsequently, the lake level receded but never dropped significantly below modern level (Markgraf *et al.*, 2003; Gilli *et al.*, 2005a). Seismically depicted sediment geometries revealed the presence of a large drift mound in the central part of the basin deposited during the last 6800 yrs. This sedimentation pattern is related to the existence of a persistent gyral lake current leading to a strong concentration of sediment in the central basin. The driving force for this lake current is likely the strong westerly winds affecting the area of Lago Cardiel inducing a movement of the water mass by surface shear stress. The presence of the drift deposition is therefore interpreted as an intensification of the southern westerlies at latitude 49° S since the Mid-Holocene (Gilli *et al.*, 2005b).

6. Limnogeological Case Studies from the Fuegian Archipelago

6.1. Lago Fagnano

Located at 54° S in the southern part of Isla Grande de Tierra del Fuego, Lago Fagnano is the southernmost and largest ice-free water body close to Antarctica. It is a latitudinally elongated lake of more than 110 km length and approximately 15 km width (Fig. 11). The lake occupies the deepest continental pull-apart basin in a series of graben-shaped sinks along the Magallanes–Fagnano transform (MFT) fault system that separates the South American plate from the Scotia plate (Lodolo *et al.*, 2003). It comprises two subbasins: a smaller and deeper basin toward the east reaching a maximum depth of 210 m, and an elongated shallower basin toward the west with ~110 m maximum water depth (Lodolo *et al.*, 2002).

The lake is located between the Cordillera Darwin in the south reaching a maximum altitude of more than 2400 m a.s.l., and the foothills of the cordillera in the north with a relatively low altitude mountainous belt (Olivero and Martinioni, 2001). The Claro, Milna, Tuerto, Valdez and Turbio rivers are the main feeders of this lake system, whereas Río Azopardo at the western extreme of the lake is the only outlet toward the Pacific Ocean through the Magallanes Strait. With a total area of more than 1650 km^2, this oligothropic lake (Mariazzi *et al.*, 1987) evolved within a glaciotectonic basin after the retreat of the glaciers at the end of the Late Pleistocene.

Modern evidence of neotectonic activity along the MFT can be found on outcrops along the Turbio River in the eastern part of the lake. In 1949 AD, a 7.7 magnitude earthquake caused the subsidence of a large area close to the lake shore forming a series of connected lagoons to the main Fagnano lacustrine system (Menichetti *et al.*, 2001). Hence, the sedimentary infilling of the lake allows to reconstruct both the paleoclimatic and the paleoseismic histories of the region. Previous work showed that glaciolacustrine sediments cover the entire Holocene and probably date back even to the LGM (Lodolo *et al.*, 2003; Tassone *et al.*, 2005). A recent seismic survey (March, 2005) revealed a more than 100 m thick sedimentary package for the eastern basin. The seismic images indicate a relatively even sedimentation often interrupted by chaotic and transparent seismic facies that can be interpreted as mass-wasting

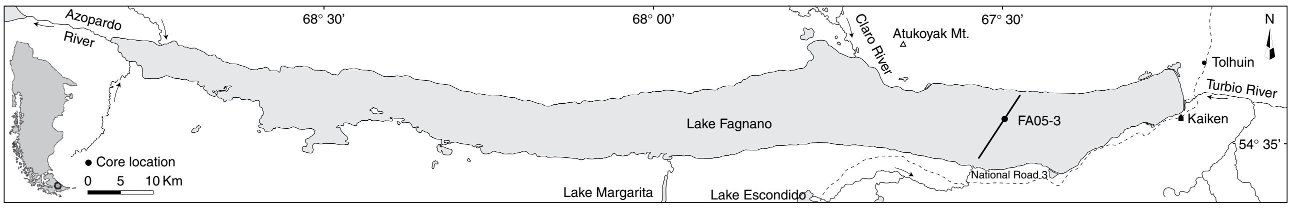

Fig. 11. Bathymetric map of Lago Fagnano showing the location of the seismic profile and sediment core shown in Fig. 12.

