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Late Quaternary hydrological variability in southeastern Patagonia – 45,000 years of terrestrial evidence from Laguna Potrok Aike

Dissertation

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Abstract

The maar lake Laguna Potrok Aike is located in the dry Patagonian steppe, an area with hitherto only scarce paleoenvironmental information. Within the project SALSA (South Argentinean Lake Sediment Archives and modelling) Laguna Potrok Aike turned out to be the key site for paleoenvironmental reconstruction in that area. With a continuous, high-resolution multi-proxy approach applied to the well radiocarbon and tephra dated sediments it was possible to distinguish between lake level high and low stands. Those do not only give information about the hydrological state of climatic periods like the Little Ice Age or the Medieval Climate Anomaly but also reflect hydrological variations for southern Patagonia during the past 16,000 cal. BP as well as Oxygen Isotope Stage 3. In this context the total inorganic carbon content was identified as a sensitive lake level indicator which was supported by various other proxies for lake level changes, minerogenic input or redox-conditions which are also suited for reconstructing paleoenvironmental conditions.

Proxies suggest a high lake level during Oxygen Isotope Stage 3 for Laguna Potrok Aike. At least similar, probably higher lake levels are assumed for the period between 16,000 and 13,100 cal. BP that possibly resulted in a Late Glacial surface outflow. From 13,100 until 11,400 cal. BP the lake level lowered. Contemporaneously, between 12,800 until 11,400 cal. BP the record suggests warm conditions. A transgression starting at 11,400 cal. BP lasted until 8,650 cal. BP when the lake level dropped to the lowest position of the record. After a transgression, shortly before 6,750 cal. BP, the lake level was variable with humid intervals. The last wet period ascribed to the Little Ice Age, was the most extended humid period since early Holocene high lake levels at Laguna Potrok Aike before 8,650 cal. BP.

Data also contain a signal of European impact which started earlier in Patagonia than previously assumed. Most obvious signals for the presence of Europeans in southern Patagonia become evident with the beginning of sheep farming.

In general, the record from Laguna Potrok Aike is consistent with the further north located record from Lago Cardiel suggesting a response to the same forcing mechanisms and a similar climatic history of today’s Patagonian steppe, maybe slightly shifted in time. In contrast, comparisons with Andean archives revealed an opposite hydrological pattern which is probably based on the fact that an intensification of Southern Hemisphere Westerlies results in a precipitation increase west of the Andes and a precipitation decrease in the steppe. This is due to blocking of precipitation carrying easterly winds responsible for most of the precipitation at Laguna Potrok Aike.

Zusammenfassung

Der heute oberirdisch abflusslose Maarsee Laguna Potrok Aike liegt in der trockenen Steppe Patagoniens, über die nur wenige Informationen bezüglich der Paläoumweltbedingungen vorliegen. Im Rahmen des Projektes SALSA (Süd Argentinische Seesediment Archive und Modellierung) erlangte die Laguna Potrok Aike zentrale Bedeutung für die Paläoumweltrekonstruktion in diesem Gebiet. Mit einem kontinuierlichen, hoch auflösenden multiproxy Ansatz, der auf die mit der Radiokarbonmethode und durch Tephrochronologie präzise datierten Sedimente angewendet wurde, war es möglich, zwischen Hoch- und Niedrigwasserständen des Sees zu unterscheiden. Diese geben nicht nur Auskunft über den hydrologischen Zustand klimatischer Abschnitte wie der Kleinen Eiszeit oder der Mittelalterlichen Klimaanomalie, sondern spiegeln auch hydrologische Schwankungen während der letzten 16.000 Jahre und des Sauerstoffisotopenstadiums 3 wider. Es stellte sich heraus, dass der gesamte anorganische Kohlenstoff als Seespiegelindikator genutzt werden kann. Dieser Parameter wurde durch andere Proxies für Seespiegelschwankungen, minerogenen Eintrag und Redoxbedingungen, die ebenfalls zur Paläoumweltrekonstruktion geeignet sind, unterstützt.
Die Proxies deuten auf einen hohen Seespiegel während des Sauerstoffisotopenstadiums 3 hin. Zumindest gleich hohe, wahrscheinlich jedoch höhere Seespiegel, die möglicher Weise einen oberirdischen spätglazialen Abfluss verursachten, werden zwischen 16.000 und 13.100 cal. BP angenommen. Von 13.100 bis 11.400 cal. BP sank der Seespiegel. Zeitgleich deutet der Datensatz erhöhte Temperaturen zwischen 12.800 und 11.400 cal. BP an. Eine Transgression, die um 11.400 cal. BP anfing, hielt bis 8.650 cal. BP an. Zu dieser Zeit fiel der Seespiegel auf seinen niedrigsten Stand. Nach einer erneuten Transgression, die vor 6.750 cal. BP begonnen haben muss, war der Seespiegel sehr variabel, unterbrochen durch einige feuchtere Phasen. Die letzte Feuchtphase, die der Kleinen Eiszeit zugeschrieben wird, war die ausgedehnteste seit den früh-holozänen Seespiegelhochständen vor 8.650 cal. BP.
Die Daten beinhalten ebenfalls Informationen über die von den europäischen Eroberern verursachten Umweltveränderungen. Diese begannen in Patagonien viel früher als ursprünglich angenommen. Die offensichtlichsten Zeichen für die Anwesenheit der Europäer in Südpatagonien traten mit dem Beginn der Schaafzucht auf.
Der Datensatz der Laguna Potrok Aike zeigt Übereinstimmungen mit dem des weiter nördlich gelegenen Lago Cardiels. Dies lässt auf eine gleichartige Reaktion auf die natürlichen Steuerungsfaktoren und auf eine eventuell zeitlich leicht versetzte, ähnliche Klimaentwicklung des Gebietes der heutigen patagonischen Steppe schließen. Im Gegensatz dazu weisen Vergleiche mit andinen Archiven gegensätzliche hydrologische Muster auf, was vermutlich auf die Tatsache zurückzuführen ist, dass eine Verstärkung der südhemisphärischen Westwinde eine Erhöhung des Niederschlages in den Anden und eine Verringerung desselben in der Steppe hervorruft. Dies beruht wahrscheinlich auf einer Blockade der niederschlagsbringenden östlichen Winde, die hauptverantwortlich für den Niederschlag an der Laguna Potrok Aike sind.

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In memory of Jürgen Bachinger

Chapter 1:

Introduction

1. The framework

Investigations at Laguna Potrok Aike started within the project SALSA (South Argentinean Lake Sediment Archives and modeling – 01.09.2001-31.08.2006) initiated in the framework of the German Climate Research Program (DEKLIM). SALSA focuses on high-resolution multi-proxy analyses of sediment cores from southern Patagonia as archives for paleolimnological and paleoclimatological data of the southern hemisphere. Thus, insights into the natural variability of the climate system and its controlling mechanisms in high southern latitudes were envisaged to be elaborated.

Proposed benefits of SALSA were:

- to obtain the first continuous high-resolution multi-proxy and multiple-dated palaeoclimate record for southern South America;
- to determine a long-term record of Patagonian climate;
- to identify the phasing of wet-dry cycles in southern South America;
- to constrain the timing and character of high-frequency shifts in the climate system;
- to assess linkages between continental climate records from high latitudes of Patagonia with records from low latitudes of South America and with marine and ice core data.

SALSA is based on four working groups bringing together their results in a multi-proxy approach. The groups are: SALSA I (University of Bremen) responsible for sedimentology and dating, SALSA II (University of Cologne) responsible for paleobiology and climate reconstruction, SALSA III (Research Center Jülich) responsible for stable isotopes and system dynamics. Initially, SALSA IV should perform climate modeling and circulation reconstruction but was substituted by the modeling project MIDHOL (Transient simulation of the MIDdle HOLocene with a coupled atmosphere-ocean general circulation model based at GKSS Geesthacht) in the course of the DEKLIM program.

During the project SALSA, Laguna Potrok Aike (Fig. 1.1 and 1.2) turned out to be the key-site due to its sediment thickness inferred from seismic investigations and high accumulation rates. Though a number of cores were obtained from various other sites like Laguna Azul, Laguna Media Agua, Laguna Cháltel, Laguna las Vizcachas

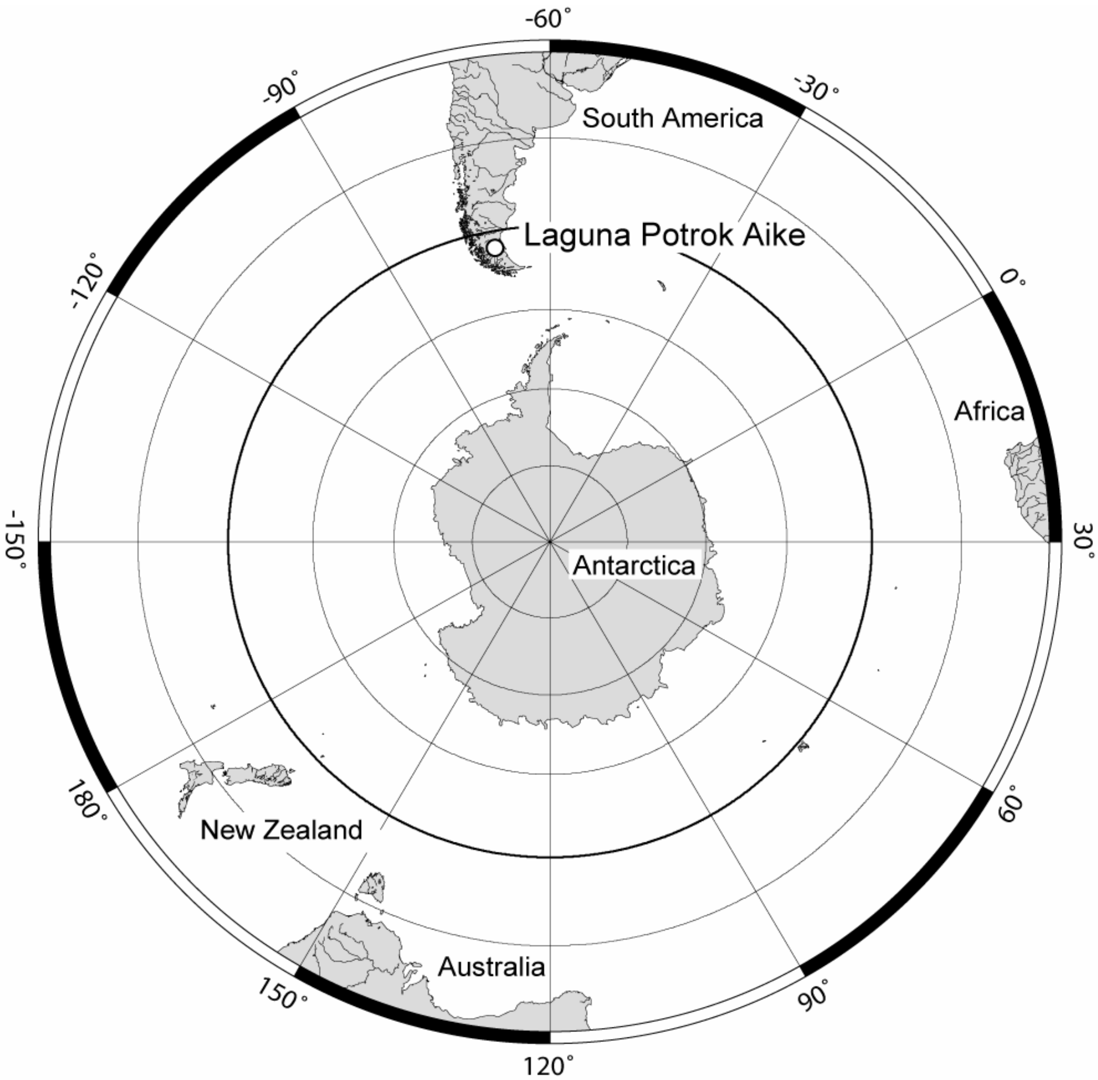

Fig. 1.1: Location of Laguna Potrok Aike. Note the southward latitudinal extension of the continents South America, Africa and Australia (including New Zealand).

or Lago del Desierto (all Fig. 1.2) during SALSA and follow-up projects, none of those records yielded the potential of Laguna Potrok Aike. Up to now, 63 m of sediment have been recovered from Laguna Potrok Aike. 45 m of it have been investigated with the focus on different time slices during this study.

Fig. 1.2: Research area and locations discussed in the text.

In addition to sedimentological studies the SALSA team focuses on paleoenvironmental reconstructions from Laguna Azul (Fig. 1.2, Mayr et al., 2005), palynological studies from Laguna Azul and Laguna Potrok Aike (Schäbitz et al., 2003), physico-chemical characteristics of lacustrine systems in the surrounding of Laguna Potrok Aike (Zolitschka et al., in press) and isotopic characterizations of lakes, rivers, groundwater and precipitation in southeastern Argentina (Mayr et al., subm.).

2. Reasons for choosing southern Patagonia

Southern South America is the only continental landmass between 38°S and Antarctica (Fig. 1.1). Thus, it represents a unique opportunity to reconstruct terrestrial paleoclimatic conditions for the southern hemisphere in an area that is subject to shifts in polar and mid-latitude wind fields and precipitation regimes (Zolitschka et al., in press). Due to the large ice cover and the vast extent of the oceans, the southern hemisphere plays a key role in the global climate system (Gersonde et al., 1996). Wind velocities over southern South America (Patagonia) are a direct response to the dynamics of the Southern Ocean, sea surface temperatures and corresponding air-pressure gradients between Antarctica and the equator. The intense interaction between terrestrial, marine and glacial environments makes southern South America one of the most interesting locations for the investigation of the global climate system. However, well dated continuous high-resolution paleoenvironmental data coverage from this region remains limited. This especially becomes evident if high-resolution terrestrial records from the southeastern Patagonian steppe spanning the Holocene and the Late Glacial are concerned (Huber et al., 2004). Until today nearly all terrestrial climate records from Patagonia are restricted to pollen (Heusser, 1998; Heusser and Rabassa, 1991; Mancini, 2002; Markgraf, 1983; Schäbitz, 1991) and charcoal studies (Heusser, 1987; Huber and Markgraf, 2003a, 2003b; Huber et al., 2004; Markgraf and Anderson, 1994) of peat bogs and mires or archaeological investigations (Barberena et al., subm.; Borrero, 1999).

Before SALSA started, Lago Cardiel (Fig. 1.1) was the only examined lake south of 45°S (Gilli et al., 2001; Stine, 1994, 1998; Stine and Stine, 1990). SALSA filled the gap between Antarctica and lower latitudes by concentrating on promising sites on the southernmost Argentinean mainland – particularly Laguna Potrok Aike.

3. Reasons for the investigation of lacustrine sediments

The only way to explore climate system dynamics beyond instrumental records is to study natural archives, e.g., lacustrine and marine sediments, ice, trees and corals (Zolitschka et al., in press). Until now, nearly all terrestrial records are limited to pollen and charcoal studies which often are in coarse resolution due to the enormous amount of work involved. The radiocarbon time control of those records mostly is restricted to a few data points. Also marine records in the majority of cases are only available with coarse resolution (Meyers, 2003). In addition, marine records from the latitudes of Patagonia have only been obtained from the Pacific, i.e., west of the Andes (Kaiser et al., 2005; Kim et al., 2002; Lamy et al., 2001; Lamy et al., 1999; Lamy et al., 2004). The shelf region of the Atlantic hitherto is an area of future perspectives for geoscientific investigations. Additionally, marine archives always have to cope with a reservoir effect in radiocarbon dating which was demonstrated to be absent in Laguna Potrok Aike (Chapter 2).

Despite their potential, long and high-resolution lacustrine records have rarely been reported from southern Patagonia. The only exception giving continuous information during the Late Glacial and the Holocene from the steppe area in Patagonia is Lago Cardiel (Fig. 1.2). However, this lake lacks information around 11,220±85 BP (13,120 $^{+140}/_{-175}$ cal. BP) as it fell dry during this time (Gilli, 2003; Gilli et al., 2001; Gilli et al., 2005; Markgraf et al., 2003). Other studies either are based on short events like glacier fluctuations in the Northern and Southern Patagonian Ice Field (Aniya, 1996; Glasser et al., 2002; Glasser et al., 2004; Mercer, 1970; Röthlisberger, 1986; Wenzens, 1999) and dating of lake terraces (Galloway et al., 1988; Stine and Stine, 1990) and marine terraces (Aguirre, 2003; Aguirre et al., 2006), or are located further north (Bennett et al., 2000; Bianchi et al., 1999; Massaferro et al., 2005; Moreno et al., 2001; Piovano et al., 2002; Thompson et al., 2000) or in Antarctica (Blunier and Brook, 2001; EPICA community members, 2004; Hodgson et al., 2005; Petit et al., 1999; Petit et al., 1990).

In the extremely windy region of the “Furious Fifties” in southern Patagonia, most terrestrial deposits are prone to unconformities. Only bog and lake sediments provide the unique opportunity for continuous reconstructions of late Quaternary environmental changes. This is very important as most closed lakes in southern

Patagonia are receding since 1940 (Gilli et al., 2001; Stine and Stine, 1990) and hence tend to desiccate during dry summers which causes discontinuous deposition or even erosion. With a current water depth of ca. 100 m this is unlikely to happen to Laguna Potrok Aike. With the exception of Laguna Azul (Fig. 1.2, Mayr et al., 2005), this maar lake is presently the only investigated permanently water-filled lacustrine system in the southeastern Patagonian steppe south of 49°S.

In general, the surrounding area of Laguna Potrok Aike, the Pali Aike Volcanic Field (52°S, 70°W), is quite comparable to the West Eifel Volcanic Field, Germany (52°N, 6°E) in latitudinal position, age and presence of maars, although the origin of volcanic activities is different. Therefore, it was assumed, that it should be possible to recover high-resolution sedimentary records spanning the Late- and the Postglacial from these sites as it has been done for European maar lakes (Negendank and Zolitschka, 1993), especially in the Eifel (Zolitschka et al., 2000) or in southern Italy (Allen et al., 1999; Zolitschka and Negendank, 1996).

4. Objectives and Outline

This study mainly focuses on the reconstruction of paleoenvironmental conditions in an area with hitherto rare paleoclimatic information. Emphasis was on the identification and reconstruction of hydrological variations on the basis of sedimentological and geochemical parameters obtained from the maar lake Laguna Potrok Aike. In detail, those examinations included laboratory analyses on the sediment cores like gamma-ray density, magnetic susceptibility, p-wave velocity, dry density, water content, total carbon, total nitrogen, total sulfur, total organic carbon, total inorganic carbon, biogenic silica, grain sizes, frequency dependent magnetic susceptibility and XRF elemental analyses (for methods see following chapters). Further emphasis was on field observations like the identification of lake level terraces or gullies also giving information about past hydrological variations in combination with the examination of maps and seismic profiles.

The different chapters of this study, examining various sediment cores from Laguna Potrok Aike, are the basis for further analyses performed by SALSA partners on the sediments of this lake. Chapter 2, 4 and 5 provide lithological descriptions as well as age-depth models for different sediment cores prior to the interpretation of the geochemical and sedimentological parameters.

A first short core of 100 cm was recovered during a site survey in austral summer 2002. This record revealed hydrological changes in southern Patagonia with subdecadal resolution. Results were published in the *Journal of Paleolimnology* (Chapter 2, Haberzettl et al., 2005). Furthermore, that record yielded information about the controversy of European impact versus climate fluctuations which had already been discussed vividly (Heusser, 1987; Huber and Markgraf, 2003a). Conclusions of those results were accepted for *Quaternary International* (Chapter 3, Haberzettl et al., accept.).

With the objective of getting further back in time long cores have been recovered from Laguna Potrok Aike during field work in austral summer 2003. A 1892 cm long composite record from the center of the lake and a 900 cm record from a subaquatic lake level terrace were taken and investigated. Both records revealed details about the hydrological past of southern Patagonia. The composite record spanning the last 16,000 cal. BP (Chapter 4) was submitted to *The Holocene* (Haberzettl et al., subm. a). The record form the subaquatic lake level terrace spans the last 7,000 cal. BP and due to an unconformity gives information about Oxygen Isotope Stage 3 in southern Patagonia (Chapter 5). This is in review with *Palaeogeography, Palaeoclimatology, Paleoecology* (Haberzettl et al., subm. b).

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Chapter 2:

Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina)

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Abstract

The volcanogenic lake Laguna Potrok Aike, Santa Cruz, Argentina reveals an unprecedented continuous high resolution climatic record for the steppe regions of southern Patagonia. With the applied multiproxy approach rapid climatic changes before the turn of the first millennium were detected followed by medieval droughts which are intersected by moist and/or cold periods of varying durations and intensities. The “total inorganic carbon” content was identified as a sensitive lake level indicator. This proxy suggests that during the late Middle Ages (ca. 1230-1410 AD) the lake level was rather low representing a signal of the “Medieval Climate Anomaly” in southeastern Patagonia. At the beginning of the “Little Ice Age” the lake level rose considerably staying on a high level during the whole period. Subsequently, the lake level lowered again in the course of the 20th century.

Keywords: Lacustrine Sediments, Lake Level Changes, Medieval Climate Anomaly, Little Ice Age, Southern Patagonia, Argentina

1. Introduction

Well dated high resolution climate archives in southern South America and especially in southeastern (steppe) Patagonia are scarce. Lake terraces and sediments of Lago Cardiel (48°57`S, 71°26`W, Fig. 2.1)(Gilli et al., 2001; Markgraf et al., 2003; Stine and Stine, 1990) as well as glacier fluctuations in the Northern and Southern Patagonian Ice Field (Glasser et al., 2002; Luckman and Villalba, 2001; Röthlisberger, 1986; Warren and Sugden, 1993) indicate alternating warm/dry and

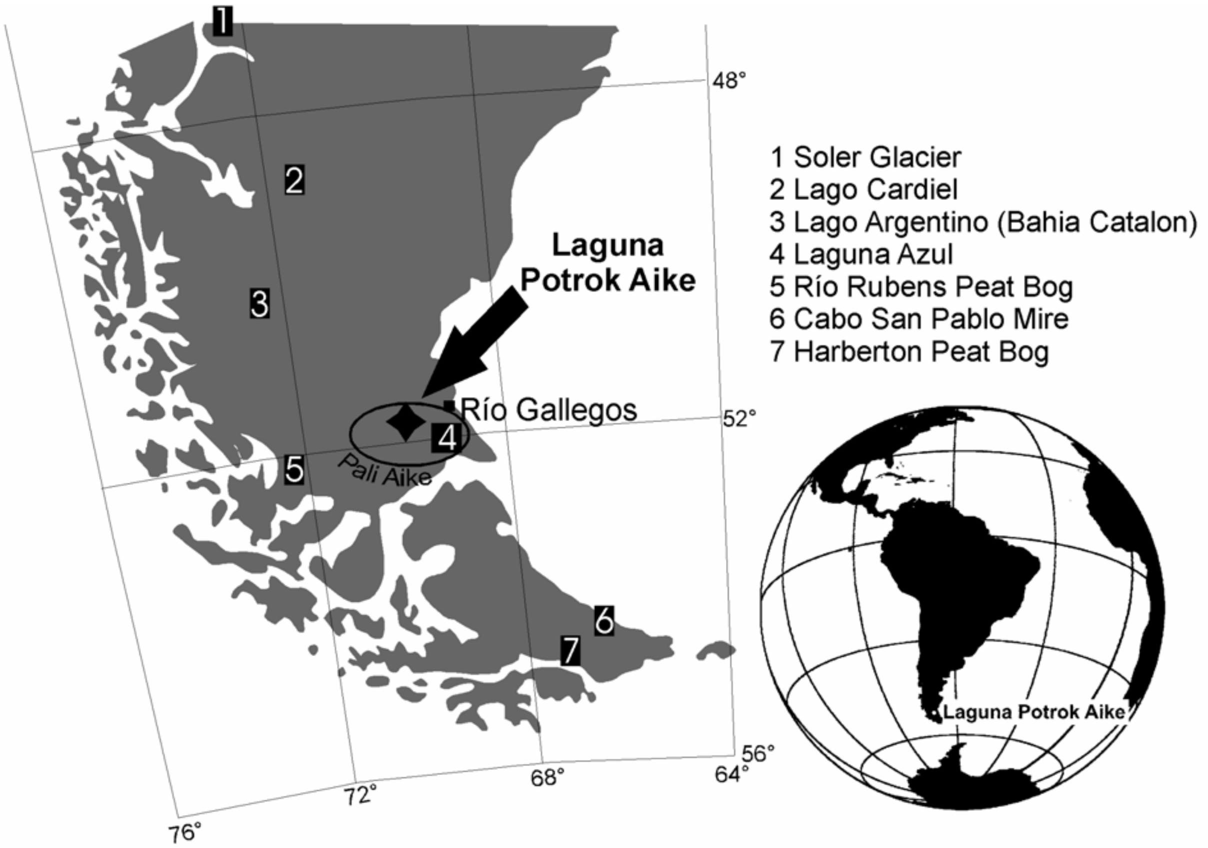


Fig. 2.1: Location of research area in southern South America and locations mentioned in the text.

cool/wet periods during the Holocene. As there are marked environmental and climatic differences between 40°S and 50°S (Luckman and Villalba, 2001; Rosenblüth et al., 1995), it is essential to obtain further paleoclimatic information south of 50°S for a better understanding of the paleoenvironmental conditions. Other paleolimnological studies mainly were performed further north (Bianchi, 1999; Piovano et al., 2002; Schwalb, 2003; Valero-Garcés et al., 2000). Laguna Potrok Aike (51° 58`S, 70° 23`W, Fig. 2.1) is one of the few permanently water filled lakes in the dry-lands of southern Patagonia which assures a continuous sediment record even during dry periods. This is important, as many closed lakes in Patagonia have been receding since 1940 (Gilli et al., 2001) and hence most archives are affected by erosion. Therefore, Laguna Potrok Aike offers great potential for obtaining a continuous record of the paleoenvironment in southeastern Patagonia providing information about climatic events like the “Medieval Climate Anomaly” (Stine, 1994), the “Little Ice Age” (Bradley, 2000; Glasser et al., 2002; Luckman and Villalba, 2001) or the 20th century “Global Warming”.

Here first results of the project SALSA (South Argentinean Lake Sediment Archives and modeling; www.salsa.uni-bremen.de) are presented. SALSA focuses on high-resolution multi-proxy analyses of sediment cores from southern Patagonia as ideal archives for paleolimnological and paleoclimatological data for the southern hemisphere.

2. Site description

Laguna Potrok Aike, a supposed maar lake, is located in southern Santa Cruz, Patagonia, Argentina. Roughly 90 km west of the city of Río Gallegos and 80 km north of the Strait of Magellan, it is situated in the Pali Aike Volcanic Field (Fig. 2.1). The geological and volcanological development of these back arc Patagonian plateau lavas has been discussed in detail (D`Orazio et al., 2000; Mazzarini and D`Orazio, 2003; Skewes, 1978). With a maximum W-E-extension of about 150 km and a maximum N-S-extension of approximately 50 km the Pali Aike Volcanic Field covers an area of ~4500 km² (Mazzarini and D`Orazio, 2003).

The circular lake (shoreline development: 1.1) has a maximum diameter of 3470 m (Fig. 2.2). The catchment area (>200 km^2) reaches far south into the Chilean part of the Pali Aike Volcanic Field. However, linear runoff only occurs episodically through a few canyons and arroyos mainly after snow-melt in spring. In summer 2002 the lake level was at 100 m a.s.l. and the maximum water depth was approximately 100 m. Interannual lake level fluctuations are estimated to be in the range of 0-7 m.

The dominating climatic element of this area is the westerly wind constituting more than 50% of the wind directions and reaching mean monthly wind speeds of 9 m s^{-1} during early summer (Endlicher, 1993). The rain shadow effect east of the Andes results in a precipitation decrease from west to east (less than 150 mm at Laguna

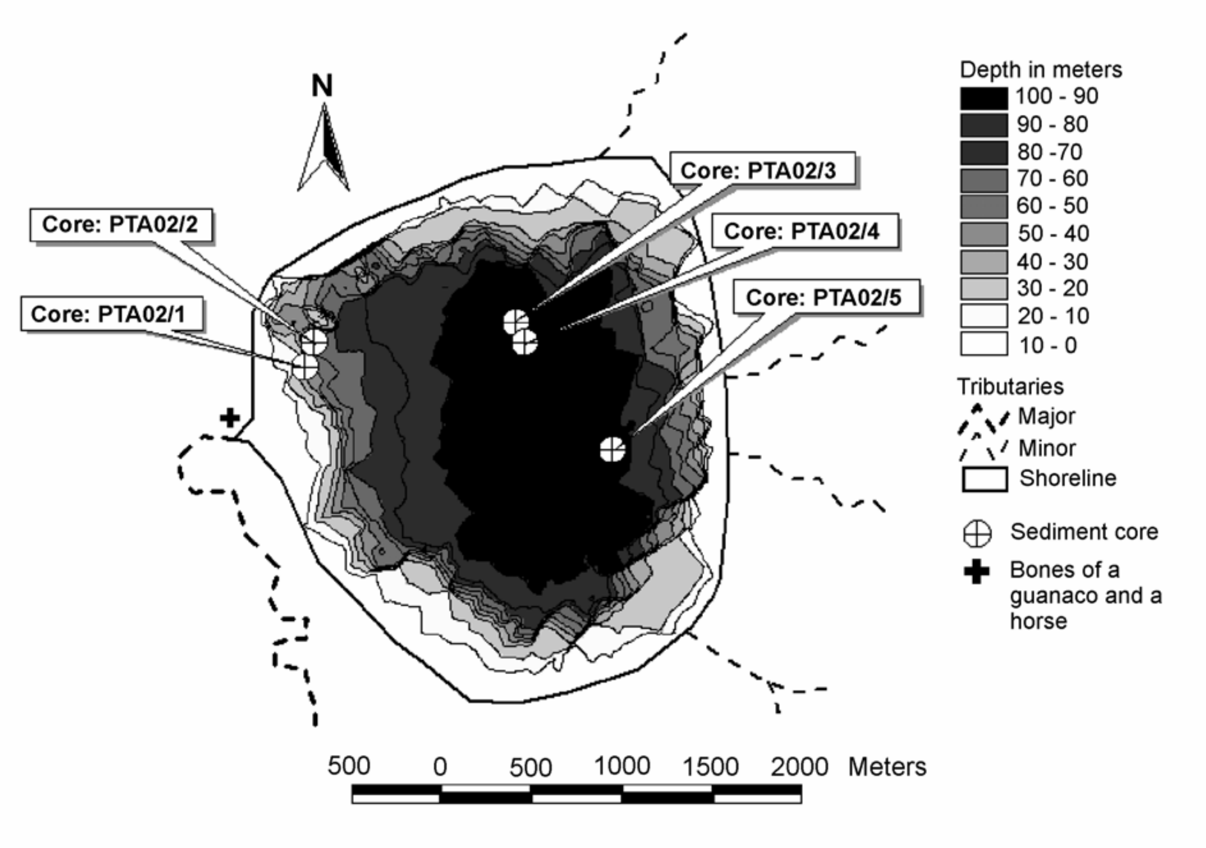


Fig. 2.2: Bathymetry of Laguna Potrok Aike, coring positions, tributaries and location of dated bones.

Potrok Aike). With a potential evaporation of 0.5-10 mm per day (Borrelli and Oliva, 2001; Endlicher, 1993), this area has an annual evaporation/precipitation ratio (E/P) of up to 24. This leads to a negative water balance throughout the year. Therefore, this area is considered as a cold semi-desert (Soriano, 1983).

The largest part of eastern Patagonia between the Andes and the Atlantic coast is covered with different Patagonian steppe formations. Most prominent in the Pali Aike Volcanic Field is the dry (xeric) type of the Magellanic steppe showing *Festuca gracillima* as dominant. South and southeast towards the Strait of Magellan and the Atlantic Ocean vegetation changes into a moister (mesic) Magellanic steppe type, mainly characterized by *Festuca pallescens* (Pisano, 1985; Roig, 1998). Since the introduction of sheep farming by Europeans around AD 1880, the entire region is altered by overgrazing (Eriksen, 1972; Liss, 1979). Therefore, soil erosion is widespread and the flora has been modified (Aagesen, 2000).

As a result of ancient lake level fluctuations several terraces covered with different vegetation have developed. The northern, eastern and southern beaches are covered with pebbles whereas the western beach is made up by sand and silt. Above this vegetation-free belt almost pure stands of *Acaena* sp. occur around the lake. The western lake shore is different as stands of *Adesmia boronioides* (30-100 cm high shrubs) protect the surface of the entire slope from wind and wave erosion. On the northern, eastern and southern shores terraces above the *Acaena* belt are covered with grasses (e.g., *Festuca* sp., *Poa* sp., *Stipa* sp.) mixed with other plants like *Colobanthus subulatus* and *Azorella filamentosa* cushions, *Peretia recurvata* and few bushes of *Berberis heterophylla*. Patches of *Empetrum rubrum* are restricted to the northwestern shore.

Further information about the geomorphology of the Pali Aike Volcanic Field and Laguna Potrok Aike as well as physico-chemical and paleoenvironmental results of other lakes (e.g., Laguna Azul, 52°05`S, 69°35`W, Fig. 2.1) in that area are published elsewhere (Zolitschka et al., in press; Zolitschka et al., 2004).

3. Field and Laboratory Methods

Five gravity cores (PTA02/1 to 5) with lengths up to 113.5 cm were recovered from Laguna Potrok Aike during the first SALSA field campaign in 2002 using a modified ETH-gravity corer (Kelts et al., 1986) equipped with a messenger system. Three cores are from the 100 m deep central basin and two from shallower parts of the lake (Fig. 2.2). In the laboratory sediment cores were stored dark and cool at +4°C. First analyses were non-destructive magnetic susceptibility and GRAPE-density measurements carried out on closed cores with the GEOTEK™ multisensor core logger (MSCL) in one centimeter increments (Gunn and Best, 1998; Zolitschka et al., 2001). A second non-destructive core scanning method was applied for one selected split core (PTA02/4) with the CORTEX XRF-scanner which provides qualitative analyses of the chemical elements K, Ca, Ti, Mn, Fe, Cu and Sr (Zolitschka et al., 2001).

Magnetic susceptibility was used for correlation and selection of the cores to be opened and further analyzed. Cores were split, photographed, described lithologically and sampled continuously and volumetrically in one centimeter intervals.

Additionally, smear slides were prepared from selected depths for microscopic description. For detailed investigations core PTA02/4 from the center of the lake was chosen. Plant macro-remains and gastropods were picked out for later species determination and for AMS ^{14}C dating. In total 13 samples of PTA02/4 were selected for AMS ^{14}C age determination carried out at the Poznań Radiocarbon Laboratory, Poland. For comparison purposes different kinds of material were dated (Tab. 2.1).

Tab. 2.1: AMS radiocarbon dates from core PTA02/4, from animal bones of fluvio-lacustrine sediments and from a modern water plant of Laguna Potrok Aike (dates used in the age model are printed in bold, pMC = percent of modern carbon, SHC = Southern hemisphere calibration).

Sediment depth / Location	^{14}C Age	Error	Sample description	SHC median age (BC/AD)	SHC error to present	SHC error to past	Lab. No.
19-20 cm	2190 BP	±40	bulk sediment	190 BC	140	155	Poz-1688
29-30 cm	3760 BP	±50	bulk sediment	2110 BC	155	175	Poz-1689
43-44 cm	440 BP	±30	one larger (1cm) part of an aquatic plant	**AD 1500**	125	55	Poz-834
49.5-50.5 cm	655 BP	±25	bulk sediment	**AD 1350**	55	45	Poz-897
57-58 cm	735 BP	±25	calcite of bulk sample	**AD 1310**	75	40	Poz-3570
69-71 cm	1330 BP	±35	few parts of aquatic plants, mm-scale	AD 740	115	80	Poz-900
73-74 cm	1580 BP	±30	layer with many parts of aquatic plants	AD 520	85	85	Poz-899
81-82 cm	2440 BP	±40	bulk sediment	540 BC	145	225	Poz-1686
92-93 cm	1470 BP	±40	layer with many parts of aquatic plants	**AD 610**	50	50	Poz-896
97-98 cm	2140 BP	±35	one small (mm) part of an aquatic plant	120 BC	120	225	Poz-902
fluvio-lacustrine sediments above present lake level	160 BP	±50	bone of a guanaco	AD 1820	135	150	Poz-3590
fluvio-lacustrine sediments above present lake level	65 BP	±35	bone of a horse	AD 1870	95	165	Poz-3589
flooded shore	115.2 pMC	±0.4	modern *Potamogeton* (water plant)	AD 1991 or AD 1957			Poz-3573

Radiocarbon analyses were carried out on five bulk samples, four sieved samples containing remains of aquatic macrophytes (>100 µm) and on the calcite fraction of one sample. Additionally, two bones, one of a guanaco (*Lama guanicoe*) and one of a modern horse (*Equus caballus*) found in fluvio-lacustrine sediments above the recent lake level and stems of modern submersed aquatic plants (*Potamogeton pectinatus*) from the littoral zone were dated (Tab. 2.1). ^{137}Cs and ^{210}Pb dating of uppermost sediments of PTA02/4 failed due to very low contents of the radionuclides. This phenomenon is typical for the southern hemisphere.

All volumetric sediment samples were freeze-dried for determination of dry density and water content in one centimeter intervals. Prior to measuring total nitrogen (TN), total carbon (TC) and total sulfur (TS) using a CNS elemental analyzer (EuroEA, Eurovector), dried samples were ground in a mortar and homogenized. For determination of total organic carbon (TOC) subsamples were subsequently treated with 3% and 20% HCl at 80°C to remove any carbonates and then measured with the CNS analyzer. Total inorganic carbon (TIC) was calculated as the difference between TC and TOC. Low-frequency and frequency-dependent magnetic susceptibility were determined on separate samples using a Bartington sensor (type MS2B). Additionally, biogenic silica was analyzed according to Müller and Schneider (1993), mineralogy was determined for selected samples using x-ray diffraction (XRD) techniques (Philips X´Pert Pro MD equipped with an X´Celerator Detektor-Array) and thin sections of selected segments were prepared.

Samples of soils, terrestrial plants and aquatic macrophytes were collected in Laguna Potrok Aike and its vicinity and analyzed isotopically to characterize potential terrestrial and aquatic sources of organic matter. Sediments for isotopic analyses were freeze-dried, homogenized and sieved. Only the fraction <200 µm was analyzed. For $\delta^{15}N$ determination bulk sediment was weighed into tin capsules and combusted at 1080°C in an element analyzer (Eurovector) linked to an isotope ratio mass spectrometer (Micromass, Isoprime). Analytical precision was 0.14‰. For analyses of carbon isotope ratios of organic matter, sediments, soils and water plants were decarbonized with HCl (5%) for 6 hours in a water bath at 50°C, afterwards rinsed with deionized water, centrifuged and freeze-dried. Carbon isotope ratios were determined on decarbonized samples with the same system as for nitrogen isotope analyses. Analytical precision for $\delta^{13}C_{org}$ determinations was 0.08‰. Isotope ratios are reported as δ values in per mil according to the equation

$$\delta = (R_s/R_{st} - 1)*1000 \qquad (1)$$

with R_s and R_{st} as isotope ratio ($^{13}C/^{12}C$, $^{15}N/^{14}N$) of the sample and international standards (VPDB for carbon, AIR for nitrogen), respectively.

For calculation of pollen and charcoal concentrations two tablets of *Lycopodium* spore markers were added to the sediment samples (Stockmarr, 1971). Samples were then treated with HCl and KOH. For heavy liquid separation $ZnCl_2$ was used. After acetolysis the samples were sieved using ultrasonic treatment and stored in glycerin. Pollen slides were mounted with paraffin. Each pollen sample was counted to 500 grains excluding aquatic taxa and spores. Due to low pollen content few samples have a lower pollen sum. Additionally, charcoal particles >20 µm were counted on the pollen slides.

Diatom samples were heated with hydrogen peroxide to oxidize organic material and mounted onto microscope slides following standard procedures (Battarbee, 1986). Permanent slides for light microscopy were prepared with Naphrax®. A minimum of 400 valves per slide were counted in order to calculate relative frequencies. The microfossil diagram and a cluster analysis were processed using TILIA, TILIAGRAPH, TGVIEW and CONISS software (Grimm, 1987).

4. Results

4.1. Chronology

As the sediments of Laguna Potrok Aike contain calcite, at first it was tested, whether there is any hard water effect. The ^{14}C dating from a modern aquatic plant (*Potamogeton pectinatus*) from the littoral zone shows 115.2 ± 0.4 pMC (percent of modern carbon) and no hints for old carbon. This is supported by the field survey where no carbonates have been detected in the catchment of Laguna Potrok Aike. A hard water effect therefore can be excluded. Further evidence was given by ^{14}C dating of autochthonous precipitated calcite which matches the age model (Fig. 2.3). This is only possible if the carbon incorporated in $CaCO_3$ during precipitation in the surface water of the lake originates from atmospheric CO_2. Radiocarbon ages were calibrated with the southern hemisphere calibration curve (McCormac et al., 2002) using the software CALIB 4.4 (Stuiver et al., 2003). For comparison with literature, data calibrated with the northern hemisphere calibration curve (NHC) were recalibrated and marked by the prefix SHC for Southern Hemisphere Calibration. If original dates were available, CALIB 4.4 was used otherwise the following equation was applied:

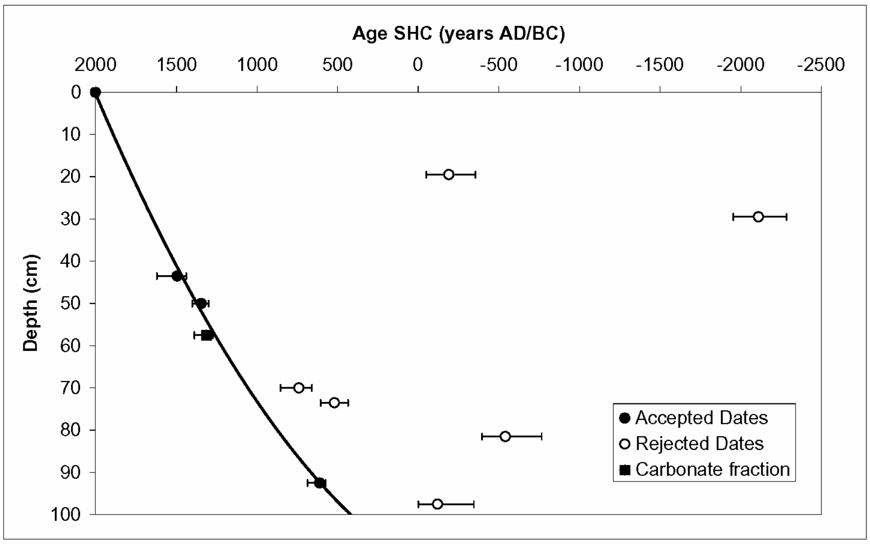
$$SHC = NHC * 0.9906 + 32.427 \qquad (2)$$

This equation results from the regression of age models calculated for Laguna Potrok Aike using northern and southern hemisphere calibration curves (R^2=0.9996). Ages used for comparison without prefixes (SHC or NHC) are historical or dendrochronological dates.

The sediment/water interface serves as time marker for the year of coring, i.e., 2002. A second order polynomial function through the reliable ^{14}C dates ($y=-2*10^{-5}x^2-0.0154x+109.22$) yields a mean sedimentation rate of 0.7 mm a^{-1} (Fig. 2.3). For the calculation of the age model the medians of the 2σ-probability distribution of the accepted ^{14}C dates were used representing more realistic results than means, which in some cases were not within the 2σ-probability distribution at all or modi which were difficult to use with bimodal probability distributions.

The ^{14}C datings revealed ages between 440 and 3760 years BP (Tab. 2.1). Unfortunately, some dates have to be rejected due to the fact that they were contaminated with old autochthonous (C/N-ratio <11) carbon, probably reworked from ancient terraces during lake level high stands and therefore caused too old ages. For that reason only the youngest dates were considered for the age model (Fig. 2.3).

Fig. 2.3: Polynomial age model of sediment core PTA02/4 inferred from AMS ^{14}C dates. Open circles refer to rejected dates due to contamination with old carbon. The sediment-water interface was used as time marker for the year of coring (2002). The square refers to the dated carbonate fraction of a bulk sample. Each southern hemisphere calibrated AMS ^{14}C date (SHC) is shown as median with error bars (2σ).



4.2. Sediment analyses

All cores consist of brownish gray laminated silts with variations in the shades of gray and brown (Fig. 2.4). Silts are interrupted in PTA02/4 by thin layers of plant macro-remains at 68 cm, 74 cm, 88-89 cm and 93 cm. Although the visible plant fragments were excluded from analyses, related sediment sections show higher C/N-ratios (Fig. 2.5). As far as microfossil data is concerned, in total 38 pollen, six spore and two algae types were found.

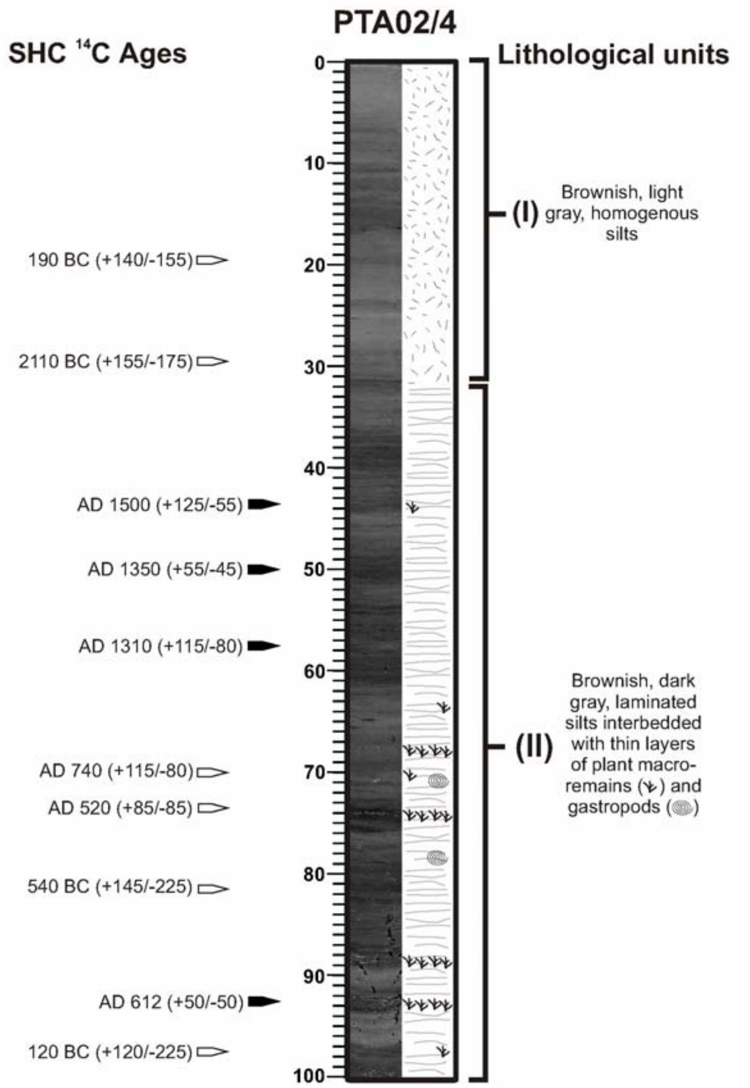


Fig. 2.4: Lithology of core PTA02/4 from Laguna Potrok Aike including southern hemisphere calibrated (SHC) radiocarbon dates. Dates used for the age model are marked with filled arrows close to the core.