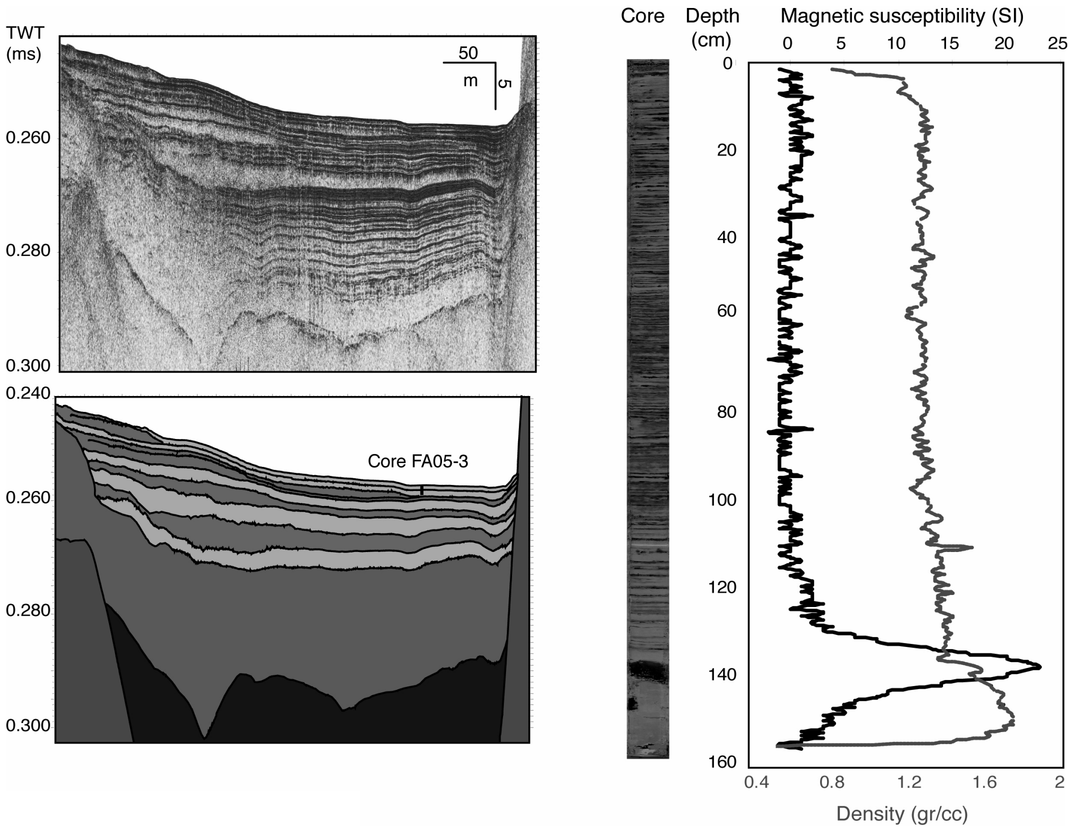

Fig. 12. Original and interpreted seismic profile of Lago Fagnano showing well-defined mass-wasting events. The petrophysical properties of the well-laminated core displayed on the right confirm the potential of these lake sediments to study both the environmental history and the tectonic events.

events (Fig. 12). These episodic facies are most probably triggered by paleoearthquakes along the MFT fault zone. Physical properties analysis of the sediments clearly show density and magnetic susceptibility peaks correlating with sedimentary features indicative of single mass flow events (Waldmann *et al.*, 2008). A detailed inspection of the sediments shows an excellent laminated sequence mostly composed of diatoms, amorphous organic matter and clays with very low carbonate content. Further, chemical and isotopical analyses of these sediments are in progress. Additionally, in March 2006 more than 90 m of sediment cores were retrieved in both subbasins at selected locations using the results of the seismic profiling. They will allow to further calibrate the seismic dataset and to constraint the timing of both climatic and tectonic events.

7. Outlook

Coordinated seismic surveys and sediment coring allowed obtaining optimal paleoclimate records from several lake sites in Patagonia. The presented examples illustrate the use of a limnogeological approach integrating a large number of proxies to obtain a comprehensive picture of each lake system at various temporal and spatial scales. Amalgamating the petrophysical, sedimentological and geochemical data, this broad approach allowed the calibration of seismic reflection sequences for both lake level and environmental change reconstructions.