Based on variations of sedimentary parameters (Fig. 2.5) six different units (P-1 to P-6) have been identified for core PTA02/4. This zonation is fairly well supported by CONISS cluster analysis of the pollen and diatom data (Fig. 2.6). From bottom to top the different units are characterized as follows:

P-6 (100-68 cm / SHC AD 400-1120) is characterized by oscillations of the sedimentary parameters. The overall trend of these oscillations is a start with a minimum at the bottom of the core with an increase over the whole unit as visible in $\delta^{13}C_{org}$ or C/N-ratios. The oscillations tend to be regular in intensity (same values in

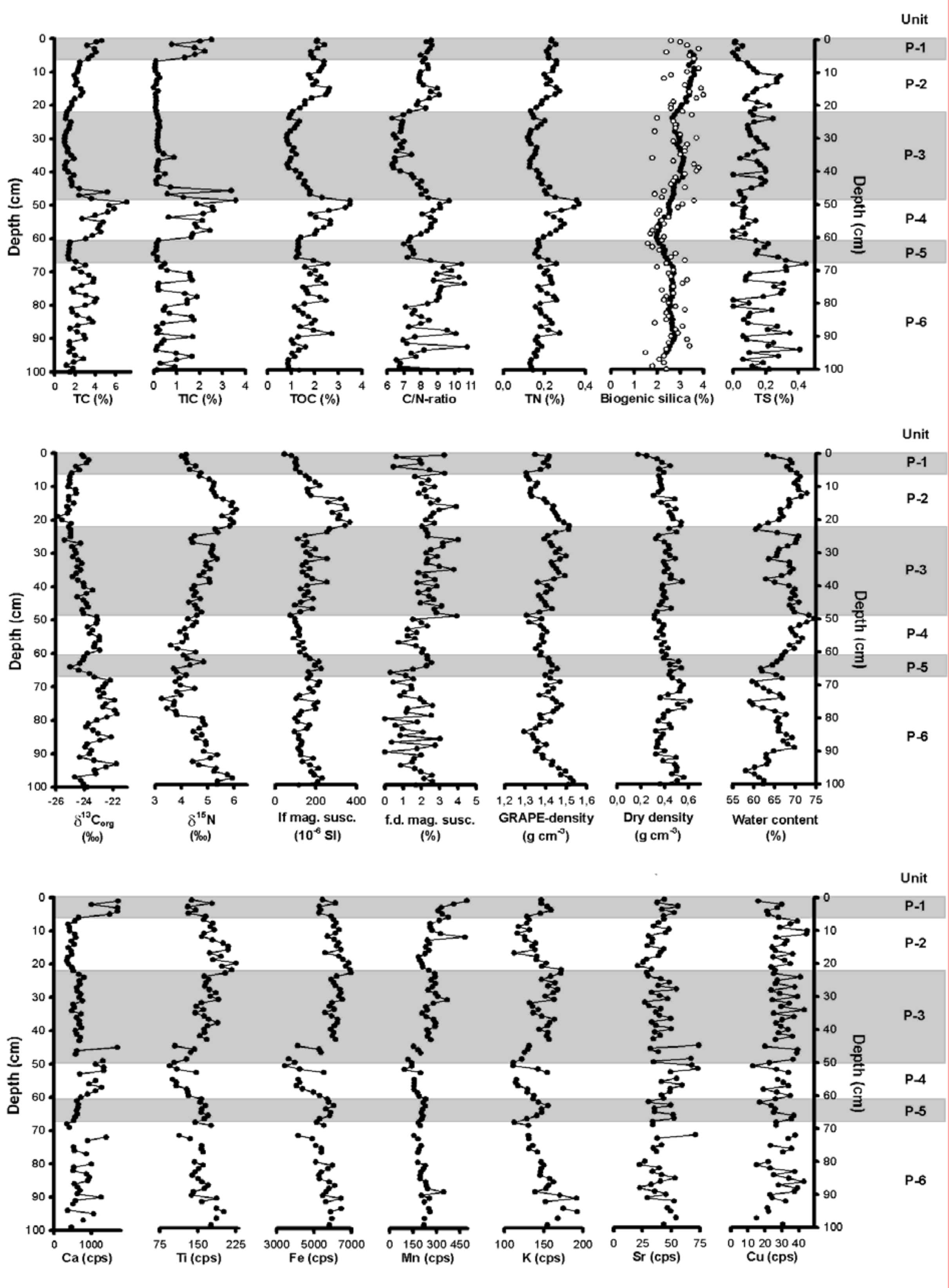


Fig. 2.5: Profiles of geochemical, isotopical, geophysical and XRF-scanning elemental analyses of PTA02/4. Results of biogenic silica are displayed as original values (open circles) and seven point running means (dark circles). Lf mag. susc. refers to low-frequency magnetic susceptibility and f.d. mag. susc. to frequency-dependent magnetic susceptibility. XRF-data is plotted as counts per second (cps) of the respective element. The missing values are caused by previously sampling for AMS ^{14}C dating.

maxima and minima) and duration (similar intervals). Exceptions are $\delta^{15}N$, GRAPE-density, Ti, Fe and K which start with a maxima and decrease continuously. The pollen spectrum shows Poaceae percentages of 64% at 100 cm which decrease to 43% at the top of P-6. Other abundant herbs are Asteraceae (Tubuliflorae) with an average of 8%, *Acaena* (average 4%) and Ericaceae (average 1%). *Nothofagus dombeyi*-type representing pollen from Andean forest occur with contributions of 15% at 100 cm core depth, increasing to 30% towards the top of the unit. Diatom concentrations increase as well with a marked dominance (39 to 87%) of *Cyclotella agassizensis*, a planktonic species and epiphytic *Cocconeis placentula* var. *euglypta* (5 to 18%). Benthic and aerophilic taxa are rarely represented.

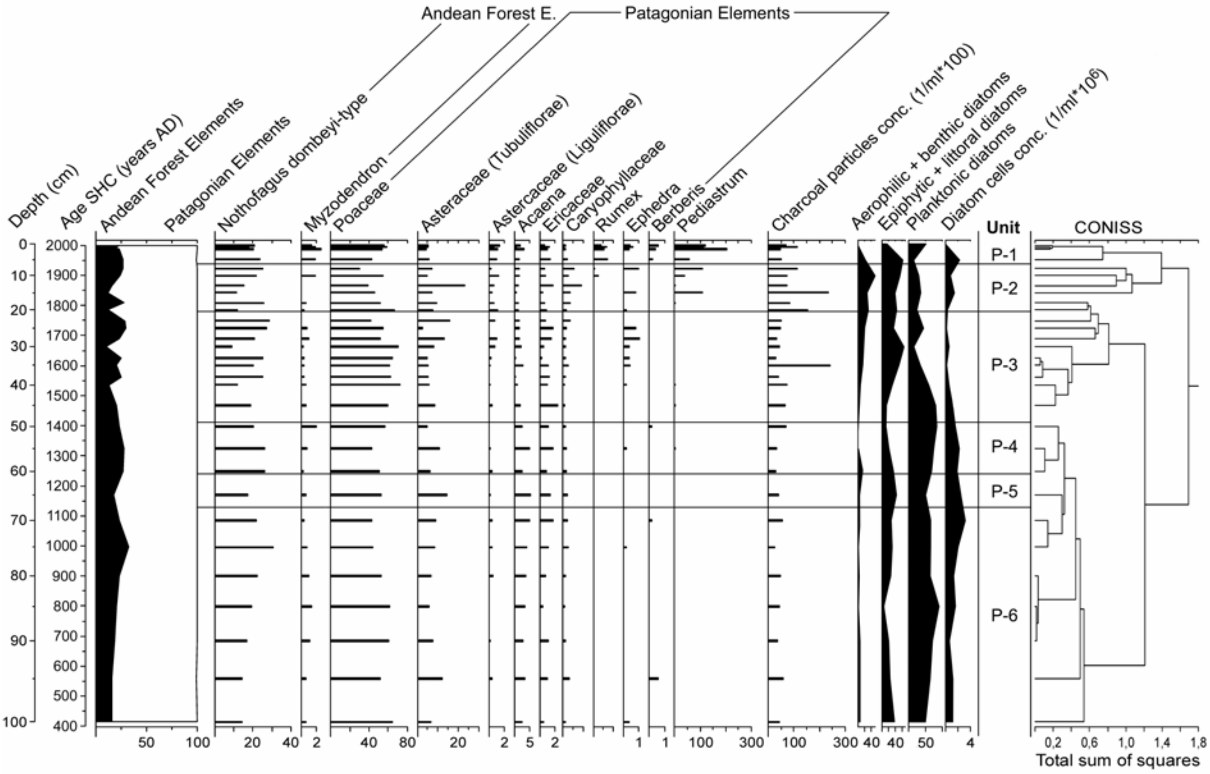


Fig. 2.6: Summary pollen and diatom diagram of sediment core PTA02/4.

In P-5 (67-61 cm / SHC AD 1120-1240) a minimum is visible in TIC, Ca, $\delta^{13}C_{org}$, C/N-ratio, TOC, TC and TN profiles. $\delta^{15}N$, low-frequency- and frequency-dependent magnetic susceptibility, Ti, Fe and K values show a maximum in this unit.

Biogenic silica and TS decrease, while water content starts with a minimum and increases subsequently. P-5 is represented by only one pollen sample, however a decrease in the contribution of *Nothofagus dombeyi*-type to 17% and an increase of Poaceae (43% to 52%) and Asteraceae (Tubuliflorae, 9% to 15%) values are visible. Epiphytic and littoral diatoms show a maximum whereas planktonic species show a minimum in P-5.

In P-4 (60-49 cm / SHC AD 1240-1410) $\delta^{15}N$, biogenic silica and frequency-dependent magnetic susceptibility increase after a drop in the lower part of the unit. Low-frequency magnetic susceptibility, Ti, Fe, K and Mn decrease slightly. TIC, Ca, $\delta^{13}C_{org}$, C/N-ratio, TOC, TC, TN and water content show one broad extended peak which can be divided into two separate maxima. GRAPE-density and TS show very low values in P-4. Percentages of *Nothofagus dombeyi*-type decrease from 26% at 60 cm to 20% at 50 cm. *Acaena* (5%), Asteraceae (Tubuliflorae, 11%) and Ericaceae (3%) show a maximum at 55 cm. The contribution of Poaceae increases from a minimum of 43% at 55 cm to values of 57% at the top of this unit.

Diatom concentrations and the relative abundance of epiphytic and littoral (mainly *Fragilaria construens* var. *venter* and *Fragilaria pinnata*) diatoms progressively decrease. *Cyclotella agassizensis* dominates in all samples (65-81%).

The transition between P-3 and P-4 is characterized by a marked shift visible in TC, TIC, TOC, C/N-ratios, TN, $\delta^{13}C_{org}$, low-frequency magnetic susceptibility, frequency-dependent magnetic susceptibility, GRAPE-density, Ca, Ti, Fe, Mn and Sr. P-3 itself (49-21 cm / SHC AD 1410-1770) is dominated by very low values of TIC, Ca, TOC, TN, TC and C/N-ratio. In the lower part of this minimum a single value maximum is visible in TC, TIC and Ca. TS, biogenic silica, GRAPE-density, water content, low-frequency magnetic susceptibility and frequency-dependent magnetic susceptibility are variable. $\delta^{13}C_{org}$ decreases whereas $\delta^{15}N$ increases. Ti, Fe, Mn, K are on a high level. *Nothofagus dombeyi*-type pollen (average 21%) and Poaceae (average 60%) are still the dominant taxa with an increasing contribution of Asteraceae (Tubuliflorae, 5-16%). In this unit pollen of Asteraceae (Liguliflorae) and *Ephedra* occur continuously with values of 1%.

Diatom concentrations and the relative abundance of planktonic diatoms decrease to their lowest values. Epiphytic and littoral species increase remarkably. *Fragilaria construens* var. *venter* and *Diploneis smithii* (benthics) and *Cocconeis placentula* var. *euglypta* (epiphytic) replace *Cyclotella agassizensis* as the dominant species.

In P-2 (20-7 cm / SHC AD 1770-1940) TIC and $\delta^{13}C_{org}$ values stay on a similarly low level like in P-3. $\delta^{15}N$, GRAPE-density and low-frequency magnetic susceptibility decrease, TC, TS and Mn increase and TOC, TN, C/N-ratios, frequency-dependent magnetic susceptibility and biogenic silica oscillate on a high level. Percentages of *Nothofagus dombeyi*-type increase from 12% to 25%, whereas Poaceae decrease from 66 to 30%. Caryophyllaceae values reach their maximum (average 4.4%) and for the first time *Rumex* pollen and coenobia of *Pediastrum* appear. In P-2 the concentration of charcoal particles doubles (average 12.3 particles ml^{-1}) compared to lower lithological units (average 5.5 particles ml^{-1}).

Diatom concentrations increase and the relative abundance of littoral and epiphytic diatoms is higher than 40% of the total diatoms. There is a marked increase in the relative abundance of benthic and aerophilic taxa (*Diploneis smithii, Amphora copulata, Navicula radiosa*).

P-1 (6-0 cm / SHC AD 1940-2002) is characterized by an increase in TIC, Ca, $\delta^{13}C_{org}$, Mn, TC and GRAPE-density interrupted by a drop between 2 and 3 cm core depth in TIC, Ca and TC. Water content decreases in P-1. TS decreases to almost zero. The other geochemical and geophysical proxy data show the same trend as in P-2. *Nothofagus dombeyi*-type values reach an average of 20%. Percentages of Poaceae increase again to 59%, *Rumex* reaches highest values (average 6%) and pollen from the insect-pollinated *Berberis* was found (average 0.3%). Compared to the underlying unit the average contribution of *Pediastrum* coenobia increases (43% to 124%), whereas the concentration of charcoal particles drops to an average of 7.0 particles ml^{-1}.

Diatom concentrations remain high. They are dominated by *Cyclotella agassizensis* (24-37%), *Fragilaria construens* var. *venter* (11-24%) and *Cocconeis placentula* var. *euglypta* (8-16%).

Values of Cu are too low to be interpreted in the whole profile (Fig. 2.5). Though many elements like Mn or Cu obtained by XRF scanning remain quite stable others show good correlations with different parameters. TIC for example has a positive correlation with Ca (R^2=0.51) and a negative correlation with Fe (R^2=0.57) and Ti (R^2=0.46). Furthermore, Fe and Ti show a positive correlation (R^2=0.80). Negative correlations can be observed between Fe and Ca and Ti and Ca (both R^2=0.51). $\delta^{13}C_{org}$ is negatively correlated with $\delta^{15}N$ (R^2=0.46), Fe (R^2=0.40) and Ti (R^2=0.31) and positively with C/N ratios (R^2=0.31). $\delta^{15}N$ likewise is correlated with Fe (R^2=0.35) and Ti (R^2=0.42), but less with C/N (R^2=0.15). Ca vs. Sr and TIC vs. Sr only show good correlations in sections where calcite is present.

In addition to C/N-ratios measured from sediments of PTA02/4 (mean value: 8.04), C/N-ratios for modern submerged aquatic plants were determined. Obtained data range between 24 and 49 whereas ratios of land plants with values up to 86 are, as expected, much higher.

5. Indicators for lake level changes

At Laguna Potrok Aike TIC is only produced autochthonously. Allochthonous carbonates have not been recognized. Therefore, it is hypothesized that in this case TIC can be used as a sensitive proxy for lake level changes, supported by lake level trend indicators like $\delta^{13}C_{org}$ and C/N-ratio.

Lacustrine calcareous sediments can be formed as a combination of five processes (Dean and Fouch, 1983; Kelts and Hsü, 1978):

1a. Primary inorganic precipitation and sedimentation of carbonate minerals,

1b. Photosynthesis induced, inorganically precipitated carbonate,

2. Biogenic carbonate consisting of calcareous skeletons, structural parts and internal waste products from living organisms,
3. Clastic input of allochthonous carbonates by erosion and transport and
4. Post depositional changes or early diagenetic reactions producing carbonates.

As there are no carbonaceous rocks in the catchment and remains of gastropods were picked out prior to analyses, the main source for TIC in Laguna Potrok Aike sediments must be related to inorganic or organic induced precipitation and subsequent sedimentation of carbonate minerals. Post depositional changes and diagenetic reactions, however, cannot be excluded completely. X-ray diffraction and smear slide analysis show that almost all inorganic carbon is present as calcite ($CaCO_3$). Precipitation of calcite is controlled by biogenic and physico-chemical factors (Kelts and Hsü, 1978; Koschel et al., 1987) which both influence the CO_2 partial pressure and hence availability of CO_3^{2-} and HCO_3^- which are necessary for the formation of $CaCO_3$. Calcium released from weathered basaltic rocks in the catchment area is supposed to be the main source of Ca^{2+} into the lake water.

Biogenic factors controlling calcite precipitation in Laguna Potrok Aike are plant activities, i.e., assimilation of CO_2 by photosynthesis of algae or higher aquatic plants. This process is influenced by nutrient and light availability but also by the physical factor temperature. Temperature not only affects biogenic factors but also the solubility of CO_2 in water (Schwoerbel, 1999; Sigg and Stumm, 1996). Also, through temperature-dependent evaporation the total volume of water influencing the ion concentration within the lake is modified.

These dilution and concentration processes themselves are not only dependent on temperature (evaporation, solubility) but also on the amount of rainfall or meltwater. On the other hand rain- and snowfall have an effect on temperature: higher meteoric precipitation usually means an increase in cloudiness which reduces solar radiation and consequently results in lower temperatures (Villalba, 1990). This reduces the loss of water in the lake and due to the larger water volume more energy is required for heating-up the water to reduce the solubility of $CaCO_3$. This again inhibits the precipitation of calcite. Therefore the profile of inorganic carbon (TIC in Fig. 2.5, 2.7) is interpreted as an indicator for concentration and dilution processes within the lake reflecting the water balance of the lake and resulting lake level changes (Fig. 2.7). Further evidence for this hypothesis is given by calcite saturation indices (Ω) calculated after Ohlendorf and Sturm (2001) for Laguna Potrok Aike. A comparison of the values for the dry austral summer 2001/02 and the wet austral summer 2002/03 shows remarkable differences. The values of late summer 2002 reveal maximum saturation indices of Ω=78.5 being about four times higher than the values of Ω=22 for late summer 2003. Both years show strong supersaturation but the increase in precipitation leads to a pronounced decrease of saturation indices.

Not only are the components of calcite (Ca^{2+}, CO_3^{2-} and HCO_3^-) affected by concentration and dilution processes but so are factors leading to precipitation of $CaCO_3$. The pH for example decreases with rising amounts of water available for

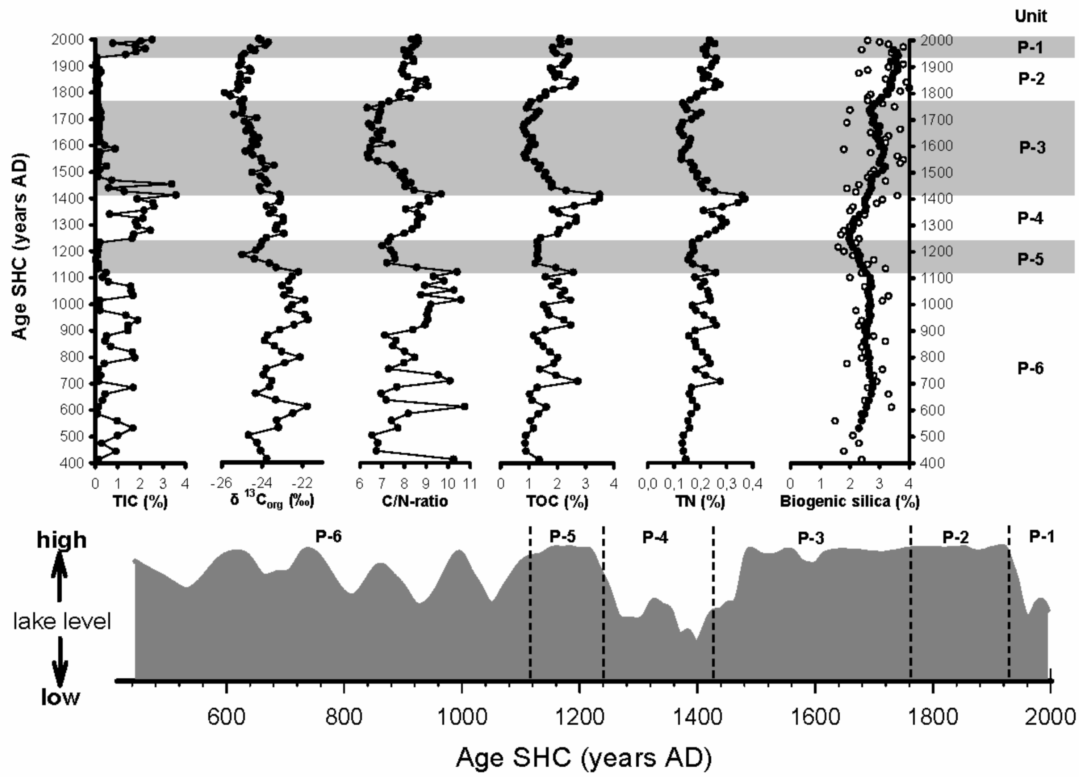


Fig. 2.7: Selected sediment parameters on time scale reflecting significant environmental changes and resulting lake-level curve of Laguna Potrok Aike from SHC AD 400 to present.

dilution as observed during the dry summer of 2002 (pH=9.1) and the wet summer of 2003 (pH=8.7). An increase in pH in dry years resulting from ionic concentration supports the precipitation of calcite.

To summarize, the higher the value of TIC within the sediment record, the lower the lake level was during the time of sedimentation. Therefore, the inorganic carbon record in the cores of Laguna Potrok Aike represents a sensitive, continuous and high resolution proxy for lake level variations and thus hydrological changes. From the plant physiological point of view it is an indicator for water stress or drought during lake level low stands. This is mainly influenced by water supply and evaporation, the latter being highly correlated with wind speed (Walter and Box 1983), temperature, radiation and humidity (Mancini, 1998).

Datings of bones of a horse (*Equus caballus*) and a guanaco (*Lama guanicoe*) deposited in fluvio-lacustrine sediments several meters above the modern lake level support the interpretation of TIC as a lake level indicator. They were deposited

SHC AD 1820 ($^{+135}/_{-150}$) and SHC AD 1870 ($^{+95}/_{-165}$), respectively. During this period of a higher-than-present lake level TIC is constantly low.

Isotopic analyses and C/N support the lake level changes derived from TIC. In Laguna Potrok Aike $\delta^{13}C_{org}$ and $\delta^{15}N$ are negatively correlated (R^2=0.46 / Fig. 2.5). Positive correlations were observed in lakes where $\delta^{13}C_{org}$ and $\delta^{15}N$ of sediment organic matter reflected changes in productivity (Talbot, 2001). This interpretation would imply that sediment organic matter is predominantly of autochthonous planktonic origin which is obviously not true for the lower core sections with higher C/N ratios, partly above 10, the threshold for algal organic matter (Meyers and Lallier-Vergès, 1999). Although plant macro-remains were excluded from C/N analyses, sections which contained plant macro-remains in the lower part of the core show higher C/N-ratios (Fig. 2.5) pointing to a certain amount of finely dispersed aquatic macrophyte debris. Submersed aquatic macrophytes collected from Laguna Potrok Aike have C/N values between 24 and 49 and are the most probable source of organic matter for core sections with elevated C/N.

$\delta^{13}C_{org}$ variations in the lower half of the core generally are positively correlated with C/N variations indicating that differential contents of fine dispersed aquatic macrophyte debris ($\delta^{13}C$ values of modern aquatic macrophytes are between -10.1‰ and -16.1‰) controls carbon isotope ratios in this core segment. Thus both C/N and $\delta^{13}C$ most likely reflect changes in the source of organic matter. As aquatic macrophytes have much higher $\delta^{13}C_{org}$ values than algae and are restricted to shallow–water habitats, $\delta^{13}C_{org}$ values can be used as an indicator for paleoshoreline distance from the basin where the core was recovered. Higher $\delta^{13}C_{org}$ values in the mixture of planktonic and macrophytic origin represent a higher macrophytic component and hence lower lake levels due to two considerations: (1) At lower lake levels the belt of submersed shoreline vegetation moves closer to the center of the lake (coring location) and (2) sediments containing aquatic macrophytes can be reworked from dry lake level terraces by arroyo formation during lake level low stands. The latter was observed by local people in 2002. Due to the same reasons C/N-ratios of the sediment can be applied as an indicator of paleoshoreline proximity as performed at Lake Victoria, East Africa (Meyers and Teranes, 2001). This is only valid for units P-6 to P-3 as correlations between both parameters break down at the end of P-3.

Usually, allochthonous input to depositional environments and hence run-off and rainfall is represented by the Ti content (Haug et al., 2003). For Laguna Potrok Aike Fe is correlated with Ti (R^2=0.80) and should allow the same conclusion. On the other hand negative correlations of both elements with TIC (R^2=0.46/0.57) point to dilution of the allochthonous input by precipitated $CaCO_3$. As the sum of the counts of the elements detected by XRF-scanning remains constant it cannot be decided from XRF data alone, if Fe and Ti values only co-vary with changes in Ca or if their variations reflect also variable allochthonous input into the lake. However, $\delta^{15}N$ is correlated positively with both Fe and Ti (R^2=0.35/0.46) but to a lesser degree with TIC (R^2=0.15). Considering these correlation patterns and the fact that modern soils from the vicinity of Laguna Potrok Aike have the highest $\delta^{15}N$ values (4.6-8.7‰) of all potential organic matter sources investigated (soils, terrestrial plants, aquatic macrophytes), high Fe, Ti, and $\delta^{15}N$ may indicate high input of allochthonous soil material into the lake, whereas low values of these parameters may indicate low soil input. Additionally, higher values for magnetic susceptibilities might be interpreted as inwashed inorganic allochthonous material (Thompson et al., 1975). Showing a negative correlated pattern with TIC, they seem to represent variations of the input of magnetic particles from the surrounding of the lake and thus changes in run-off and related rainfall.

Implications of lake level changes for the age model

As deposition of TIC and TOC often coincide (Koschel et al., 1987), e.g., by adsorption of dissolved organic matter to $CaCO_3$ (Otsuki and Wetzel, 1974; Uhlmann and Horn, 2001), they basically show a comparable downcore pattern though R^2 is only 0.23. This weak correlation might be the result of the sensitivity of TOC to numerous other changing parameters like particle sinking times in water, burial rates at the lake bottom, decomposition, etc. (Meyers, 1990). Additionally, reworked TOC is carried into the system from lake level terraces partially explaining the comparable downcore pattern. Similar observations were made in Pyramid Lake (Nevada, USA) where sediments formerly deposited along the lake margins have been progressively resuspended by wave turbulences as water levels dropped (Meyers and Lallier-Vergès, 1999; Tenzer et al., 1997).

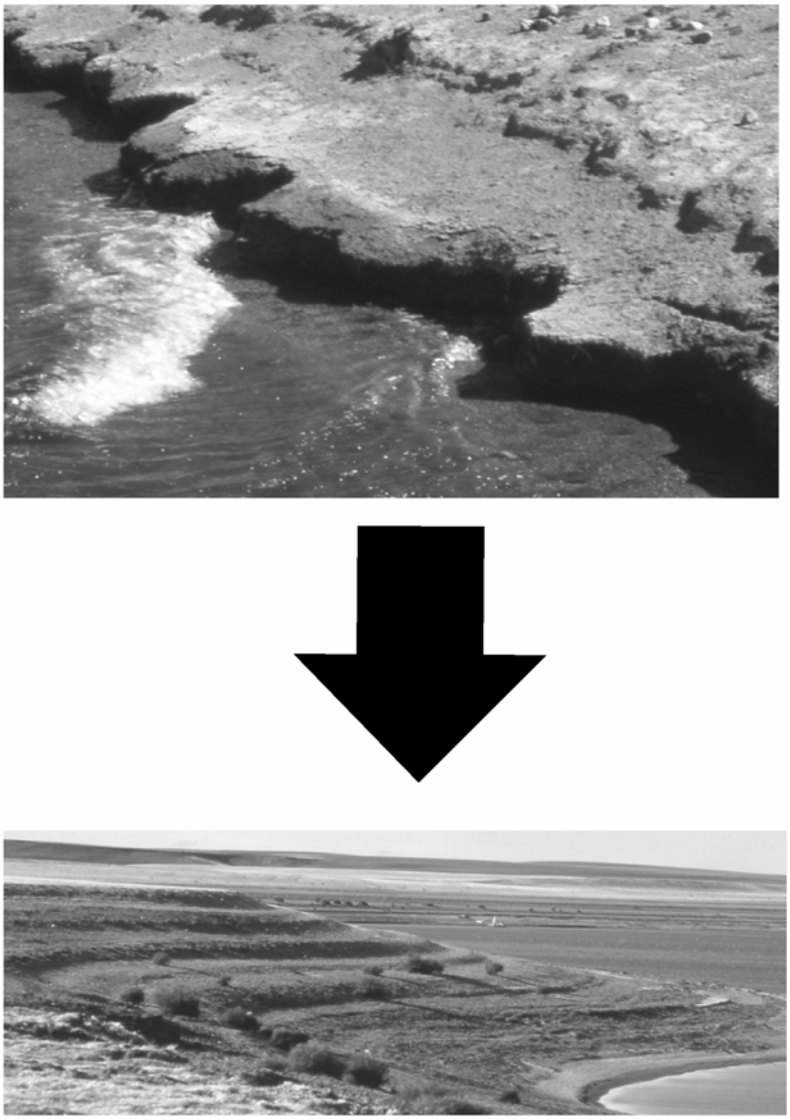


Fig. 2.8: Permanent wave action redistributes material from the shoreline. This process builds lake level terraces.

This implies, that through wave erosion in combination with annual lake level changes sediment redistribution occurs continuously in Laguna Potrok Aike as observed during the field campaign in 2003 (Fig. 2.8). Therefore, if the lake level rises, material of older lake level high stands is redistributed. As mostly small particles are eroded and redeposited in the lake center, this is the reason why some radiocarbon dates have to be rejected in the age model due to this kind of “reservoir effect” (Fig. 2.3, Tab. 2.1). TIC, however, is not affected by this redistribution from high lake level terraces because if the lake level is high, calcite is not precipitated.

6. Paleoenvironmental reconstruction

6.1. SHC AD 400-1120 (P-6)

Between SHC AD 400 and SHC AD 1120 rapid fluctuations in almost all proxies point to unstable conditions (Fig. 2.7). Dry periods lasting three to eight decades alternate with longer episodes of moist conditions. At the end of this period TIC, $\delta^{13}C_{org}$ and C/N-ratio fluctuations decrease and indicate a transition from dry to wet conditions prevailing in P-5 which is also supported by the decrease of planktonic and the increase of epiphytic diatoms and Fe and Ti, respectively.

Nowadays the regional vegetation around Laguna Potrok Aike is dry steppe mainly dominated by grasses. The pollen record shows that this applies also for P-6. However, the Andean pollen taxa increasingly contribute to the pollen spectra of this time. Pollen from these taxa are transported from the Andes to Laguna Potrok Aike by strong westerly winds. The increasing amount of Andean pollen and the corresponding decrease of steppe pollen might indicate an overall trend to drier conditions caused by a less dense vegetation cover of the steppe and an increase of the contribution of long distance transported pollen. *Acaena* pollen represents a local component of the pollen record. Nowadays *Acaena* is the first plant occupying the part of the lake shore which is affected by annual water level fluctuations. As *Acaena* is more abundant during this period compared to later times it might indicate that lake level fluctuations were stronger and/or more frequent and therefore the area of *Acaena* dominance around the lake was larger.

6.2. SHC AD 1120-1240 (P-5)

Since the start of this time interval TIC, $\delta^{13}C_{org}$ and C/N-ratio fluctuations are in phase. Low values of these parameters indicate a high lake level in Laguna Potrok Aike and therefore wet climate conditions. Epiphytic and littoral diatoms increase probably due to an enlarged habitat due to a higher lake level. TOC, TN and biogenic silica indicate low lacustrine production due to lower temperatures. Although this time interval is represented by only one pollen sample, a decrease of contribution from

Andean forest taxa and an increase of steppe taxa is recognizable. This is in agreement with the assumption of more humid conditions that caused a denser steppe vegetation and a decline in long distance transported pollen.

6.3. SHC AD 1240-1410 (P-4)

Maxima of TIC, TOC, TN, C/N, and $\delta^{13}C_{org}$ indicate low lake levels and warm and dry climate from the mid 13th century until the early 15th century (Fig. 2.7). Minimum values of littoral and epiphytic diatoms point to a reduction of shallow-water habitats. However, a short interruption with colder and wetter climatic conditions occurred around SHC AD 1340.

Decreasing contribution of Patagonian steppe pollen between SHC AD 1240 and SHC AD 1350 and a contemporaneous increase of Andean forest pollen mainly from *Nothofagus dombeyi*-type indicate warmer/drier climate conditions that cause a lower lake level. A maximum of *Acaena* at SHC AD 1330 points to an enlarged vegetation belt near the lake shore and therefore strengthens the hypothesis of lower lake levels.

6.4. SHC AD 1410-1770 (P-3)

An increasing amount of steppe pollen from about SHC AD 1410 onwards indicates wetter conditions. At the same time a marked shift in frequency-dependent magnetic susceptibility and low-frequency magnetic susceptibility as well as an increase in $\delta^{15}N$ values and Fe and Ti contents indicate intensified soil erosion most likely caused by the increased precipitation as expected from the high lake level. From the early 15th to the late 18th century low values of TIC, $\delta^{13}C_{org}$ and C/N-ratios point to high lake levels and therefore to wetter conditions. Pronounced one value peaks of TC, TIC and Ca at the bottom of this unit point to a very short lasting lake level drop. The respective sample was analyzed several times to exclude an error in the analysis. However, an error due to a possibly unnoticed gastropod which then would not have been sorted out might have occurred. TOC and TN indicate a drop in production and hence lower temperatures. Higher lake levels also explain the supply of more diatoms from the littoral zone of the lake due to an enlarged habitat.

Pollen spectra show a change in vegetation as elements of the presently common steppe association, like Asteraceae and *Ephedra*, become more abundant. Constantly high values of Poaceae may be interpreted as dense vegetation cover of the Patagonian steppe formation reflecting less water stress and higher lake levels. Therefore, it is assumed that during this time interval the presently common steppe association spread out. Lake level was high with some less important fluctuations as indicated by still small proportions of *Acaena*.

6.5. SHC AD 1770-1940 (P-2)

According to TIC and $\delta^{13}C_{org}$ the lake level remained high until the beginning of the 20th century. Eutrophication tendencies are reflected by increasing values of TOC, TN and biogenic silica during the 18th century (Fig. 2.7). This either points to warmer conditions or to eutrophication tendencies due to human impact before the first sheep farmers settled in the vicinity of Laguna Potrok Aike at the end of the 19th century (Mainwaring, 1983; Wilhelmy and Rohmeder, 1963). Nevertheless, early eutrophication might be related to European impact as maps reveal countless expeditions crossing the vicinity of Laguna Potrok Aike (Martinic, 1999) which may have had an impact on the conditions in the lake. These man made changes explain the decoupling of the lake level indicator C/N-ratio from TIC and $\delta^{13}C_{org}$ in P-2.

This matches with the first appearance of *Pediastrum coenobia* and the high relative abundance of *Fragilaria construens* var. *venter,* which is indicative of meso-eutrophic water conditions (Whitmore, 1989). The different indicators together point to a change in lake ecology. They probably mirror an increase of the trophic level of the lake due to external nutrient input. This is also indicated by the first occurrence of *Rumex* pollen introduced by Europeans as well as an increased amount of charcoal particles. The first peak of *Pediastrum* is contemporaneous with the start of *Rumex* abundance around SHC AD 1845. The earliest peak of *Rumex* can be dated to SHC AD 1880 and thus is contemporary with the arrival of European sheep farmers.

6.6. SHC AD 1940-2002 (P-1)

According to TIC a change to subsequently lower lake levels under drier conditions is recorded for Laguna Potrok Aike. Only during the late 1980s a period of somewhat higher lake levels and wetter conditions was detected.

Due to the increasing influence of settlers it is not sure to which extent changes in the pollen spectra are caused by climate factors or human impact. However, the first appearance of *Berberis* in the record, a maximum of *Rumex* pollen and *Pediastrum* coenobia may be related to an intensification of land use by pasture. The recorded decrease of charcoal to values still higher than before European occupation indicates that the steppe was under use but fire frequency and extent was probably managed by farmers.

7. Comparison with other paleoenvironmental archives from Patagonia

7.1. 1st millennium AD

Evidence from other locations for the lake level fluctuations observed in P-6 is poor. In Lago Cardiel (Fig. 2.1: 48°57`S, 71°26`W) dated wood provided an age of SHC AD 620±180 for a lake level high stand, which is consistent with ages of artifacts found on a terrace of the same level (Galloway et al., 1988). Stine and Stine (1990) interpreted other radiocarbon dates from Lago Cardiel (SHC AD 540±95/ SHC AD 880±100) as early and mid stages of a lake transgression. Considering the errors of radiocarbon dating, the mentioned dates from Lago Cardiel coincide with lake level high stands and short interrelated regressions in Laguna Potrok Aike. For the same time interval δD values of moss cellulose at Harberton Peat Bog, Tierra del Fuego (Fig. 2.1: 54°53`S, 67°10`W), indicate rapidly changing temperatures from SHC 10 BC to SHC AD 1270 (Pendall et al., 2001) corroborating the interpretation for Laguna Potrok Aike.

7.2. AD 1000-1250

Stumps rooted in marshes near Bahía Catalon (Lago Argentino, Fig. 2.1: 50°28`S, 72°58`W) display between 50 to 100 growth rings and have death dates around SHC AD 1160±115 (Stine 1994). This is interpreted as a dry period when trees could grow, followed by an increase in water level that led to the drowning of the trees. Similar observations during the same time were made at Lago Cardiel. Drowned shrubs dated to SHC AD 1150±110 and radiocarbon dates of organic detritus (SHC AD 1110±105) give evidence for the recovery of the lake from one of its lowest stands during the Holocene (Stine, 1994; Stine and Stine, 1990). This dry/wet transition is represented in the TIC record of Laguna Potrok Aike by the uppermost distinct peaks of TIC, $\delta^{13}C_{org}$ and C/N-ratio fluctuations in P-6 and the following minima of P-5 (Fig. 2.7). A reconstructed precipitation record for a mire at Cabo San Pablo, Tierra del Fuego (Fig. 2.1: 54°18`S, 66°45`W), in many parts very similar to the lake level proxies of Laguna Potrok Aike, implies a trend towards rising effective rainfall in the second millennium AD following a drier period (Heusser and Rabassa, 1991). Soils (mollisol) from southern Patagonia developed after an increase in humidity following an episode of severe drought (Favier Dubois, 2003). Several dates point to a development of this soil around the end of the first millennium AD. From pollen analyses in the Lago Argentino area (Fig. 2.1: 50°20`S, 72°18`W) increased availability of moisture associated with a decrease in temperature is indicated by the development of grass steppe at that time (Mancini, 2002). The lake level high stand of P-5 was also detected at Lago Cardiel. The single date of 800 BP (SHC AD 1220±170, Markgraf et al., 2003) corresponds to the end of P-5.

7.3. AD 1250-1410

The low lake levels at Laguna Potrok Aike during this time interval coincide with a lack of glacier advances. There is only scattered evidence for extended glaciers during the 14th to 16th century (Luckman and Villalba, 2001). These few glacial advances may be related to one of the intervening short lake level high stands like in the mid 14th century (Fig. 2.7).

Earlier climatic correlations on the basis of glacier fluctuations are almost impossible because data from Patagonia is too scarce to study the relationship between glacier fluctuations and climatic changes (Kadota et al., 1992; Warren and Sugden, 1993). As pointed out above, climatic fluctuations were very rapid before SHC AD 1250 hence more than one cooler period could be responsible for a single glacier advance. Since then, however, climatic trends last long enough to enable a comparison between glacier fluctuations and climatic proxies from Laguna Potrok Aike.

7.4. AD 1410-1940

The wet and cold conditions of P-2 and P-3 correspond to three radiocarbon ages from Lago Cardiel (Fig. 2.1), all dating mid stages of lake transgressions at SHC AD 1426±25 and SHC AD 1735±215 (Stine and Stine, 1990). The classical “Little Ice Age” advances of glaciers are also found in most areas of South America during the 17th through the early 20th centuries (Luckman and Villalba, 2001). Röthlisberger (1986) however mentions a number of advances in South America between 34°S and 52°S already from 400 to 100 BP (SHC AD 1540-1820). Logbook evaluations of early Spanish seafarers document wet conditions in spring and summer in the Strait of Magellan between AD 1520 and AD 1670 (Prieto and Herrera, 1998). A severe decrease in $\delta^{13}C_{org}$ was observed for the 16th century from sediments of Laguna Azul (52°05’S, 69°35’W) and was attributed to a rapid climatic cooling (Zolitschka et al., 2004).

Reconstructed temperature patterns from tree rings for the southern sector of the southern Andes show an extended period of cold years persisting from 1640 to 1850 (Villalba et al., 2003). A large moraine system dating back to NHC AD 1940 (SHC AD 1950) is located at Soler Glacier in the North Patagonian Icefield (Fig. 2.1: 46°56`S, 73°9`W) terminating the period of advances (Glasser et al. 2002). This is consistent with the subsequently lake level lowering at Laguna Potrok Aike after SHC AD 1940.

7.5. AD 1940-2002

This time interval is characterized by the globally recorded warming trend of the 20th century. At Río Gallegos (Fig. 2.1 / 51° 36`S, 69° 30`W) a warming of 2.5 °C has been recorded from 1931 to 1990 (Villalba et al., 2003). In Chile, between Puerto Aysén (45° 26`) and Punta Arenas (53°S) a mild warming began in the 1950s that leveled off in the 1980s. On the Argentinean side the transect from Comodoro Rivadavia via Río Gallegos to Ushuaia exhibits a similar trend that starts a little earlier (Rosenblüth et al., 1997). Correspondingly, an overall trend of receding glaciers is reported from Patagonia (Glasser et al., 2002; Warren and Sugden, 1993).

At Laguna Potrok Aike this warming might be reflected by drier conditions in the course of this century interrupted by a short period of moister conditions towards the end of the century. The same trend is reflected in records from Lago Cardiel (Markgraf et al., 2003) as well as in many other closed lakes of Patagonia. After a lake level drop since 1940 Lago Cardiel reached its latest low stand in 1990. Since then it has risen approximately 4 m (Markgraf et al., 2003; Stine and Stine, 1990). In addition to that, Laguna Potrok Aike subsequently shows a recession in the uppermost part of the record.

8. The Medieval Climate Anomaly (MCA)

As became obvious from the comparison of proxies derived from Laguna Potrok Aike with results from other regional climate archives in southern Patagonia, information always has been very discontinuous or with medium or low time resolution. The record of Laguna Potrok Aike combines continuous multi-proxy information with high resolution in the dry lands of southeastern Patagonia where there is hardly any paleoenvironmental data at all (Fig. 2.1). This enables a closer look to the sequence of events which is regarded as one uniform climatic period like the Medieval Climate Anomaly.

The geographic extent and timing of the Medieval warmth is still a matter of debate (Crowley and North, 1991; Stine, 1998). The term Medieval Warm Epoch (MWE) was coined by Lamb (1965) summarizing and evaluating a variety of non-instrumental records. The conclusion was that the period NHC AD 1080-1200 was characterized by warm summers throughout Europe. With the exception of a cool interlude some time between NHC AD 1050 and NHC AD 1150, this MWE persisted until around NHC AD 1300 and can be extended beyond Europe (Stine, 1998). As demonstrated earlier, the original time span of the European MWE was rather wet and cold in southeastern Patagonia (P-5). Hence, it is of greater significance that there were distinct rainfall anomalies during that time. Stine (1994) therefore proposed the expression Medieval Climate Anomaly (MCA). During this period many areas experienced pronounced drought episodes (Bradley, 2000). Stine (1998) registers a change to conditions that define the start of the MCA at about NHC AD 850 (SHC AD 870). This is consistent with all variables indicating low lake levels at Laguna Potrok Aike but Stine (1998) postulates an abrupt and marked alteration in climate (wetter) as late as NHC AD 1110 (SHC AD 1130).

Laguna Potrok Aike reveals a split picture for the MCA. C/N-ratios support the hypothesis of a persistent drought in southeastern Patagonia during unit P-6. $\delta^{13}C_{org}$ shows fluctuations but still points to rather low lake levels, whereas TIC points to an elevated lake level between SHC AD 980 and SHC AD 1010 (P-6). This is supported by the postulated moist conditions beginning around SHC AD 1000 (Favier Dubois, 2003; Mancini, 2002).

Nevertheless, the moist conditions of P-5 recorded in almost all proxies of Laguna Potrok Aike were also found by Stine (1998). In P-4 of Laguna Potrok Aike conditions begin to get drier and presumably warmer again to almost the same or even a higher extent as before the moist period. According to Stine (1998) this phase lasted until NHC AD 1350 (SHC AD 1370). In this context another important consideration is that temporary regional shifts between wet and dry conditions may occur on decadal, but not on multidecadal timescales during the MCA. Thus the term MCA should indicate persistent but not necessarily constant conditions. Trusting the presented proxies from Laguna Potrok Aike SHC AD 1370 is just a short discontinuity which is followed by even more pronounced drought conditions in southeastern Patagonia interrupted by at least one further short moist interval. Therefore, referring to the presented data, the MCA ends during the 15th century followed by the so called “Little Ice Age”. Summing up, the traditional MCA in southeastern Patagonia should not be regarded as one period of drought or warm conditions because at least two distinct moist interruption were determined with high resolution data from Laguna Potrok Aike during the Middle Ages (P-6,P-5 and perhaps in P-4).

9. Conclusions

The sediment record of Laguna Potrok Aike reveals an unprecedented sensitive continuous high resolution lake level, vegetation and climate record for southern Patagonia since SHC AD 400. Total inorganic carbon (TIC) turned out to be a sensitive proxy for lake level changes. From the 5th to the mid 13th century highly variable sedimentation parameters point to unstable climatic conditions and lake level fluctuations. Afterwards a generally drier period, coincident with the so-called “Medieval Climate Anomaly” of Stine (1994) lasted until the 15th century.

As far as the most sensitive hydrological proxy (TIC) is concerned, the climate in southeastern Patagonia was rapidly fluctuating at the start of the MCA interval proposed by Stine (SHC AD 870). Longer lasting periods of constant lake level (high or low stands) started first in P-5 (early 12th century) but more obviously in P-4, P-3 and P-2. This implies that Medieval drought conditions in southeastern Patagonia commenced much later, i.e., from the mid 13th to the 15th century (P-4). At the same time the MWP in Europe (sensu Lamb 1965) had already ended.

Regarding the question of whether it was warmer during P-4 than during the 20th century, there is evidence for lower lake levels during the MCA than today in every proxy. The existence of lower lake levels in former times was demonstrated by seismic studies which revealed hitherto undated fossil lake level terraces ca. 30 m below the present lake level (Zolitschka et al., 2004).

TOC and TN as proxies reflecting productivity also show higher values during the MCA than today, though present TOC and TN values are elevated due to anthropogenic eutrophication. This altogether implies that it might have been warmer during P-4.

In the course of the 15th and 16th century moisture increased, culminating in the so called “Little Ice Age” conditions. During the 18th century a rise in lacustrine productivity points to eutrophication possibly due to human impact of European explorers. In the course of the 20th century Laguna Potrok Aike reacted like many other Patagonian lakes with a lake level lowering after 1940, culminating in 1990, and followed by a subsequent rise and recession, as seen in the uppermost part of the record.

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Chapter 3:

Environmental change and fire history of southern Patagonia (Argentina) during the last five centuries

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Abstract

Geochemical, geophysical, charcoal and pollen analyses from the very poorly investigated south Patagonian steppe area show that in the vicinity of Laguna Potrok Aike (Santa Cruz Province, Argentina) and north of the Strait of Magellan the detectable impact of Europeans as explorers, settlers and farmers on fire intensity, vegetation and lake ecosystems started with first regional signs during the 1840s. A massive anthropogenic impact on a supra-regional scale followed as the result of the introduction of sheep farming at the end of the 19^{th} century. Furthermore, since the first European explorations, fires in the steppe areas of southernmost Patagonia as recorded at Laguna Potrok Aike occurred contemporaneously in the steppe-forest ecotone further west and probably also in the Andean forest itself. Environmental changes which are not caused by anthropogenic influence are also revealed and were most likely the result of temperature variations and enhanced and reduced wind speeds, respectively. A fire event around AD 1600, before the arrival of European settlers, occurred during a dry period in the forest and steppe-forest ecotone and followed a wet phase in the steppe that caused favorable ignition conditions in all environments.

Keywords: Paleoenvironmental change, European impact, charcoal, Santa Cruz, lake sediments

1. Introduction

For various reasons fire is an important ecological factor in the southern Patagonian steppe environment, as e.g., burned areas are more prone to deflation processes. It has clearly been a highly influential factor in the development of past vegetation by changing plant successions and altering the composition of plant communities (Innes et al., 2004). The importance of the two principal factors controlling fire frequency in Patagonia, human impact and climate has already been discussed vividly (Heusser, 1987; Markgraf et al., 2003). Analyses of fire periodicities from records between 36°S and 55°S in Patagonia show that fire frequency is driven by climate, primarily caused by recurrence of droughts (Markgraf and Anderson, 1994) resulting in at least favorable ignition conditions in the woodlands and steppe forest ecotone. On the other hand fire in the steppe is not dependent on dry fuel but on fuel in general which is produced during moister conditions (Brown et al., 2005; Clark et al., 2002; Huber and Markgraf, 2003). Nevertheless, reasons for historical fire events, i.e., after the arrival of Ferdinand Magellan in Patagonia in AD 1520 (Mainwaring, 1983; Martinic, 1997), still remain vague and need to be investigated further. A sediment record from Río Rubens peat bog (52°08`15``S, 71°52`53``W) situated at the steppe-forest ecotone (Fig. 3.1), shows a major charcoal peak around AD 1600. However, the level of decomposition of peat does not definitely yield evidence for drier conditions (Huber

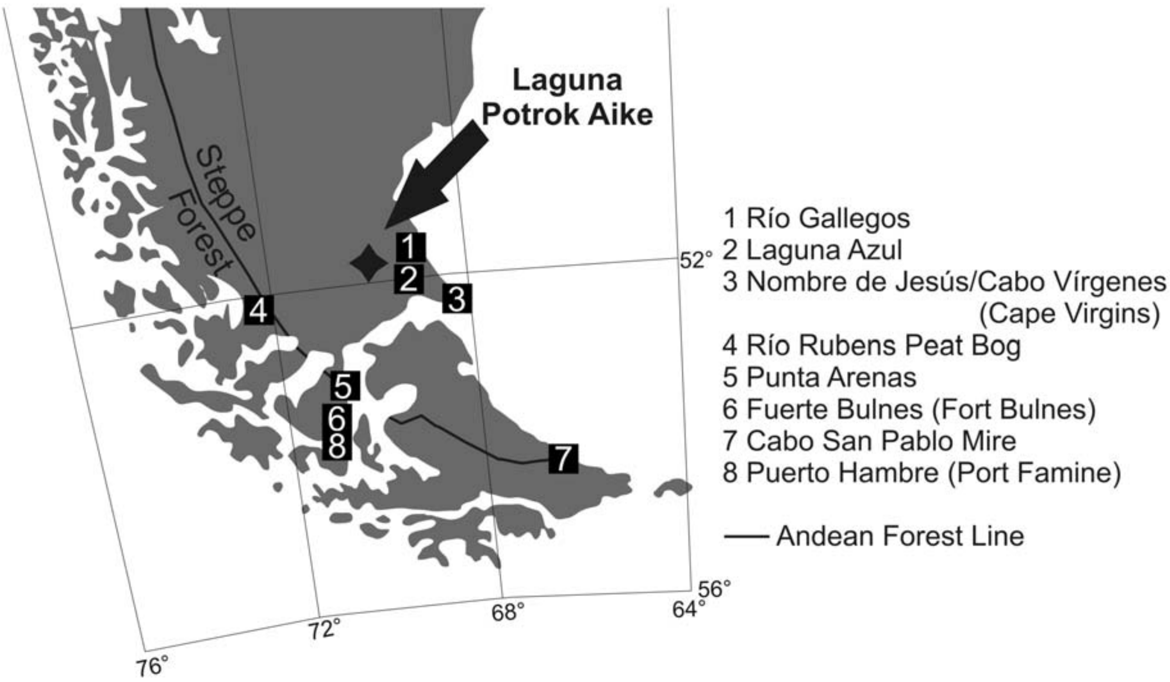

Fig. 3.1: Research area with Andean Forest Line and other locations discussed in the text.

and Markgraf, 2003), which would allow to conclude that climate might have also been the cause for fire during this time.