Several general conclusions can be assessed despite the existing differences among datasets for each individual record. A clear stepwise evolution for the Lateglacial–Holocene transition emerges from all the presented examples covering this time interval independently of their latitude. These truly multiproxy datasets are challenging early views, indicating a smooth warming east of the Andes during this transition (e.g. Mercer, 1983, 1984). Furthermore, intrahemispheric correlations of comparable datasets like Lago Mascardi (Argentina) and Lago Huelmo (Chile) show the same behavior and timing of key events during the deglaciation at both sides of the Andes. This comparison is a good example of the use of a limnogeological approach to tackle previous disagreements between records most often based on one proxy only.

The exact timing of the observed environmental changes during the deglaciation, however, seems to differ at various latitudes, and a better and more detailed dating of the records is still necessary. This is similar to the present situation in Antarctica (*PAGES News*, 2006) and more efforts are needed to elucidate the regional pattern of changes.

The early Holocene in Lago Mascardi (~41° S) is marked by warming temperatures and further retreating ice. A clear latitudinal variation in precipitation is observed during this interval. Paleoshoreline data from Lago Cardiel (~49° S) indicate that lake levels at this time slice were the highest during the past 20,000 yrs (~55 m higher than today). Seismic and core data document that these paleoshorelines developed after a rapid lake-level rise of ~80 m in a few hundred years. Pollen records from farther south in southern Tierra del Fuego, however, provide evidence for relatively dry conditions with an increase in fire frequency that has been related to fluctuations in the latitudinal position of the westerlies (Markgraf, 1993). Ongoing research in Lago Fagnano and Laguna Potrok-Aike will provide new multiproxy data to clarify this issue.

Advancing glaciers and cooling conditions in Patagonia have been proposed during the Mid to Late Holocene (e.g. Porter *et al.*, 1984; Ariztegui *et al.*, 2000). Neoglacial ice advances have been reconstructed from moraine sequences in the Cordillera Darwin at ~6.5 ka BP, and increasing in frequency and extent toward the late Holocene (Strelin *et al.*, 2002). Isotopic studies of mosses recovered from peat bogs indicate an overall increase in moisture during this period with no significant changes in temperature (Pendall *et al.*, 2001). An increase in the wind stress after ~6.8 ka BP has been shown for Lago Cardiel through wind-driven current deposition (Ariztegui *et al.*, 2004; Gilli *et al.*, 2005b;). All these data would indicate that perhaps changes in precipitation more than temperature may have dominated the Late Holocene, producing the observed glacial advances in southernmost Patagonia.

Evidence of the LIA is clear in Lago Frías sediments allowing good dating and comparison with recent moraines and instrumental data. Further to the south, Lago Cardiel evidence from both shoreline outcrops (Stine, 1994) and sediment cores (Gilli, 2003) is less clear. Stine (1994) has indicated drought conditions coinciding with at least part of the Medieval Warm Period (MWP) that precedes the LIA. It has been suggested that these droughts may have been caused by redirecting the mid-latitude storm tracks either by a general contraction of the circumpolar vortices or by a change in the position of their waves. Based on oxygen isotope ratios on authigenic carbonates, Gilli (2003) further concluded that an opposite precipitation signal dominates both the MWP and LIA intervals. This is in agreement with other Patagonian limnogeological records from Chile and Argentina showing warm-dry and cool-moist conditions during the MWP and LIA, respectively (Piovano and Ariztegui, 2006). Hence, the often underestimated role of precipitation during LIA is now emerging from the multiproxy analyses of these lacustrine records in Patagonia.

As compiled in this book, numerous different proxy records have been used to reconstruct the Late Cenozoic in Patagonia. Many of these records, however, are discontinuous with a low time resolution preventing to register environmental variability at decadal or centennial time scales. Pollen profiles have so far had the best distribution to secure regional reconstructions of environmental change. They alone can often have multiple interpretations regarding paleoclimate. Paleoenvironmental reconstructions derived from lacustrine sediments in Patagonia combined with pollen and other proxies can provide critical evidence to obtain more realistic reconstructions of environmental changes at different time and regional scales.

The challenging issue of retrieving lacustrine sequences covering several glacial–interglacial cycles in Patagonia may soon be achieved through a multidisciplinary ICDP (International Continental Scientific Drilling Program) initiative (Zolitschka *et al.*, 2006). Further comparisons of these lake records with other lacustrine, geomorphological and tree-ring evidence from the Southern Hemisphere as well as with high latitude marine and Antarctic ice core records will improve our understanding of both hemispheric and interhemispheric climate linkages.

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