Another topic of discussion is the environmental impact of Europeans as explorers, settlers and farmers in Patagonia. For a long time, the first appearance of pollen from the European weed *Rumex acetosella* was used as an indicator for disturbance of the natural vegetation and therefore as time marker for late 19th century permanent European settlement (Huber and Markgraf, 2003; Mancini, 1998; Mancini, 2002). However, in the Río Rubens peat bog record *Rumex* already appeared in the early 17th century (Huber and Markgraf, 2003).

This paper aims to reconstruct the European impact and also natural environmental changes that influenced southeastern Patagonia. The reconstruction is based on geochemical, geophysical and pollen data as well as on a new charcoal record from Laguna Potrok Aike, Santa Cruz (51°58`S, 70°23`W, Fig. 3.1). This maar lake is situated in the steppe region of Patagonia, an area with hitherto no charcoal record at all (Huber et al., 2004). Furthermore, the focus will be directed to the identification of the sources and effects of fire as this is an essential part of any fire regime reconstruction (Whitlock and Anderson, 2003). Results from Laguna Potrok Aike will be compared to the record from Río Rubens peat bog in order to obtain information about synchronous fire events in the steppe and steppe-forest environments and to identify fire causes in historical time. Both archives are located at the same latitude at a distance of 100 km from each other in representative locations for steppe and steppe-forest environments. The dominating climatic element of Patagonia is the westerly wind constituting more than 50% of the wind directions and reaching mean monthly wind speeds of 9 m s^{-1} during early summer (Endlicher, 1993). This element is also responsible for the present day permanent mixing of the water column of Laguna Potrok Aike. The rain shadow effect east of the Andes results in a precipitation decrease from west to east with less than 200 mm of annual precipitation at Laguna Potrok Aike during dry years which is one of the causes for the steppe environment. However, Laguna Potrok Aike belongs to the few permanent lakes in the dry-lands of southern Patagonia which assures a continuous sediment record even during dry periods (Haberzettl et al., 2005). More detailed information about Laguna Potrok Aike (Haberzettl et al., 2005; Schäbitz et al., 2003; Zolitschka et al., 2004) and Río Rubens peat bog (Huber and Markgraf, 2003; Huber et al., 2004) is provided elsewhere.

2. Methods

Five gravity cores (PTA02/1 to 5) with lengths of up to 113.5 cm were recovered from Laguna Potrok Aike during the first SALSA (South Argentinean Lake Sediment Archives and Modeling) field campaign in 2002 using a modified ETH-gravity corer (Kelts et al., 1986) equipped with a messenger system. In the laboratory sediment cores were stored dark and cool at +4°C. Cores were split, photographed, described lithologically and sampled continuously and volumetrically in one centimeter intervals. Detailed multiproxy investigations were carried out on core PTA02/4 with a length of one meter from the center of the lake (Haberzettl et al., 2005).

Samples for pollen analyses were treated following standard procedures (Faegri and Iversen, 1989) with a subsequent heavy liquid separation by $ZnCl_2$. Pollen concentrations were calculated with the help of Lycopodium spore tablets (Stockmarr, 1971). The detailed pollen percentage diagram is shown elsewhere (Haberzettl et al., 2005). Charred particles >20 µm were quantified on pollen slides. A second set of sediment samples, each consisting of about 2 cm^3 of sediment, was sieved through a 100 µm mesh after KOH treatment and macroscopic charcoal fragments were counted under a binocular microscope. Sample position of this second set in most cases was one centimeter above or below the pollen samples. This method should extend the information about local fires as in contrast to that pollen slide charcoal typically is exported preferentially from the burn area (Clark et al., 2002) and hence local fires normally are not recorded. In order to enhance comparability to the Río Rubens record accumulation rates were calculated for sieved macroscopic charcoal.

All volumetric sediment samples for geochemical analyses were freeze-dried. Prior to measuring total nitrogen (TN) and total carbon (TC) using a CNS elemental analyzer (EuroEA, Eurovector), dried samples were ground in a mortar and homogenized. For determination of total organic carbon (TOC) subsamples were treated with 3% and 20% HCl at 80°C to remove carbonates and then measured with the same device. Total inorganic carbon (TIC) was calculated as the difference between TC and TOC. Biogenic silica was determined using a continuous flow system with UV-VIS spectroscopy (Müller and Schneider, 1993). From the element distribution data (Ti, Fe, Mn) obtained with a CORTEX XRF-scanner

(Zolitschka et al., 2001) Fe/Mn-ratios were calculated. Frequency-dependent magnetic susceptibility was determined using a Bartington sensor (type MS2B).

The chronology of the 100 cm long and 1,600 year old record of Laguna Potrok Aike is based on a second-order polynomial function derived from four radiocarbon dates (Haberzettl et al., 2005) calibrated with the southern hemisphere calibration curve (McCormac et al., 2002). The Río Rubens time scale of the uppermost 43 cm of the record representing the last 1,300 years is based on a third-order polynomial regression derived from nine ^{210}Pb- and three ^{14}C-datings (Huber and Markgraf, 2003). As the time of European impact is the main object of this paper only the last 500 years are plotted. However, both records go much further back in time.

3. Results

Except for charcoal, data in general shows low variations in the older part of the record. First trends to more positive values in many parameters can be observed from the early 18th century onward, further in- or decreasing in the early 19th century.

Rumex and *Pediastrum* are not present in the oldest part of the Laguna Potrok Aike record (Fig. 3.2). Only charcoal and TIC show a distinct peak shortly before AD 1600. Until the early 19th century most proxies do not show marked variations except for TN, TOC, biogenic silica and Fe/Mn-ratios which increase during the late 18th century (Fig. 3.2).

During the first half of the 19th century *Rumex* and *Pediastrum* appear for the first time with increasing values to the top. Values for TN, TOC and biogenic silica still rise and stay on a high level showing decreases in the mid 20th century. Fe/Mn-ratios show a continuous decrease from the early 19th century to present day with a minima in the 1880s.

TIC values are below detection limit before they increase during the mid 20th century. Poaceae show low values in the early 20th century followed by a continuous increase. Charcoal values decrease after a peak in the 1840s with a slight increase in recent times (Fig. 3.2).

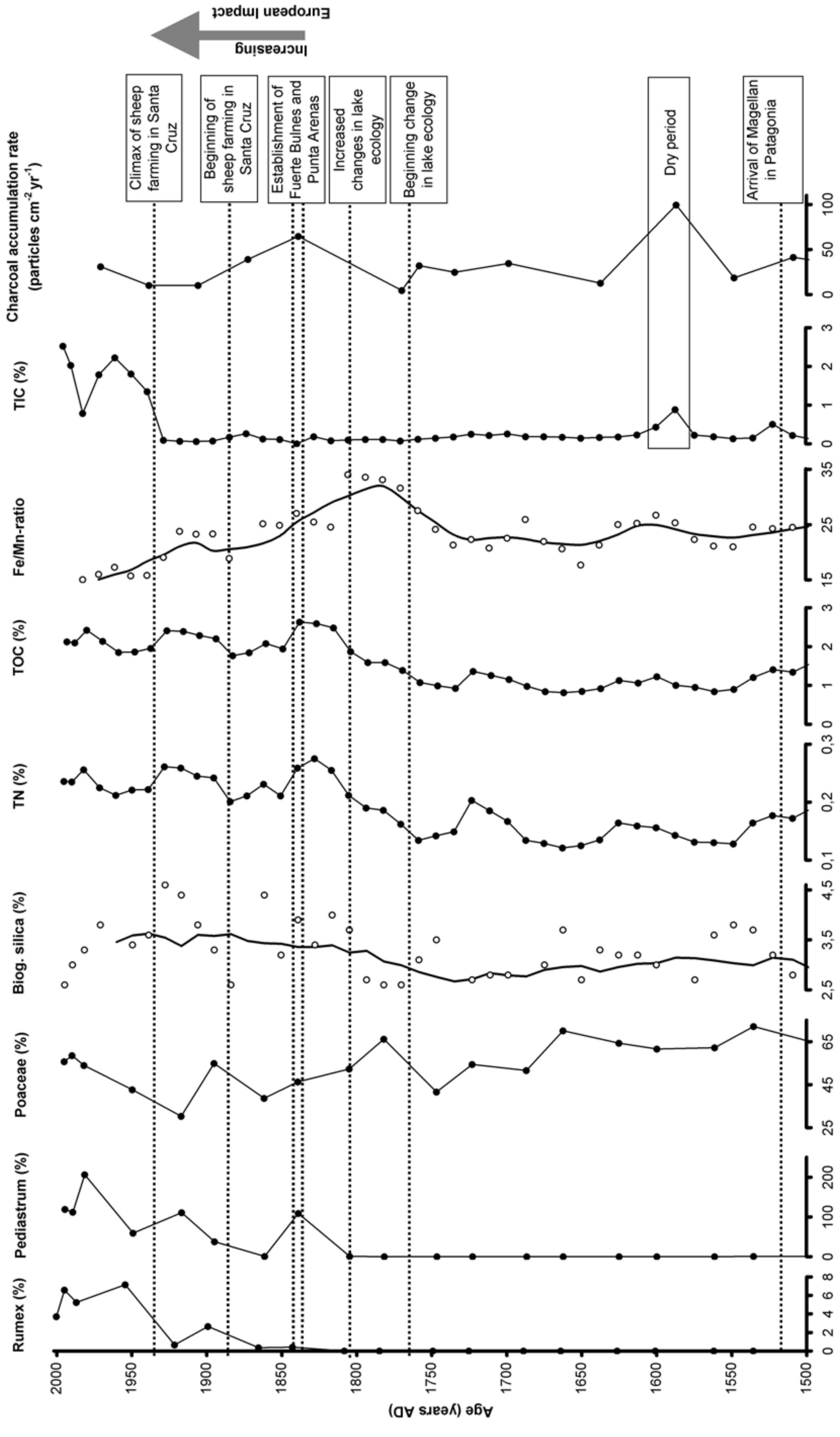

Fig. 3.2: Profiles of selected pollen, charcoal and geochemical data.

Altogether, two prominent peaks around AD 1600 and in the 1840s are visible in the sieved charcoal record from Laguna Potrok Aike (Fig. 3.3). Another period with increased charcoal values is between ca. AD 1650 and ca. AD 1770 with a slight peak in the 1760s.

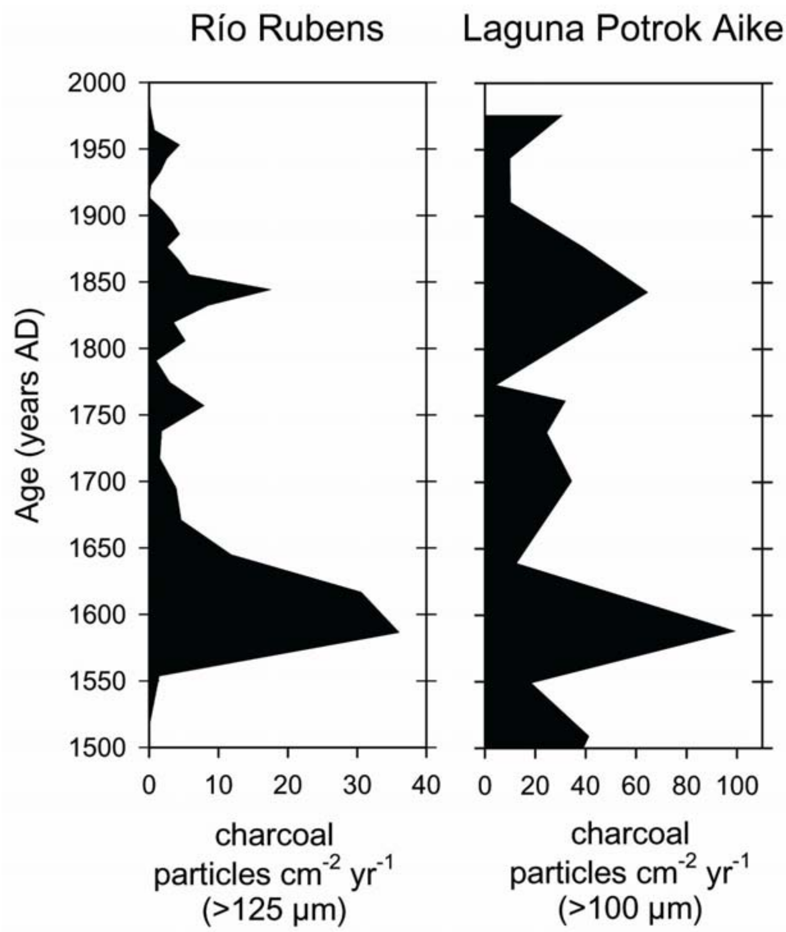

Fig. 3.3: Charcoal accumulation rates for Laguna Potrok Aike and Río Rubens peat bog with similar patterns.

For better comparison Pollen slide charcoal concentrations are plotted on a depth scale. The profile shows slightly more peaks (Fig. 3.4-3.6) at 1 cm (mid 1990s), 15 cm (1840s), 20 cm (1780s) and 35 cm (around 1600) sediment depth (Fig. 3.4-3.6). A less prominent peak is at 8 cm (1920s). Extended minima are visible between 2 (late 1980s) and 13 cm (1860s) as well as between 23 (1740s) and 33 cm (1620s). Further minima are observed at 18 cm (around 1800) and 38 cm (1560s, Fig. 3.4-3.6).

Andean forest pollen, consisting of *Nothofagus dombeyi* (>15%), *Myzodendron* (<3%), *Podocarpus* (<2%), *Drimys*, *Gunera* and *Nothofagus obliqua* (all <1%), show an inverse pattern to pollen slide charcoal (Fig. 3.4). Peaks in pollen percentages are found at 0.5 cm (around 2000), 18 cm (around 1800), 33 cm (1620s), 38 cm (1560s) and 45 cm (around 1500) and broad maxima are between 2 (late 1980s) and 13 cm (1860s) as well as between 23 (1740s) and 28 cm (1680s). According to that distinct minima are at 15 cm (1840s), 20 cm (1780s), 30 cm (1660s) and lower values can be observed at 1 cm (mid 1990s), 35 cm (around 1600) and 40 cm (1530s, Fig. 3.4).

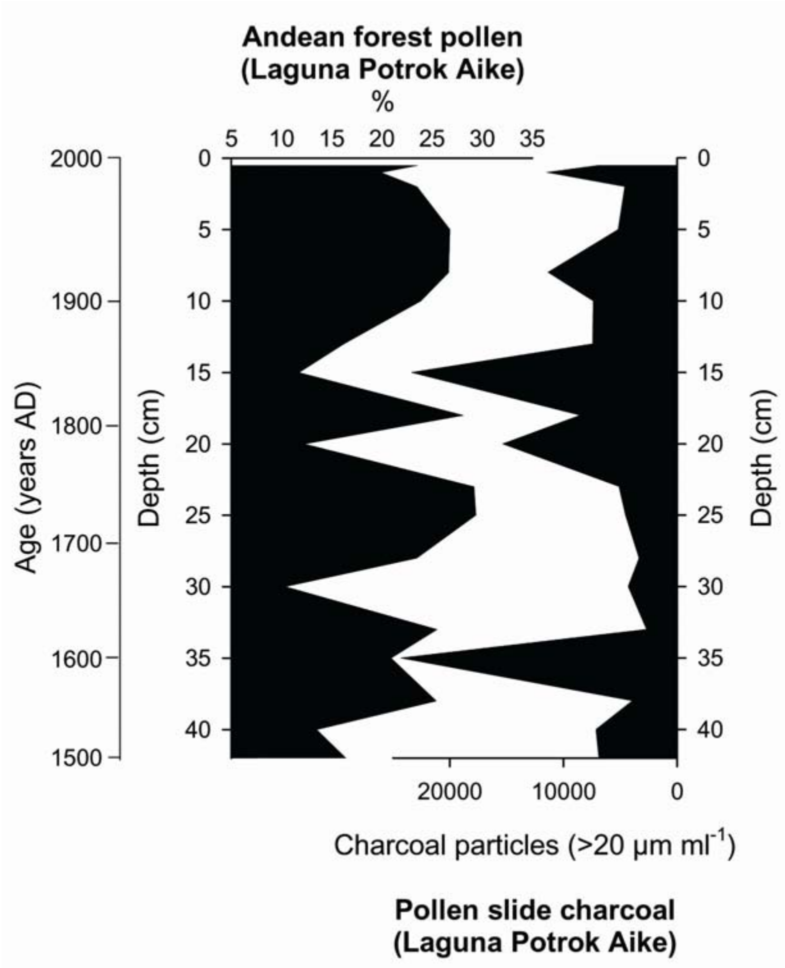

Fig. 3.4: Comparison of pollen slide charcoal with the amount of Andean forest pollen (95% Nothofagus) showing an inverse correlation pattern in the Laguna Potrok Aike record.

Frequency dependent magnetic susceptibility given as percent (%) and Ti shown as counts per second (cps) show a rather variable pattern (Fig. 3.5). Maxima above 5 cm (1950s) in the record are followed by distinct minima around 5 cm (1950s). Both records increase in value to a depth of 16 cm (1830s) with various smaller peaks and minima in between. Below a minima between 17 (1850s) to 19 cm (1790s) both records increase again and Ti shows highest values of the record. Further down the record values are lower except for 2 peaks in frequency dependent magnetic susceptibility at 26 (1710s) and 35 cm (around 1600). The latter is accompanied by a slight rise in Ti although there is an obvious minima in the counts of that element in that depth. Nevertheless, frequency dependent magnetic susceptibility and Ti show very similar peaks compared to sieved macroscopic charcoal accumulation rates (Fig. 3.5).

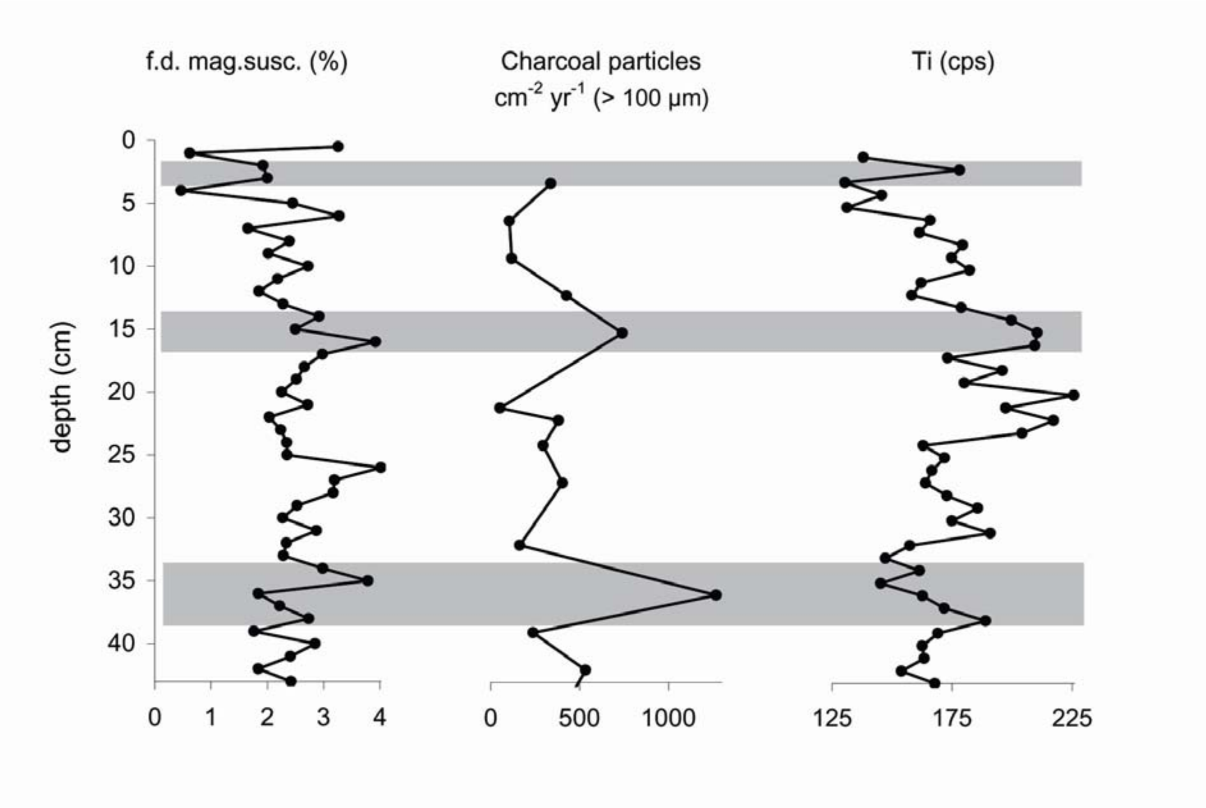

Fig. 3.5: Comparison of sieved macroscopic charcoal accumulation rates from Laguna Potrok Aike with respective frequency dependent magnetic susceptibility (F.d. MS) and titanium (Ti). Slightly different peak locations result from different measurements and sampling intervals.

Total pollen concentration shows a very similar pattern to pollen slide charcoal (Fig. 3.6). A peak at 1 cm (mid 1990s) depth is followed by a pronounced decreasing trend down to 13 cm (1860s). Further down 3 maxima are visible at 15 cm (1840s), 20 cm (1780s) and 25 cm (1720s). Lowest values of the record between 28 (1680s) and 33 cm (1620s) are followed by the highest at 35 cm (around 1600).

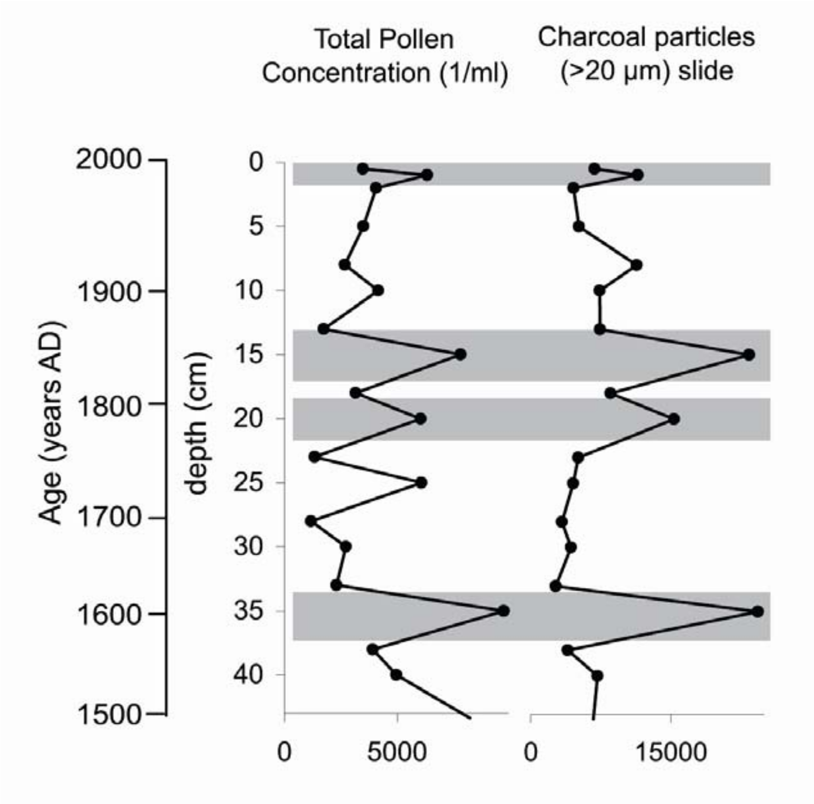

Fig. 3.6: Comparison of total pollen concentration and pollen slide charcoal of Laguna Potrok Aike.

4. Interpretation and discussion

4.1. European impact versus climate change

The beginning and continuation of European impact should be visible in almost all described parameters. For example eutrophication indicating TOC, TN and biogenic silica are expected to increase with an increased supply of nutrients, new European pollen like *Rumex acetosella* are supposed to invade southern Patagonia (Huber and Markgraf, 2003) or fire frequencies should rise due to the slash and burn activities Europeans were used to (Caldararo, 2002).

However, there might be a difference in the magnitude of a signal depending on the distance to the origin and the transport mode. Aeolian transport (e.g., pollen) for example, should reflect a more supra-regional signal, whereas episodic fluvial input (e.g., Ti, Haberzettl et al., 2005) is expected to mirror a more local signal.

4.2. Charcoal peaks in southern Patagonia around AD 1600

The arrival of Magellan in Patagonia in AD 1520 (Goodall, 1979; Mainwaring, 1983; Martinic, 1997) had no detectable impact on Laguna Potrok Aike (Fig. 3.2). Neither had the first two European settlements that were established along the northern shore of the Strait of Magellan in AD 1584, Nombre de Jesús near Cabo Vírgenes (Fig. 3.1) and Puerto Hambre (Fig. 3.1) farther to the west (Goodall, 1979; Huber and Markgraf, 2003; Mainwaring, 1983). The first hint of a European impact might be a charcoal peak around AD 1600 (Fig. 3.2), which could be caused by settlement activities, changed hunting- or cultivation strategies, etc. This peak distinctly exceeds the amount of charcoal found in older sections of Laguna Potrok Aike (Haberzettl et al., 2005). Within the dating uncertainties this peak matches with the establishment of the settlements but contemporaneous charcoal peaks were found in the record of Río Rubens peat bog (Fig. 3.1, 3.3). As Río Rubens is located northeast of the settlements this indicates that fire during this period seems to have been a widespread regional phenomenon.

In the Río Rubens profile the charcoal peak is interpreted as a possible result of a decrease in effective moisture (Huber and Markgraf, 2003). This assumption is based on strongly decomposed peat below the charcoal horizon related to a desiccation of the bog. However, increased humification below a charcoal layer can also be related to ´ash fertilization` with a substantial increase in nutrients and microbial activity and thus intensified decomposition (Huber and Markgraf, 2003; Markgraf, 1993). A hydrology reflecting pollen record from Cabo San Pablo Mire (Fig. 3.1) in Tierra del Fuego (Heusser and Rabassa, 1991; Huber and Markgraf, 2003) which shows similar paleoenvironmental conditions yielded no further evidence for a decrease in effective moisture due to the low temporal resolution of that record.

In the high resolution record of Laguna Potrok Aike, TIC was demonstrated to be a lake level indicator reflecting the hydrological regime (Haberzettl et al., 2005).

High values are caused by calcite precipitation during lake level low stands and therefore indicate dry conditions whereas low values due to dilution processes in the lake reflect lake level high stands and therefore moister conditions (Haberzettl et al., 2005). The TIC-record of Laguna Potrok Aike points to a drier period during the fire event around AD 1600 and a wet period preceding this period (Fig. 3.2). That implies if hydrological conditions at Laguna Potrok Aike could be transferred to the West during that time that several decades of wet and favorable conditions for plant growth, which also means an enhanced fuel production in the forest as well as in the steppe and steppe-forest ecotone, were followed by a short, dry phase. During this drought plants might have suffered from water stress causing favorable ignition and expansion conditions for fire in all environments (for modern fire-climate relations in Patagonia see e.g., Dentoni, 2001). However, recent findings in a longer record from Laguna Potrok Aike (unpublished data) indicate that hydrological conditions between Laguna Potrok Aike and the Andean region might have been inverse. This would imply drier conditions in the Andes before and after the TIC peak (dry conditions) at Laguna Potrok Aike at AD 1600 which would also explain why after AD 1600 a relationship between fires and droughts is not visible at Laguna Potrok Aike. The TIC record shows only wet conditions except for around AD 1600 and since AD 1940 (Fig. 3.2). Hence, conditions at Laguna Potrok Aike have been wet and if conditions were inverse near the Andes it was dry which causes favorable ignition conditions in both environments as in the steppe environment grasses desiccate quickly and are commonly dry enough to support fires even during non-drought years (Brown et al., 2005; Clark et al., 2002; Huber et al., 2004). This might also be an explanation why Laguna Potrok Aike and Río Rubens peat bog show a similar charcoal pattern (Fig. 3.3).

4.3. Limnological changes and European impact during the late 18th and early 19th century

The increase of Fe/Mn-ratio, TN and TOC during the late 18th and early 19th century as well as the increase of biogenic silica and the subsequent rapid decrease of the Fe/Mn-ratio during the early 19th century, indicate a change in lake ecology (Fig. 3.2). Though today Laguna Potrok Aike is a polymictic lake due to its exposure to the strong westerly winds, it is supposed that during the Little Ice Age wind speeds have been lower. This assumption is based on the fact that today during winter time wind speeds at the weather stations in Río Gallegos (Hoppe, 1997) and Punta Arenas (Endlicher, 1991) are significantly lower than during summer. Highest wind speeds are recorded during day time of the austral summer (Endlicher, 1991).

This results from less insolation during the austral winter and an intensified pressure gradient during the austral summer. This in turn is produced by a strong temperature gradient that develops during an extension of the subtropical high pressure field that meets the cold air masses of the polar region (Endlicher, 1991). In analogy to this present day phenomenon a prevalence of less windy conditions is assumed for the Little Ice Age. Furthermore, according to the TIC record in Laguna Potrok Aike and contemporaneous radiocarbon datings of bones incorporated in lake level terraces well above the present shoreline, the lake level was higher (Haberzettl et al., 2005). Thus, a permanent mixing of the water column by wind was harder to achieve. Under such conditions the establishment of thermal stratification of the water body of the lake might have occurred more often.

Under stratified conditions and due to the decomposition of increased amounts of organic matter the oxycline would have moved out of the sediment into the water column. The increased amounts of organic matter result from enhanced epilimnic primary production at the transition from cold conditions during the Little Ice Age to warmer conditions indicated by enhanced production (TN, TOC, Fig. 3.2). A stable anoxic zone might have developed at the sediment/water interface and possibly in hypolimnic waters. In this case the cycling of manganese would not have been restricted to the sediment itself anymore. Instead manganese would have remained in solution in the hypolimnion. As a result the Fe/Mn-ratio would have risen. A similar model was developed for Zugersee and Baldegersee in Switzerland (Schaller and Wehrli, 1997).

Immediately after AD 1800 wind strength increased leading to a mixing of the lake. Due to this process the manganese in the water column was oxidized and reprecipitated leading to the observed decrease in the Fe/Mn-ratio. After a stabilizing phase similar processes seem to have happened during the 1870s.

This climatic explanation (warming/increasing wind) for the changes in lake ecology is strengthened by a comparison with the behavior of the Patagonian glaciers. The most recent (Little Ice Age) glacial advances in Patagonia are dated between AD 1600 and AD 1850 (Luckman and Villalba, 2001; Wenzens, 1999), between AD 1600 and AD 1900 on the eastern side of the North Patagonian Icefield (Glasser et al., 2002) and AD 1750 and AD 1850 in the Southern Patagonian Icefield (Mercer, 1970). A scheme of Neoglacial advances developed from dendrochronological analyses identifies the Little Ice Age glaciation between AD 1600 and AD 1760 (Glasser et al., 2004). Considering the differences between the two archives (glaciers, sediments) and chronologies this supports the idea of rising temperatures after the advances (Little Ice Age), during the changes in lake ecology of Laguna Potrok Aike. As glaciers start to melt mixing due to increased wind speed starts at Laguna Potrok Aike. Therefore, changes in lake ecology during the late 18th and early 19th century might have been triggered by increasingly warmer conditions at the end of the Little Ice Age also leading to enhanced lacustrine production. This results in enhanced accumulation of organic matter in the sediment column, but also in an increase of the total amount of organic matter decomposition at the sediment water interface.

Since the foundation of the permanent settlements Fuerte Bulnes and Punta Arenas in the 1840s (Martinic, 1997), the changes in lake ecology of Laguna Potrok Aike might be enhanced by European impact. Though each settlement was about 180 km and 130 km away, an intensification of the lake internal changes at least to a smaller degree by e.g., aeolian transport might be conceivable. Moreover, maps reveal many expeditions passing the vicinity of Laguna Potrok Aike (Martinic, 1999). The name Potrok Aike is a composition of the Spanish word "potro" (foal) and the Tehuelche word "aike" (Baleta, 1999). As Laguna Potrok Aike is one of the few permanent water bodies in southern Patagonia and the native Tehuelche word "aike" implies a stopping place where meat, water and firewood were stored (Mainwaring, 1983) periodic/episodic camps (eventually with European participation) are very likely. However, there is no detailed information about that.

During the 1840s TN, TOC and biogenic silica show highest or at least elevated values (Fig. 3.2) indicating persistent changes in lake limnology. This is supported by the first peak in *Pediastrum*. Further evidence for human activity is given by the first appearance of *Rumex*, presumably *Rumex acetosella*, with very low values. This European weed is often used as evidence for European influence (Huber and Markgraf, 2003). *Rumex acetosella* in the pollen record commonly is interpreted as sign for disturbances (Mancini, 1998; Mancini, 2002), like fire and grazing as it is the case in northwestern Patagonia (Ghermandi et al., 2004).

However, *Rumex* should not be used as a time marker for permanent European settlement (Huber and Markgraf, 2003) in the direct vicinity of the respective climate archive. *Rumex* seeds are wind dispersed and pollen values in the Laguna Potrok Aike sediment record are very low until the end of the 19th century (Fig. 3.2). Considering the high wind speeds in southern Patagonia, *Rumex* pollen in the sediments of Laguna Potrok Aike can be considered as evidence for permanent European settlements at a large distance. Therefore, also if there is a human impact on Laguna Potrok Aike during the late 18th and early 19th century, it is assumed to originate from a distant source.

4.4. Impact of sheep farming

The most striking human impact on the southern Patagonian landscape, the beginning of sheep farming, is also recognizable in the Laguna Potrok Aike record. Sheep were introduced to southern Patagonia in 1877-78 (Martinic, 1997). By 1884 “all best `camps` along the Straits” (Mainwaring, 1983) and consequently in the surrounding of Laguna Potrok Aike had been leased or reserved. The massive introduction of sheep has altered the steppe ecosystem distinctly (Hoppe, 1997). Today there are no areas where sheep grazing has not taken place (Soriano, 1983).

Apparently, the ´abrir campos` practice, the clearing of forest for sheep or cattle grazing by burning and logging (Huber and Markgraf, 2003) as it is typical for human interaction with forests in the Americas after European contact (Caldararo, 2002), was not necessary in the steppe environment around Laguna Potrok Aike. This might be an explanation why only little charcoal, probably from distant sources, was found from that time (Fig. 3.2). The landscape was described as “pastures full of soft grasses” (Mainwaring, 1983); ideal conditions for sheep farming. A marked rise of biogenic silica (Fig. 3.2) as well as elevated TN and TOC values and a small re-increase of *Pediastrum* indicate further changes in lake ecology (eutrophication tendencies) during the late 19th century.

This is interpreted as a consequence of the presence of sheep. Eutrophication in the lake might be intensified due to excrements and enhanced soil erosion after the destruction of the protecting natural vegetation cover. *Rumex* reaches significantly higher values for the first time during the late 19th century indicating intensified disturbances supporting this hypothesis (Fig. 3.2).

Around 1900 and during the early 20th century biogenic silica and *Pediastrum* increase, TN and TOC constantly stay on a high level and Poaceae decrease indicating constant or even increasing eutrophication and hence enhanced impact of sheep farming until the 1940s. During this time stocks of sheep were highest and decreased since then (Hoppe, 1997). This decline might be expressed by a slight decrease of TN, TOC and *Pediastrum*, though these parameters still stay on a high level. Furthermore, this seems to be visible in the sharp decrease of biogenic silica. The persistent anthropogenic impact on Laguna Potrok Aike is indicated by values above the average in TN, TOC and *Pediastrum* as well as values below average for Poaceae, especially compared to the oldest part of the record (Fig. 3.2). High *Rumex* values indicate still intensive human impact within the vicinity of Laguna Potrok Aike. In general, an increasing European impact is recorded in the Laguna Potrok Aike sediment record possibly starting as early as the foundation of Fuerte Bulnes and Punta Arenas continuing until the climax of sheep farming persisting until present day (Fig. 3.2, indicated by arrow).

4.5. Effects of fires on the sediment record of Laguna Potrok Aike

Lithologic analyses have demonstrated to be a useful indicator of fire-related erosion in some regions (Whitlock and Anderson, 2003). Through the destruction of the vegetation cover fires enlarge areas of bare soil (Clark et al., 2002) and hence support erosion. This becomes evident by comparing the sieved charcoal accumulation rates to erosion indicating proxies like titanium (Ti) or frequency dependent magnetic susceptibility in the Laguna Potrok Aike sediment record (Fig. 3.5). Normally, peaks of those proxies are supposed to happen contemporaneously or Ti and frequency dependent magnetic susceptibility should follow the fire events immediately. If this is not exactly the case it can be ascribed to the different analytical methods used (e.g., Cortex scanner for XRF-data versus discrete samples) and the coarser resolution (average sampling distance 3.3 cm) of the charcoal record. Clastic input during the past five centuries is mainly controlled by erosion and transport by water during episodically surface runoff as shown by an inverse pattern of Ti compared to TIC (Haberzettl et al., 2005). TIC, the former mentioned lake level indicator of Laguna Potrok Aike, indicates wet conditions in most cases. Wildfires alter the infiltration response of burned watersheds by changing both the physical and chemical characteristics of the watersheds. Steady-state infiltration measurements in New Mexico and Colorado, USA revealed that infiltration rates were less at all burned sites (Martin and Moody, 2001). In steep-sided water sheds in Yellowstone National Park, USA peaks in magnetic susceptibility corresponded well with charcoal peaks suggesting a relationship to fire events (Millspaugh and Whitlock, 1995; Whitlock and Anderson, 2003).

4.6. Locations and regional extent of fires recorded in the sediment of Laguna Potrok Aike

A comparison of the steppe lake record of Laguna Potrok Aike with the record from Río Rubens peat bog situated at the steppe-forest ecotone (Fig. 3.3) reveals similarities in the distribution of charcoal peaks. This is particularly the case for the peaks shortly before AD 1600, in the 1760s and 1840s. Considering that at Río Rubens burned mosses were observed, it can be assumed that fires were locally present (Huber and Markgraf, 2003). This can be taken as evidence that fires recorded in the sediment record of Laguna Potrok Aike in many cases did not occur in the steppe exclusively.

It is likely that most pollen as well as most charcoal particles originate either from long-distance transport from the west or from the vicinity of the respective archive as prevailing winds affect charcoal transportation (Gardner and Whitlock, 2001). The validity of this assumption is also evident from large proportions of Andean forest pollen found in the pollen record of Laguna Potrok Aike (Fig. 3.4) though it is located approximately 80 km west of the present Andean forest line (Fig. 3.1). Due to the prevailing wind speeds in the “furious fifties” (Weischet, 1996) of southern Patagonia, where the southern westerlies reach their greatest strength (Heusser, 1995), a charcoal transport from the Andean forest might be conceivable.

Plume buoyancy is another factor influencing transport of particles and this is very much dependent on fire intensity (Clark and Patterson, 1997). As anemophilous *Nothofagus* pollen, which is the dominant representative of the Andean forest pollen taxa in the Laguna Potrok Aike record, is usually over-represented in pollen records (Markgraf et al., 1981), fires in dense *Nothofagus* forests have to be very large to be detected (Huber and Markgraf, 2003). An inverse correlation between charcoal and Andean forest pollen detected at Laguna Potrok Aike (Fig. 3.4) indicates, that fires in the Andean forest were massive and plumes were very high enabling transport of larger charcoal particles to Laguna Potrok Aike or fires in the surrounding of the lake happened at the same time as in the forest.

The mentioned fact that charcoal record and proportion of Andean forest pollen are inversely correlated in the Laguna Potrok Aike record is particularly visible in the charcoal fraction counted on pollen slides (Fig. 3.4). Due to the smaller size fraction on pollen-slides, in contrast to the sieving method, the recorded charcoal is more likely to encompass large source areas and therefore allows the detection of regional trends more clearly (Carcaillet et al., 2001).

All this implies that locations of fires recorded in the Laguna Potrok Aike sediments were contemporaneously located in the Andean forest and thus Andean forest pollen decreased, as a grass-dominated assemblage in a period characterized by forest taxa might indicate a fire event. Nevertheless, the inverse correlation of pollen slide charcoal and Andean forest pollen could also be triggered exclusively by fires occurring in the steppe nearby. Those could trigger an enhanced steppe pollen production following the fire event which led to a dilution of Andean pollen. One hint for that assumption maybe an enhanced total pollen concentration coinciding with most charcoal peaks (Fig. 3.6). Hence, Andean forest pollen might show lower pollen values while actually contributing a constant absolute influx.

The most probable scenario seems to be a mixture of both processes, with different fire locations in the Andes as well as in the steppe, both recorded simultaneously in the sediments of Laguna Potrok Aike. A large number of separate fires in all different environments might have occurred simultaneously or within short time spans. In the 1995-96 wildfire season for example, Patagonia was affected by approximately 500 fires (Cwielong, 1996). 82% of the affected surface area corresponded to grassland (steppe). Second position was taken by fires in native forests, where also the most extensive wildfires happened (Cwielong, 1996). Only a few areas with shrubs and reforested areas were affected by fires (Cwielong, 1996). This recent pattern supports the assumption of a reduction of Andean forest pollen production by fires in the woodlands coinciding with an increased production and dispersal of steppe pollen after steppe fires.

4.7. Implications of the methods and interpretation for different charcoal accumulation rates in Laguna Potrok Aike and Río Rubens peat bog

The different charcoal accumulation rates in the records of Laguna Potrok Aike and Río Rubens (Fig. 3.3) are based on various reasons. First of all, samples were sieved with different mesh sizes (100 µm in Laguna Potrok Aike, 125 µm in Río Rubens peat bog). Due to the narrower mesh size used for Laguna Potrok Aike sample preparation, particles between 100 µm and 125 µm are supplementary in this record. Furthermore, there might be an accumulation effect in lakes by surface inflows or secondary deposition (Clark et al., 1998) which does not occur on peat bogs (Clark and Patterson, 1997) but episodically at Laguna Potrok Aike. Thus, the absence of this process at the Río Rubens peat bog could lead to a poor representation of local non-peat fires (Huber and Markgraf, 2003). Additionally, charcoal deposited on peat bog surfaces is not protected from redistribution by wind which seems to be likely in Patagonia. In contrast, charcoal deposited in a lake is trapped by the water cover. Taking those considerations into account, charcoal of one fire event could have been accumulated in lakes during more than one year (Whitlock and Anderson, 2003).

It is suspected that sediments from centers of lakes (where the presented cores were obtained from) overestimate particle production (Clark and Patterson, 1997). Peat is therefore expected to yield lower charcoal accumulation rates than lake sediments (Clark and Patterson, 1997). This would be a further explanation for higher charcoal values in the steppe lake Laguna Potrok Aike in contrast to Río Rubens bog. Due to prevailing westerly winds the steppe lake received charcoal from fires in the Andes as well as from steppe fires, while the Río Rubens site (Fig. 3.1) only recorded fires located in the woodlands or the steppe-forest ecotone. Hence, charcoal peaks present in Laguna Potrok Aike but not in Río Rubens peat bog probably represent fire events exclusively occurring in the steppe, but absent in the Andes.

5. Conclusions

Laguna Potrok Aike was influenced by European activities much earlier than the arrival of the first sheep farmers in southern Patagonia in the late 19th century. Though the charcoal peaks recorded from ca. AD 1840 onwards are possibly human induced, the presented data point to European impact at larger distances from the lake. In this context the first appearance of *Rumex* is not believed to represent a local signal. At the beginning of the sheep farming in the late 19th century, disturbance gets obvious also in the vicinity of Laguna Potrok Aike lasting until today.

Limnological changes during the late 18th and early 19th century are believed to be the result of rising temperatures and accompanying changes in wind strength, probably marking the end of the Little Ice Age. Nevertheless European impact might have supported the changes.

The charcoal record of Laguna Potrok Aike seems to reflect fires in the steppe that coincided with fires in the Andean forest. As values for charcoal from the steppe lake Laguna Potrok Aike are generally higher and show more fire events than the Río Rubens peat bog record, it is assumed that steppe fires were more frequent and enlarged the contribution of charcoal to the lake. In general, fire events recorded in Laguna Potrok Aike are accompanied by fluvial erosion. The fire event around AD 1600 seems to be triggered by dry conditions in the Andes causing favorable fire conditions in the forest and the steppe-forest ecotone and after a wet period in the steppe.

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Chapter 4:

Wet-dry cycles in southern Patagonia - Chronology, sedimentology and geochemistry of a lacustrine sediment record from Laguna Potrok Aike (Argentina)

submitted to: The Holocene

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Abstract

With a high-resolution multi-proxy approach applied to the sediments of Laguna Potrok Aike an attempt was made to reconstruct moist and dry periods during the past 16,000 years in southeastern Patagonia. The age-depth model is inferred from AMS ^{14}C dates and tephrochronology and suggests moist conditions during the Late Glacial and early Holocene (16,000-8,700 cal. BP) interrupted by drier conditions before the beginning of the Holocene (13,200-11,400 cal. BP). Data also imply that this period was a major warm phase in southeastern Patagonia approximately contemporaneously to the Younger Dryas chronozone in the northern hemisphere (12,700-11,500 cal. BP). After 8,650 cal. BP a major drought might be related to the lowest lake level of the record. Since 7,300 cal. BP the lake level rose and was variable until the Little Ice Age which was the dominant humid period after 8,650 cal. BP.

Keywords: Holocene, Younger Dryas, Little Ice Age, lacustrine sediments, geochemistry, tephrochronology

1. Introduction

High-resolution paleoenvironmental information from southern South America, the only continental landmass between 38°S and the Antarctic Circle, is urgently needed in order to compare the southern hemisphere climate history with better known tropical and northern hemisphere paleoclimate reconstructions. These data allow to check for a possible synchrony of global climate events in the past, and to validate global climate models. However, until today most terrestrial climate records from southern South America are restricted to pollen and charcoal studies of peat bogs and mires from the Andes and the forest-steppe ecotone with a rather low time resolution (Heusser, 1998; Markgraf, 1993a; McCulloch and Davies, 2001; Schäbitz, 1991). In the extremely windy and semiarid region of southeastern Patagonia lake sediments provide an opportunity to reconstruct continuous records of Late Quaternary environmental changes (Zolitschka et al., in press). Despite their potential, so far such a record has only been reported from Lago Cardiel (Fig. 4.1). However, at 13,120 cal. BP there is a gap of information as this lake desiccated (Gilli et al., 2001). Other studies either are based on events like dating of glacier fluctuations in the Northern and Southern Patagonian Ice Field (Glasser et al., 2004; Wenzens, 1999) or dating of lake (Stine and Stine, 1990) and marine (Aguirre, 2003) terraces. Due to this restricted

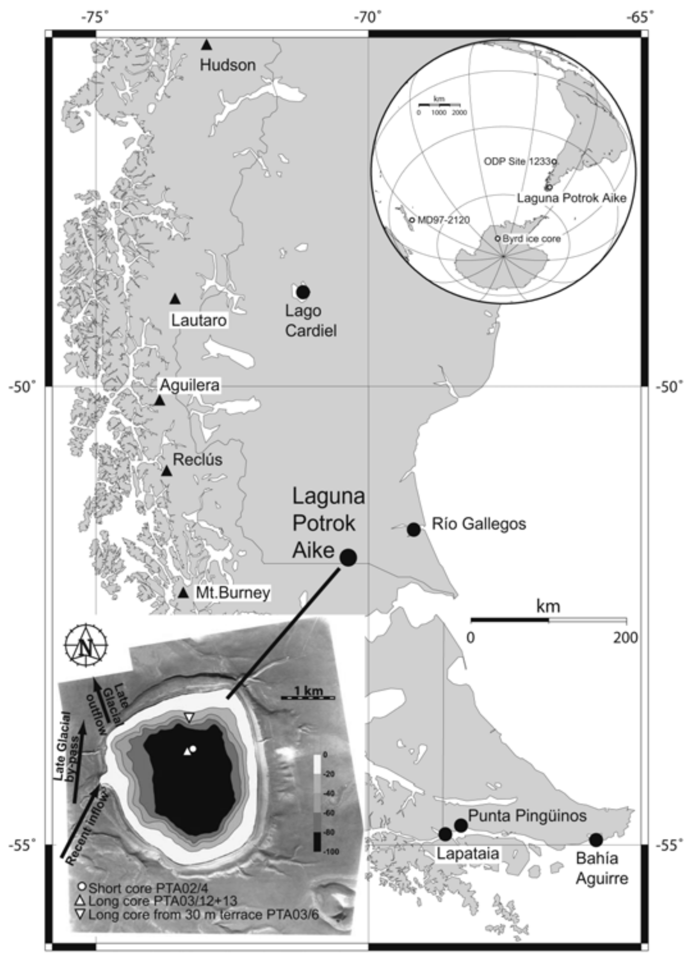

Fig. 4.1: Research area and locations discussed in the text. Maps were created with OMC (Weinelt, 1996-2004). Bathymetry of Laguna Potrok Aike and locations of analyzed cores are shown on the inset map.

data coverage many questions about regional climate evolution are still a matter of debate. For example, the existence of a Younger Dryas cold phase (12,700-11,500 cal. BP) has been discussed vividly particularly on the base of pollen records (Heusser, 1989, 1998; Heusser et al., 2000; Heusser and Rabassa, 1987; Markgraf, 1991, 1993b; Rabassa et al., 2000), chironomids (Massaferro et al., 2005), moraines (Glasser et al., 2004; Wenzens, 1999, 2003) and marine sediments (Andres et al., 2003; Kim et al., 2002).

Here a continuous high-resolution terrestrial record from Laguna Potrok Aike (51°58`S, 70°23`W, Fig. 4.1, 4.2) which was recovered within the project SALSA (South Argentinean Lake Sediment Archives and modeling) and spans the last

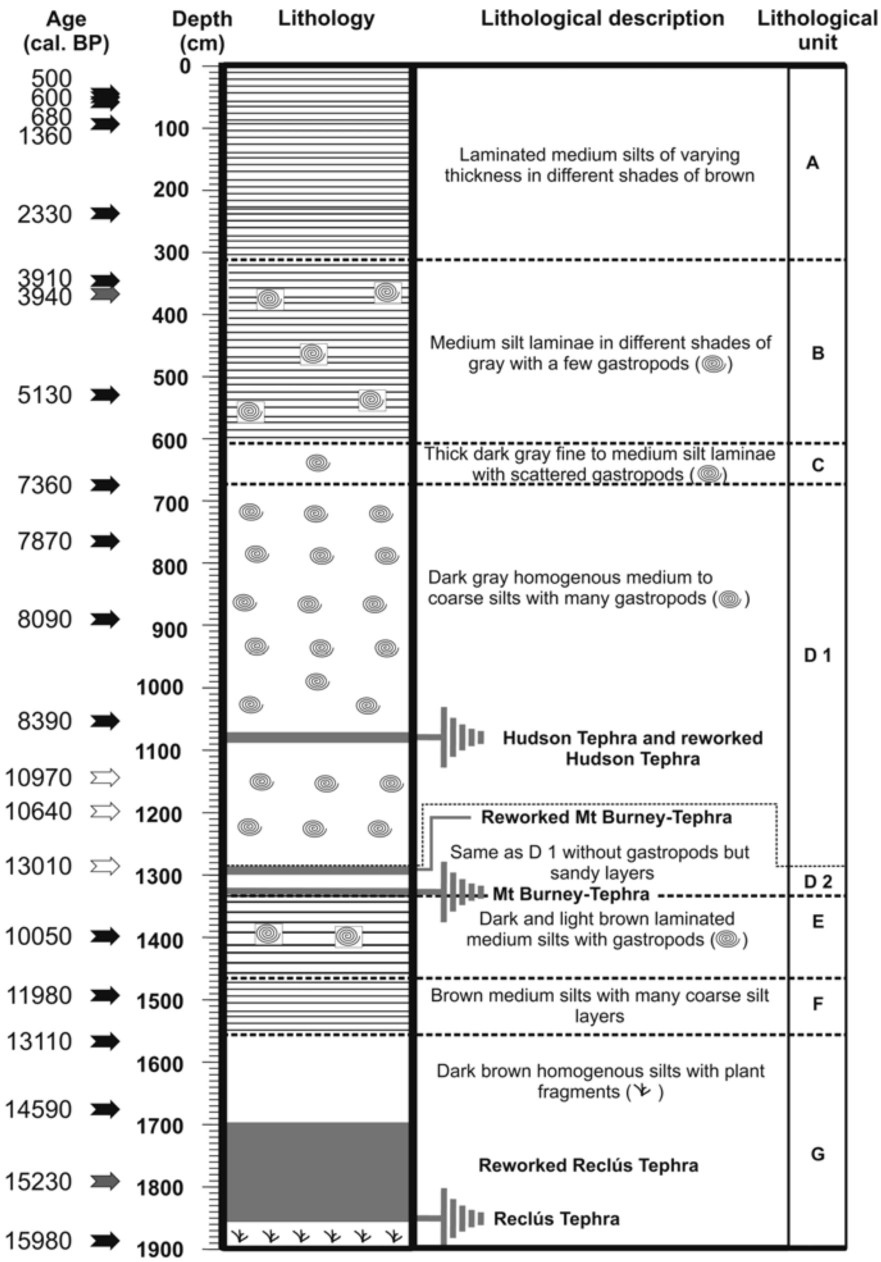

Fig. 4.2: Lithology of composite core PTA02/4, PTA03/12 and PTA03/13 from Laguna Potrok Aike including medians of calibrated radiocarbon dates (dates used for age model: black arrows; rejected dates: white arrows; validation dates: gray arrows).

16,000 cal. BP is presented. Further details about Laguna Potrok Aike, the catchment area and climatic conditions have been published elsewhere (Haberzettl et al., 2005; Zolitschka et al., in press).

Aim of this study is to present the lithology, the chronology and the sedimentology together with geochemical data obtained from two overlapping sediment cores from the deepest part of Laguna Potrok Aike. Based on these data the paleoenvironmental conditions and the hydrological history will be reconstructed.

2. Field and Laboratory Methods

Two overlapping sediment cores (PTA03/12+13) were recovered with an UWITEC piston coring system from the 100 m deep central basin of Laguna Potrok Aike (Fig. 4.1) during 2003. In the laboratory sediment cores were stored dark and cool at +4°C. One meter long core sections were split, photographed and described lithologically. Magnetic susceptibility (κ) measurements were performed on split cores with a Bartington MS2F point sensor in 1 cm resolution. An XRF-scanner, provided analyses of K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Sr and Pb (Jansen et al., 1998) in 1 cm steps. The Ca data and photographs were used to establish a composite profile. The top of the record was already studied in short core PTA02/4 (95 cm, Haberzettl et al., 2005). After correlation the total length of the composite record was 1892 cm.

Smear slides were prepared from pooled subsamples of consecutive 5 cm intervals. SEM pictures were taken with a LEO 1530 electron microscope. Bulk mineralogy was determined for selected samples using X-ray diffraction (XRD) techniques (Philips X´Pert Pro MD equipped with an X´Celerator Detector-Array). Gastropods and plant macro-remains were picked out prior to analyses. Age determinations were carried out at the Poznań Radiocarbon Laboratory, Poland. Four radiocarbon dates were already included in the short core (Haberzettl et al., 2005). Additionally, remains of aquatic macrophytes located close to a calcite dating were measured in order to test the reliability of datings obtained from the carbonate fraction. All ^{14}C ages were calibrated with the northern hemisphere calibration curve (Reimer et al., 2004) using the software CALIB 5.0.2 (Stuiver and Reimer, 1993;

Stuiver et al., 2005). Uncalibrated dates from other studies used for comparison were calibrated in the same way.

All core sections were sampled continuously in 1 cm intervals. Altogether 1892 samples were freeze-dried for determination of water content (WC). The number of freshwater gastropods (Lymnaeidae) found in each volumetrically equal sample was used as gastropod-index (GI). Total nitrogen (TN), total carbon (TC), total sulfur (TS), total organic carbon (TOC) and total inorganic carbon (TIC) were determined with a CNS-analyzer (Euro EA). A depth constrained-cluster analysis of analyzed data was performed using MVSP (Kovach Computing Services, 2005).

Tephra layers have been characterized geochemically and microscopically in order to define their volcanic sources. For comparison, tephra samples from the volcanoes Hudson, Reclús and Aguilera/Lautaro (Gilli, 2003; Markgraf et al., 2003) obtained from the sediment record from Lago Cardiel (Fig. 4.1) were analyzed as well. Samples were cleaned with 30% H_2O_2 to remove organics and surface coatings, and dried with Ethanol. Major-element chemistry of single glass shards was determined on polished thin sections by electron probe micro analyses (EPMA) using a CAMECA SX100 (WDS) instrument at GFZ Potsdam. The operating conditions for measurements were 15 kV accelerating voltage, 20 nA beam current, a defocused beam of 15 µm diameter and peak counting times of 20 s except for Na (10 s). For instrumental calibration Lipari obsidian was used as reference material (Hunt and Hill, 1996). At least ten glass shards per tephra were measured according to the homogeneity of samples. Individual analyses of glass shards with total oxide sums <95 wt.% were excluded.

3. Results

3.1. Lithology and sediment analyses

The composite profile is divided into seven lithological units (A to G, Fig. 4.2) and unit D into two subunits (D1 and D2, Fig. 4.2). This classification is based on unambiguous lithological characteristics like color variations, the distinction between laminated and homogenous sections as well as the presence of organic macro remains and gastropods. Moreover, this classification was supported by a depth constrained cluster analysis including all analyzed data. In general, the major part of the record consists of clayey and sandy silts becoming coarser with depth (Fig. 4.2). Only tephra layers and reworked volcanic ashes comprise fine to medium sand. Reworked layers were identified by the combination of their lithological characteristics (color, coarser grain size), their high content of reworked tephra material, which was detected either macroscopically or on smearslides, and the characteristic incorporation of macrophyte layers. The elements V, K and Fe are significantly correlated with Ti (R^2=0.73, 0.67, 0.66) for the whole record. Hence, Ti was chosen as a representative for these elements in Fig. 4.3.

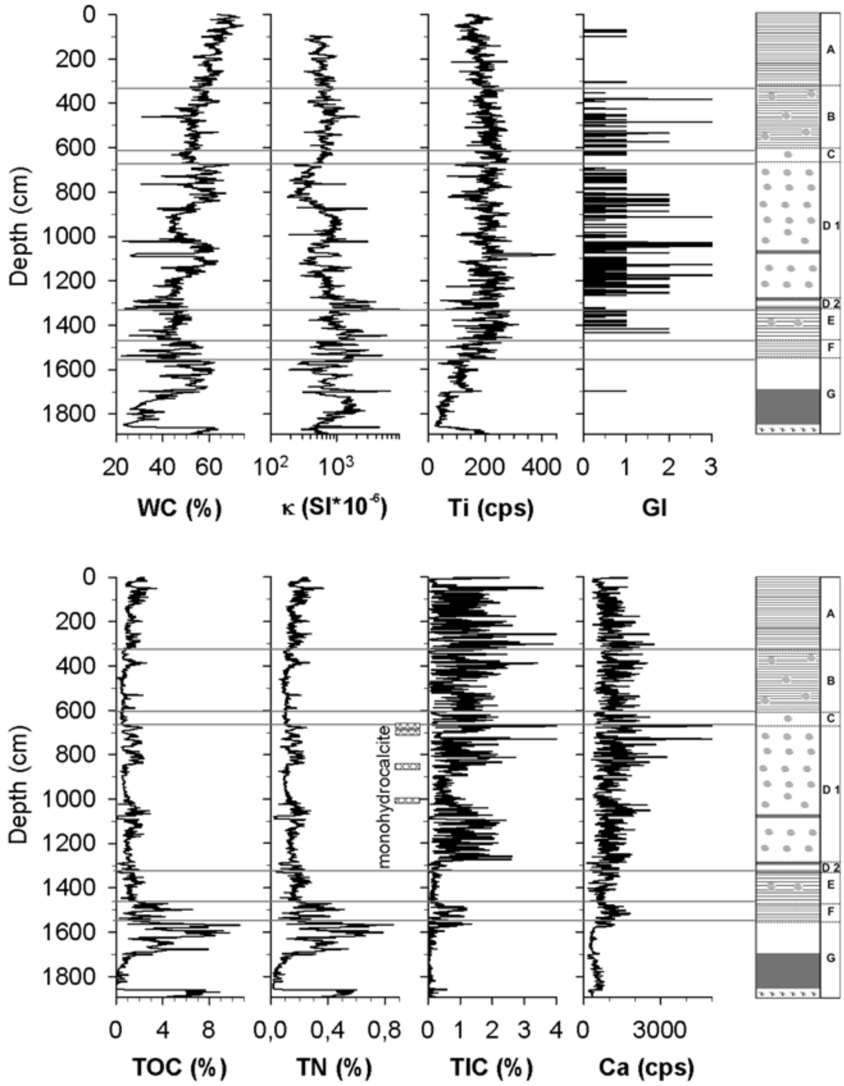

Fig. 4.3: Geochemical and geophysical data vs. depth (WC: water content, κ: magnetic susceptibility (logarithmic scale), GI: gastropod index). Elemental data are plotted as counts per second (cps).

Lithological unit G (1892-1557 cm): Ti, TN, TOC and WC show a distinct maximum in the lowermost part and high values at the top of unit G. In between, where a tephra and reworked ash was deposited, lowest values of the record, mostly below the detection limit, are observed. GI, Ca and TIC show minor variations also partly below detection limit. Only TIC and Ca peak at the uppermost part of unit G (Fig. 4.3).

Lithological unit F (1557-1465 cm): According to smearslides and SEM images this is the only unit where the green alga *Phacotus lenticularis* is present (Fig. 4.4). Unit F is characterized by peaks in TIC, Ca, TOC, TN, κ and WC (Fig. 4.3).

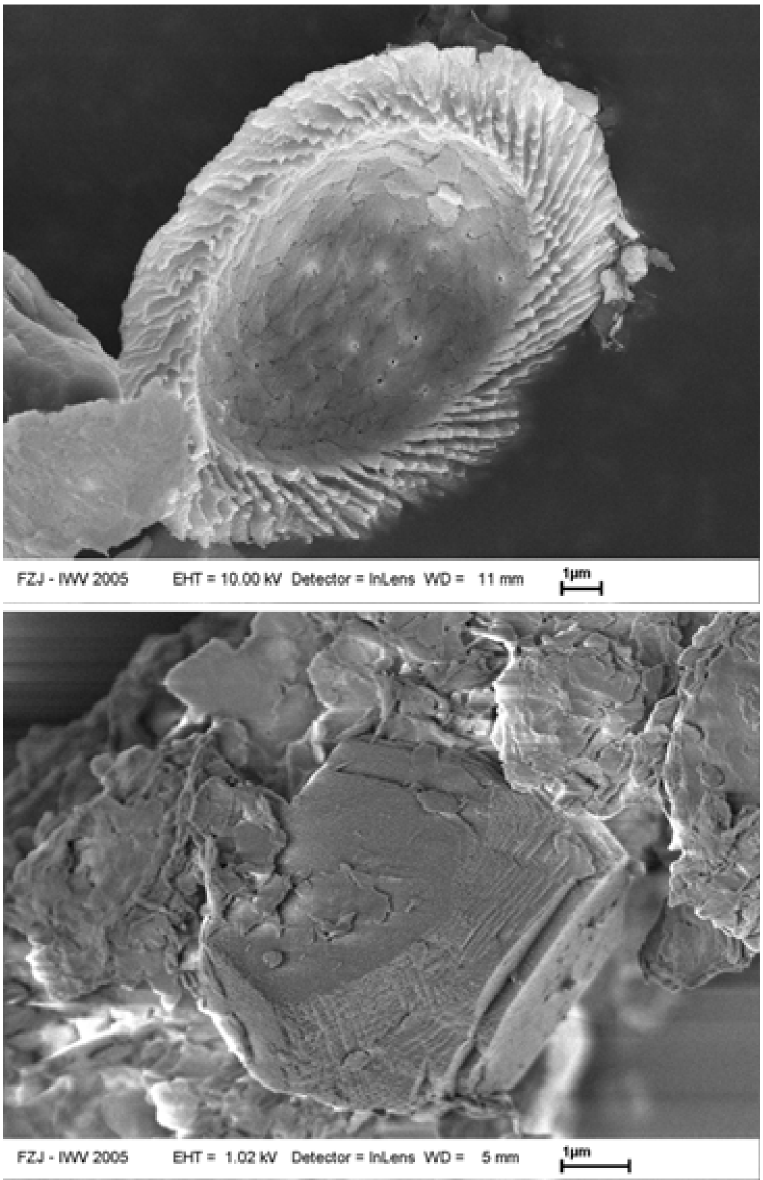

Fig. 4.4: SEM images of Phacotus lenticularis (top) and autochthonously precipitated calcite crystal (bottom).

Lithological unit E (1465-1320 cm): In unit E gastropods appear in greater numbers for the first time (Fig. 4.2, 4.3). Ti shows distinct high values for the whole unit E and κ at the base of this unit. TIC, Ca, TOC and TN are rather low.

Lithological unit D (1320-669 cm): Unit D starts with exceptionally high values of κ (<15,800 SI*10^{-6}) related to a tephra layer and reworked parts of it (Fig. 4.2, 4.3). In these sections TIC and Ca show very low values and no gastropods are present. However, highest density of gastropods in the whole core becomes evident above the reworked tephra. In contrast to TOC and TN, the magnitude of oscillations as well as absolute values of TIC and Ca increase immediately above the reworked tephra (Fig. 4.3). Nevertheless, there is a broad interval with lower values visible in all four parameters as well as in WC between 1036 and 843 cm and a secondary minimum delimited by high TIC and Ca and low Ti values from 729 to 670 cm (Fig. 4.3). Four XRD analyses at 1007, 867, 705 and 682 cm sediment depth revealed the presence of monohydrocalcite ($CaCO_3$*H_2O). κ shows the lowest values of the record between 856 and 669 cm.

Lithological unit C (669-607 cm): Lithological unit C is characterized by very low values of TIC and Ca in the upper- and lowermost part and a peak in between (Fig. 4.3). The opposite is the case for Ti and WC. Gastropods are only present in the uppermost part of unit C. All other parameters do not vary significantly (Fig. 4.3).

Lithological unit B (607-313 cm): TIC and Ca show a sequence of two maxima followed by minima (Fig. 4.3). WC, TOC and TN display minor variations with a slight maximum near the top of the unit (~387 cm).

Lithological unit A (313-0 cm): TIC, Ca, TOC and TN show a broader minimum just before values increase again in the uppermost part of the record. The TIC minimum with values below detection limit is the most prominent one observed for TIC and Ca above 12.8 m sediment depth. The opposite pattern is observed for Ti showing high values before they decrease. Gastropods are almost absent (Fig. 4.2, 4.3).

3.2. Volcanic Ashes

Laguna Potrok Aike, located in a favorable downwind position to the explosive volcanoes of the Austral Volcanic Zone (AVZ, 49°-54°S) and the southernmost Southern Volcanic Zone (SSVZ, ~46°S), has recorded three major explosive events during the last 16,000 cal. BP. The youngest tephra (1074.5 cm sediment depth) is a fine grained (≤ 100 µm) brown-greenish vitric ash. Plagioclase, alkali feldspar and colorless to light greenish clinopyroxene form the principle mineral assemblage. Lithics are represented by limestone fragments and vitric (palagonite) tuffs. Volcanic glass shards are blocky shaped and trachydacitic to dacitic in chemical composition (Tab. 4.1).

Tab. 4.1: Mean values of major-element EPMA data of glass shards from tephras occurring in the Laguna Potrok Aike profile PTA03/12+13. Numbers in parentheses: 1σ standard deviation; n: number of glass shards analyzed. Glass shards from Reclús reveal to types of glasses (a and b).

Tephra	**1090 cm**	**1334-1332 cm**	**1855-1854 cm**	
Source	**Hudson**	**Mt. Burney**	**Reclús**	
			glass type a	glass type b
SiO_2	65.30 (0.97)	75.70 (0.92)	75.38 (0.53)	66.38 (0.00)
TiO_2	1.23 (0.06)	0.14 (0.01)	0.13 (0.02)	0.42 (0.00)
Al_2O_3	16.16 (0.09)	12.88 (0.32)	12.71 (0.28)	16.33 (0.00)
FeO	4.93 (0.37)	1.05 (0.06)	1.21 (0.08)	3.71 (0.00)
MnO	0.16 (0.04)	0.03 (0.03)	0.05 (0.02)	0.11 (0.00)
MgO	1.50 (0.26)	0.24 (0.01)	0.23 (0.02)	1.81 (0.00)
CaO	2.97 (0.43)	1.18 (0.09)	1.59 (0.15)	4.20 (0.00)
Na_2O	4.47 (0.29)	3.64 (0.31)	3.00 (0.25)	3.48 (0.00)
K_2O	2.80 (0.12)	1.76 (0.07)	2.27 (0.13)	1.45 (0.00)
P_2O_5	0.35 (0.06)	0.05 (0.05)	0.03 (0.03)	0.17 (0.00)
Cl	0.13 (0.02)	0.19 (0.02)	0.17 (0.03)	0.10 (0.00)
total	100.01	96.87	96.78	98.16
	n = 19	n = 7	n = 15	n = 1

The major-element glass chemistry corresponds to the plinian eruption *H1* of the Hudson volcano (Fig. 4.5). Another tephra layer (1320 cm) represents a rather coarse grained (≤ 1 mm) whitish pumice fallout. Its mineral assemblage is made up of zoned plagioclase, clinopyroxene, orthopyroxene and amphibole phenocrysts. Aggregates of olivine and clinopyroxene microcrysts are quite common. Volcanic glasses are homogeneous rhyolitic in composition providing a major element chemistry identical to Mt. Burney volcanic ejecta (Tab. 4.1, Fig. 4.5). Due to its stratigraphic position in the Laguna Potrok Aike profile - below the *H1* tephra - it correlates with a Plinian eruption of Mt. Burney. The oldest tephra (1861 cm) is a fine grained (<150 µm), beige vitric ash layer that comprises abundant phenocrysts of clinopyroxene, orthopyroxene, zoned plagioclase and rare amphibole. Corroded quartz xenocrysts and clasts of plagioclase crystals are common. The chemical composition of micro-pumices and glass shards is heterogeneous rhyolitic and dacitic (Tab. 4.1). It most likely corresponds to a Late Pleistocene distal tephra layer from Reclús volcano.

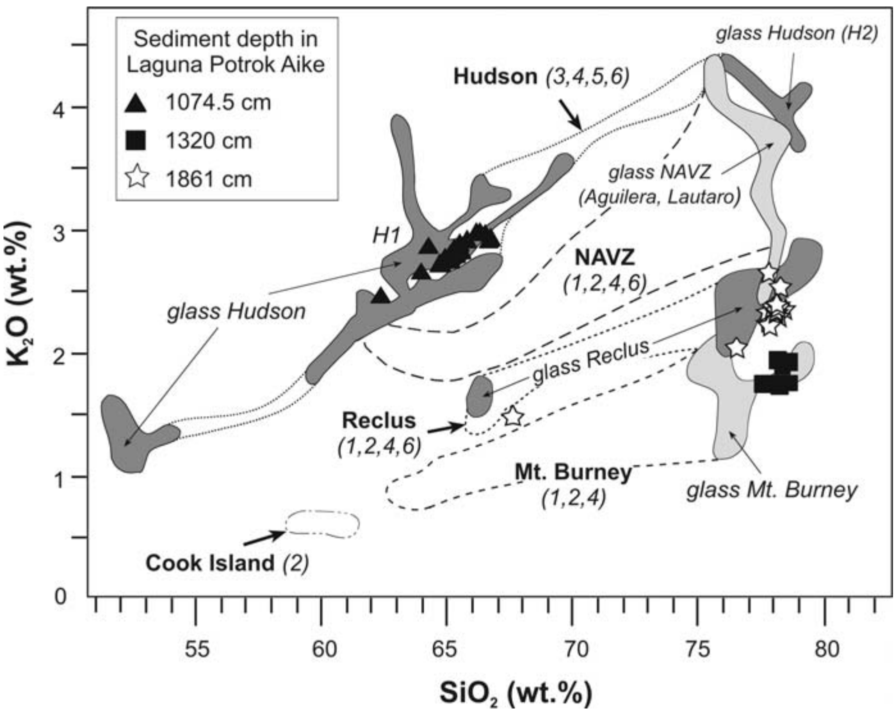

Fig. 4.5: Comparison of SiO_2 vs. K_2O data of Laguna Potrok Aike tephras with mean oxide concentrations of tephras derived from southern Patagonian volcanoes (geochemical envelopes: EPMA data of juvenile glass; dashed lines: whole rock XRF data). Data from: 1: Stern et al. (1990), 2: Stern and Kilian (1996), 3: Naranjo and Stern (1998), 4: Kilian et al. (2003), 5: Bitschene and Fernandez (1995), 6: this work.

Though a number of age determinations for the tephra layers detected in the sediment record of Laguna Potrok Aike exists, a composite of those ages would have resulted in errors larger than 2,000 years minimizing the value of such isochronous marker horizons. Thus, the latest dates (Kilian et al., 2003; McCulloch et al., 2005) calibrated with the northern hemisphere calibration curve (Reimer et al., 2004) of CALIB 5.0.2 (Stuiver and Reimer, 1993; Stuiver et al., 2005) were supposed to provide most accurate results (Tab. 4.2).

3.3. Age-depth model

The age-depth model is based on 16 radiocarbon dates performed on different materials (Tab. 4.2, Fig. 4.6) and on the Mt. Burney tephra (Kilian et al., 2003). It was necessary to include the tephra because three radiocarbon dates above that volcanic ash were too old probably because they contain reworked old carbon (Fig. 4.6). A hard water effect in the sediments of Laguna Potrok Aike has been demonstrated to be absent (Haberzettl et al., 2005). The sediment/water interface serves as time marker for the year of coring (2002) for the uppermost section of the record (PTA02/4, Haberzettl et al., 2005). The medians of the 2σ-probability distributions of all age determinations were connected linearly (Fig. 4.6). Event layers as defined above were marked with gray bars in the lithology and show the same age with increasing depth (only visible for unit G, Fig. 4.6). These events were excluded from the record in plots vs. depth.

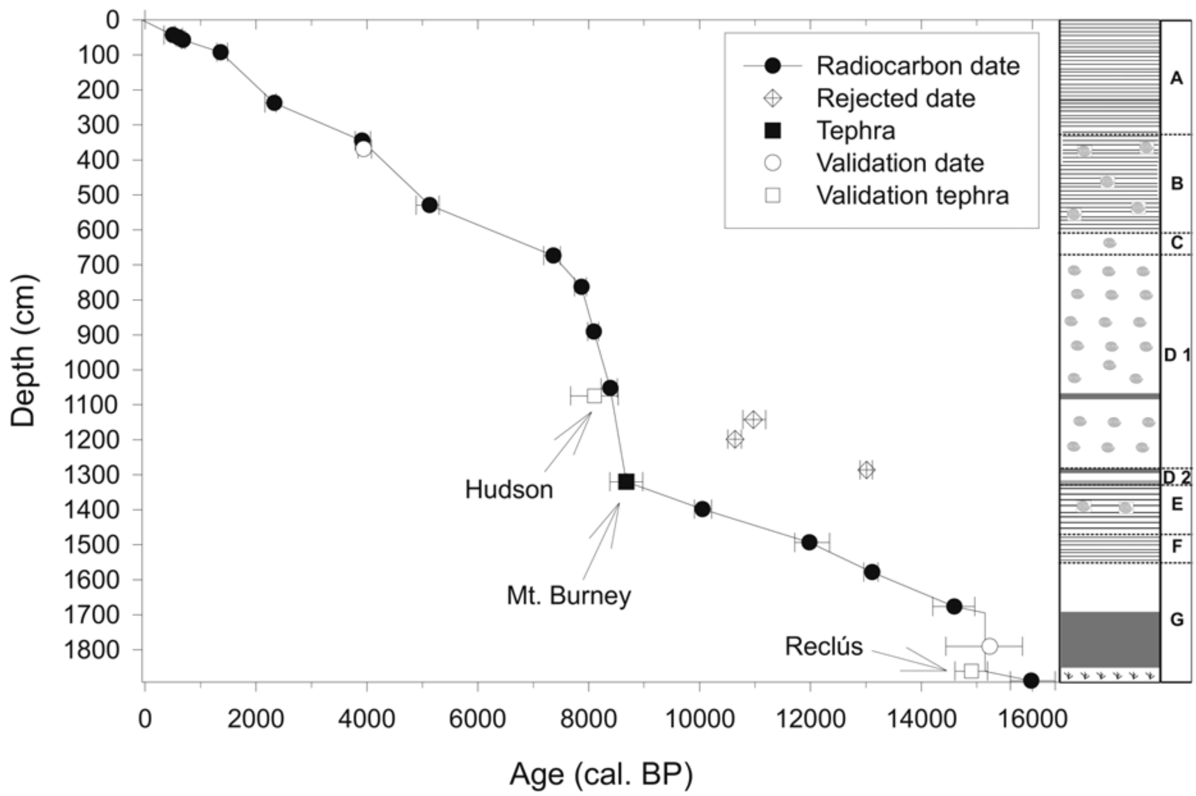

Fig. 4.6: Age-depth model based on calibrated radiocarbon dates and the Mt. Burney tephra. Each date is displayed as median of the 2σ-probability distribution with error bars. The sediment-water interface is a time marker for the year of coring (2002). Reclús and Hudson tephras as well as two radiocarbon dates were used for validation.

Tab. 4.2: AMS radiocarbon dates from Laguna Potrok Aike. Median, minimum and maximum of calibrated ages refer to the 2σ ranges. If two dates are given for one tephra sample, they refer to above and below of the respective ash layer.

Sediment depth (cm)	^{14}C Age (BP)	Error	Sample description	Median cal. age (cal. BP)	Min. cal. age (cal. BP)	Max. cal. Age (cal. BP)	Lab. no. and/or reference
43.5	440	30	Stems of aquatic moss	500	340	535	Poz-834 (Haberzettl et al. 2005)
50.0	655	25	Bulk sediment	600	560	670	Poz-897 (Haberzettl et al. 2005)
57.5	735	25	Calcite fraction of bulk sample	680	660	720	Poz-3570 (Haberzettl et al. 2005)
92.5	1470	40	Stems of aquatic moss	1360	1295	1485	Poz-896 (Haberzettl et al. 2005)
237.5	2300	35	Twig of Berberis	2330	2160	2360	Poz-5182
345.5	3600	35	Calcite fraction of bulk sample	3910	3785	4065	Poz-8549
368.5*	3625	35	Stems of aquatic moss	3940	3840	4080	Poz-8390
529.5	4465	50	Stems of aquatic moss	5130	4890	5300	Poz-8398
673.5	6440	70	Calcite fraction of bulk sample	7360	7185	7485	Poz-8550
763.0	7025	50	Stems of aquatic moss	7870	7740	7955	Poz-8391
890.5	7260	50	Calcite fraction of bulk sample	8090	7980	8175	Poz-8546
1052.5	7580	50	Stems of aquatic moss	8390	8220	8515	Poz-8392
1074.5***	6915 7635	40 40	Hudson	8100	7670	8535	Kilian et al. 2003
1142.5**	9640	50	Stems of aquatic moss	10970	10780	11190	Poz-8393
1198.5**	9410	50	Calcite fraction of bulk sample	10640	10510	10755	Poz-8547
1286**	11090	60	Stems of aquatic moss	13010	12895	13115	Poz-8394
1320***	7635 7890	40 40	Mt. Burney	8680	8380	8975	Kilian et al. 2003
1398.5	8930	50	Bone of Tuco Tuco	10050	9905	10215	Poz-5985
1493.5	10240	60	Calcite fraction of bulk sample	11980	11715	12345	Poz-8548
1578.5	11200	60	Stems of aquatic moss	13110	12960	13220	Poz-8396
1676.5	12490	70	Stems of aquatic moss	14590	14205	14960	Poz-8397
1790.5*	12850	70	Stems of aquatic moss	15230	14440	15820	Poz-5072
1861***	12638	60	Reclús	14900	14605	15190	McCulloch et al. 2005
1888.5	13450	70	Stems of aquatic moss	15980	15605	16410	Poz-5073

**Validation date*

***Date excluded from age model*

****Tephra dates from literature (re-)calibrated with calib 5.0.2*

The age ranges of tephras from Hudson (Kilian et al., 2003) and Reclús (McCulloch et al., 2005) volcanoes (Tab. 4.2) serve as a validation for the age-depth model. Further confirmation is given by two other validation dates: One of aquatic mosses found in the reworked Reclús tephra and the other of aquatic macrophytes next to a date based on autochthonously precipitated calcite, both providing similar results (Fig. 4.6). In addition to confirming the other radiocarbon date, this indicates that the calcite fraction is well suited for dating. All validation dates were excluded from the age-depth model as the age ranges of these dates intersect the linearly interpolated age-depth model (Fig. 4.6).

4. Discussion

4.1. Indicators for lake level changes

The most recent lake level variations of larger magnitude at Laguna Potrok Aike have been demonstrated by dating subaerial shorelines (Haberzettl et al., 2005) and a subaquatic lake level terrace (Haberzettl et al., subm.). A similar approach was used for Lago Cardiel (Stine and Stine, 1990). However, in all cases the dating of shorelines only provides selective events. As no single line of sedimentary or geomorphological evidence defines lake level changes unequivocally (Duck et al., 1998), a multi-proxy approach is presented here. The following proxies are related to lake level changes and provide continuous records for hydrological variations.

4.1.1. Calcium carbonates

In an earlier study the presence or absence of autochthonous calcite, represented by TIC and Ca (Fig. 4.4), was identified as a lake level indicator for the last two millennia for Laguna Potrok Aike (Haberzettl et al., 2005). These parameters provide qualitative estimations for past lake level variations with high TIC and Ca values reflecting lower lake levels and vice versa.

In lithological unit F, TIC and Ca merely reflect the remains of the calcareous shells of the green alga *Phacotus lenticularis* whereas in all other units calcite crystals are present. *Phacotus* was distinguished from other autochthonous calcites using smearslides and SEM images (Fig. 4.4). It produces $CaCO_3$ in remarkable amounts and massive blooms influence the $CaCO_3$ budget of lakes (Koschel et al., 1987; Schlegel et al., 1998). In Lake Constance mass developments of *Phacotus* were assumed to be responsible for serious depletions of calcium (Müller and Oti, 1981; Schlegel et al., 1998). This would probably stop autochthonous calcite precipitation in Laguna Potrok Aike as it was observed in Lake Tollense (Koschel et al., 1987). Laboratory experiments showed that the occurrence of *Phacotus lenticularis* directly depends on the degree of calcium supersaturation (Hepperle and Krienitz, 1997; Schlegel et al., 2000b). This implies that *Phacotus* in Laguna Potrok Aike, like other autochthonous calcite compounds, is dependent on low lake levels resulting in high calcite saturations (Haberzettl et al., 2005).

The calcite species monohydrocalcite was also recognized in the sediments of Laguna Potrok Aike. Laboratory experiments confirmed that bacteria precipitate monohydrocalcite at high salt concentrations (Rivadeneyra et al., 2000; Rivadeneyra et al., 2004). In Laguna Potrok Aike such high salt concentrations would point to an enrichment of ions due to lower lake levels.

4.1.2. Titanium (Ti) and Ca/Ti-ratio

Ti contents were previously used as an indicator for riverine clastic input e.g., to the Cariaco Basin off the Venezuelan coast (Haug et al., 2003). A similar approach was used for Lake Steisslingen, southern Germany (Eusterhues et al., 2005) and Lake Baikal, eastern Siberia (Demory et al., 2005). The presence of Ti in these lakes reflects detrital input since Ti is released from Ti-bearing rocks by physical erosion (Cohen, 2003) through weathering and minerals containing Ti are not sensitive to dissolution (Demory et al., 2005). For Laguna Potrok Aike results of the short core (Haberzettl et al., 2005) and a long core from a subaquatic lake level terrace (Haberzettl et al., subm.) show that Ti was associated with allochthonous input resulting from runoff and hence hydrological variability. Most of the time Laguna Potrok Aike had no surface outflow. Therefore, runoff is assumed to influence lake level variations, and hence, Ti can be used as indicator for lake level fluctuations. Consequently, the Ca/Ti-ratio in sediments of Laguna Potrok Aike reflects hydrological variability with high values reflecting dry phases and low values responding to moist conditions and can be used as representative for TIC, Ca and Ti.

4.1.3. Fe/Mn-ratio

The higher solubility of Mn versus Fe in the sediment (Wetzel, 1983) has been suggested as a key to the interpretation of the Fe/Mn-ratio (Cohen, 2003). The release of Mn from sediments precedes that of Fe (Brüchmann and Negendank, 2004; Wetzel, 1983). Dissolution of Mn-compounds occurs if the redox potential (E_H) decreases below 600 mV due to reduction of Mn^{4+} to Mn^{2+} (Sigg and Stumm, 1996). For iron the critical E_H for reduction of Fe^{3+} compounds to more soluble Fe^{2+} compounds is 100 mV (Sigg and Stumm, 1996). Therefore, if the redox potential drops to values between 100 and 600 mV, Fe/Mn-ratios will be increasing. Rising Fe/Mn-ratios are hence indicative for the beginning of reducing conditions (Brüchmann and Negendank, 2004; Cohen, 2003) and can be used as "paleo-redox indicator" for lacustrine sediments (Granina et al., 2004; Wersin et al., 1991). Although it cannot be excluded that E_H never dropped below 100 mV in Laguna Potrok Aike, high Fe/Mn-ratios are interpreted as being indicative of reducing conditions.

The Fe/Mn-ratio will be applied to confirm the interpretation derived from other mentioned parameters. It is assumed that mixing (i.e., oxygen supply to the sediment-water interface) and consequently a lower Fe/Mn-ratio is easier to achieve if the lake level is lower and/or wind speed is higher. Similar observations were made at Baldeggersee, Switzerland, where oxygen input by wind induced mixing resulted in a flux of MnO_2 (Schaller et al., 1997).

4.1.4. C/N-ratio (TOC/TN-ratio$_{atomic}$)

In previous studies the C/N-ratio has been used as a paleoshoreline proximity indicator for Laguna Potrok Aike (Haberzettl et al., 2005; Haberzettl et al., subm.). This is based on the assumption that algal organic matter has molar C/N-values commonly between 4 and 10, whereas higher plants produce organic matter with higher C/N-ratios (Cohen, 2003; Meyers, 1994, 2003). Submersed aquatic macrophytes collected from Laguna Potrok Aike have C/N values between 24 and 49 and were expected to be the source of organic matter for core sections with elevated C/N-ratios (Haberzettl et al., 2005). Therefore, it is assumed that during periods of lake level low stands increased amounts of vascular plants were transported to the coring location which resulted in increasing C/N-ratios (Haberzettl et al., 2005).

4.1.5. Gastropods

Freshwater molluscs are relatively poor indicators of past environmental conditions because of their generally broad environmental tolerance (Ouellet, 1975; Wetzel, 1983). However, they are abundantly preserved in nearshore deposits (Cohen, 2003). Today, freshwater gastropods (Lymnaeidae) in Laguna Potrok Aike are observed alive at the sediment/water interface of short cores in depths up to 12 m. Sporadic dead specimen, however, were recovered from greater depths (80 m). In sediments that were deposited during a lake level high stand, i.e., the Little Ice Age (Haberzettl et al., 2005) and Oxygen Isotope Stage 3 (Haberzettl et al., subm.), no gastropods were observed at all. Therefore, abundant gastropods in this sediment record indicate a rather close paleoshoreline facilitating their transport to the coring location.

4.1.6. Sedimentation rate

Extraordinarily increased sedimentation rates have only been observed for lithological unit D. Such sedimentation rates cannot be explained by usual depositional processes but may occur either if vegetation in the catchment area was reduced and/or the lake level was rather low. In both cases the catchment area was prone to erosion as it was not stabilized by vegetation and/or less resistant lacustrine sediments were exposed and easily eroded by runoff. Furthermore, even if allochthonous input remained constant, a lower lake level would imply an increased sedimentation rate at the coring location, as the area available for deposition decreased.

4.2. Paleoenvironmental reconstruction

According to the discussed lake level indicators a paleoenvironmental reconstruction emphasizing hydrological variations is performed for the entire record. This will be compared to other archives of regional and global importance.

4.2.1. High early Late Glacial lake levels

In unit G (16,000-12,800 cal. BP) low Ca/Ti values point to a long period of high lake levels at Laguna Potrok Aike. Only during the uppermost 400 years a low lake level is indicated by higher values (Fig. 4.7). This interpretation is supported by more oxic conditions in the lower part of unit G indicated by high Fe/Mn-ratios in the lower and low Fe/Mn-ratios in the uppermost part. Only minerogenic input, represented by Ti is

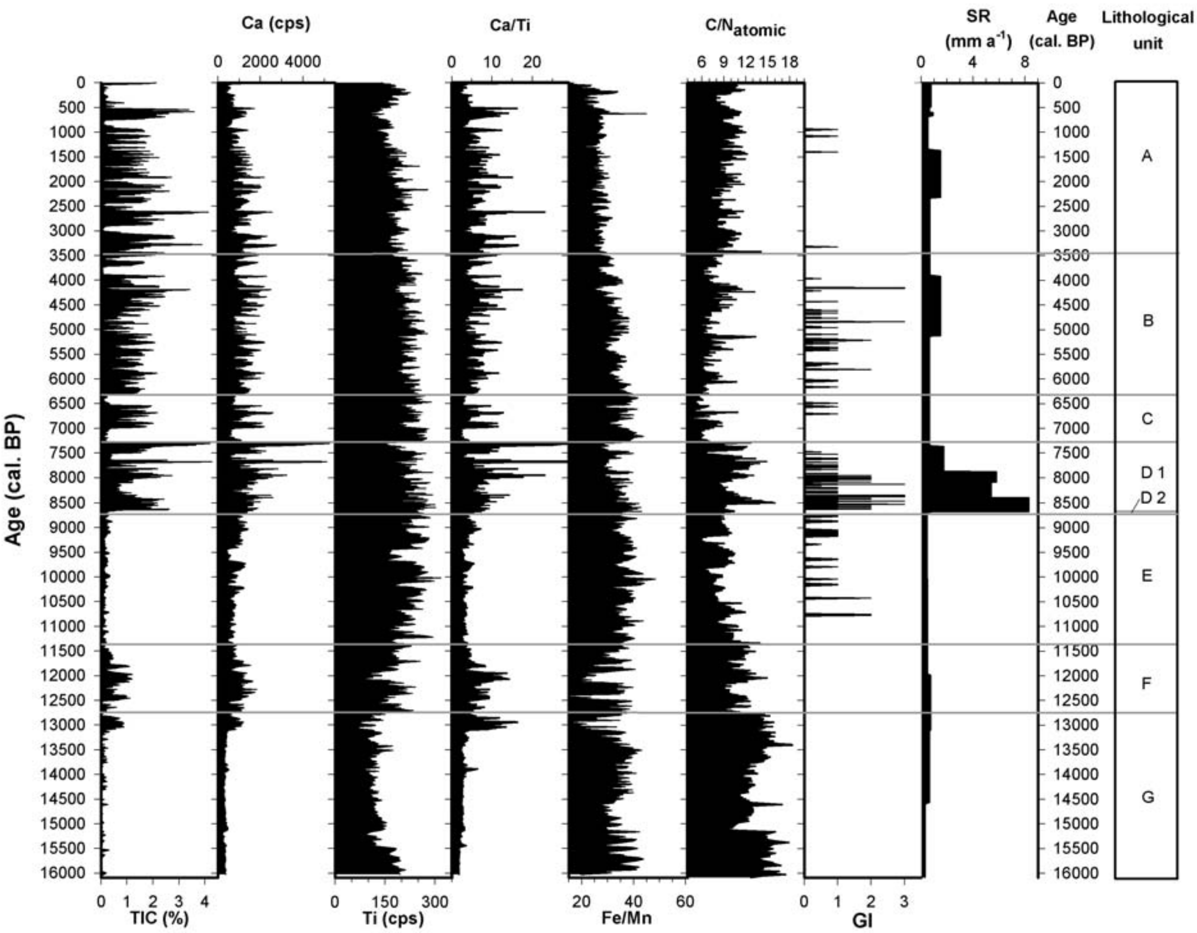

Fig. 4.7: Selected sediment parameters vs. time reflecting hydrological variations (lake level changes) at Laguna Potrok Aike (SR: sedimentation rate, GI: gastropod index).

contradictory on first sight because low values would indicate little fluvial input and hence dry conditions. Nevertheless, Ti variations in this unit are in phase with other proxies also indicating drier conditions at the top of the unit. One explanation for the low minerogenic input and the variability in this unit might be that the lake level was extremely high resulting in an outflow of the lake which today is located approximately 25 m above the lake surface. As this outflow of the lake is close to the recent inflow (Fig. 4.1) and as there is geomorphological evidence for a possible fluvial by-pass large portions of the minerogenic material which normally would have been deposited in the lake center might have passed the lake. This would also explain why TIC and Ca values are the lowest of the record.

This proposed lake level high stand and the subsequent low stand coincide with the hydrological record of Lago Cardiel (Fig. 4.1), which also points to a high lake level until 13,160 cal. BP (Gilli, 2003) followed by desiccation around 13,120 cal. BP (Gilli et al., 2005).

4.2.2. Dry and warm late Late Glacial

Unit F (12,800-11,400 cal. BP) is the only part of the record in which the calcite fraction of the sediment was produced by *Phacotus.* The ability of *Phacotus* to deplete the calcium budget of lakes (Müller and Oti, 1981; Schlegel et al., 1998) preventing the precipitation of other autochthonous calcite, suggests that high values of Ca/Ti-ratio represent a lower lake level. However, Ti shows higher values than in unit G, which would indicate more minerogenic input and hence moister conditions. Nevertheless, compared to the rest of the record values are rather low and follow the pattern of the other proxies (Fig. 4.7). This might be related to a lake level lowering which resulted in an enhanced transport of minerogenic matter to the center of the lake because there was no outflow or by-pass anymore. More oxic conditions inferred from the Fe/Mn-ratio support the hypothesis of a lower lake level during that time.

According to temperature studies in European lakes *Phacotus lenticularis* only occurs at temperatures >15.8 °C (Müller and Oti, 1981; Schlegel et al., 1998, 2000a). Therefore, the occurrence of *Phacotus lenticularis* in the sediment record from Laguna Potrok Aike suggests much warmer summers. Such high temperatures today only occur at the water surface for a few days during January (Zolitschka et al., in press). These warm conditions would result in increased evaporation and in analogy to present day observations to increased wind speeds, leading to a lower lake level and increased mixing, which would explain the oxidizing conditions.

This period is contemporaneous to the northern hemisphere Younger Dryas chronozone (12,700-11,500 cal. BP). The idea of warmer conditions during the Younger Dryas in the southern hemisphere is supported by various other archives showing warming and/or peaks in temperature-sensitive parameters on a level never reached again until today. Such a warming, for example, is recorded in the alkenone-based sea surface temperature reconstruction from ODP Site 1233 off Chile (Fig. 4.1, Lamy et al., 2004), which is similar to the deglacial warming determined for the Byrd ice core, Antarctica (Fig. 4.1, Blunier and Brook, 2001). Further evidence comes from marine sediment core MD97-2120 (Fig. 4.1) east of New Zealand (Pahnke et al., 2003) where the highest peak of $\delta^{18}O$ occurs during that time. All mentioned records suggest a southern hemisphere millennial-scale warming pattern (Lamy et al., 2004).

Support for a drought in the steppe area of Patagonia is provided by the sediment record from Lago Cardiel, which shows the lowest lake levels ever recorded in the mentioned time span (Gilli, 2003). Additional evidence for warmer and/or drier conditions on Tierra del Fuego is given by dated basal peat layers evidencing a glacial melting before 11,720 cal. BP at Punta Pingüinos and Lapataia (Fig. 4.1) and at 12,890 cal. BP for tributary glaciers at Bahía Aguirre (Fig. 4.1, Rabassa et al., 2000).

4.2.3. Humid early Holocene

Unit E (11,400-8,700 cal. BP) is characterized by consistently moister climate conditions as evidenced by all proxies from Laguna Potrok Aike. Lower Ti and Ca values around 9.500 cal. BP are caused by a rough sediment surface in the liner during XRF-measurements which made it impossible to obtain accurate results in this part of the core (Fig. 4.7).

Analyses of grass cuticles in sloth dung from Tierra del Fuego dated between 10,530 and 9,500 cal. BP indicate a mixture of steppe and Magellanic Moorland environment which points to moister than modern conditions (Markgraf, 1983). Tufa deposits at Lago Cardiel (Stine and Stine, 1990) reveal a high lake level between

11,200 and 10,780 cal. BP. However, the lake level of Lago Cardiel receded during that time (Stine and Stine, 1990). In contrast no signs for regression were found at Laguna Potrok Aike.

During the early Holocene westerly storm tracks are supposed to have been more tightly focused between 45° and 50°S, leaving Andean regions north and south drier than today (Grimm et al., 2001). As drier conditions west of the Andes will cause wetter conditions east of the Cordillera (Schneider et al., 2003), increased rainfall and runoff are expected for Laguna Potrok Aike which was probably the cause for the high lake levels.

4.2.4. Early mid-Holocene dry events

Unit D (8,700-7,300 cal. BP) is the largest section of the record. This is due to remarkably high sedimentation rates based on two successive reasons:

(I) According to the lake level indicators TIC and Ca the lake level was still high at the very beginning of unit D-2 (8,700-8,650 cal. BP). This is confirmed by reducing conditions related to high lake levels and increased minerogenic input inferred from Fe/Mn-ratio and Ti. Macroscopically, a number of coarse layers can be distinguished, either pointing to amplified erosive forces (water, wind) and/or instability of surrounding soils. As D-2 is directly preceded by the Mt. Burney tephra and particles of that tephra are found in the coarser layers, an impact of the ash layer on the high sedimentation rate is assumed. A hint for a disturbance of the ecosystem is the absence of gastropods which might have suffered from an ash cover on submersed littoral plants.

(II) After this rather short unit containing tephra, dramatic changes in most proxies occur around 8,650 cal. BP (D-1). A major shift in Ca/Ti-ratio points to a lake recession (Fig. 4.7) intercepted by two short transgressions (8,350-8,100 and 7,640-7,500 cal. BP). A displacement of the shoreline further away from the coring location during these two transgressions can also be inferred from the C/N-ratio (Fig. 4.7). The general recession is confirmed by decreasing minerogenic input (Ti) and a trend to more oxic conditions (lower Fe/Mn-ratio). The high sedimentation rates point to erosion of now uncovered former littoral sediments which were easily eroded. Further evidence for this hypothesis comes from the rejected radiocarbon dates which probably contained reworked carbon. Furthermore, the abundance of gastropods and high C/N-ratios point to a shoreline generally closer to the coring location. Severe dry conditions are also corroborated by the occurrence of monohydrocalcite in all XRD-samples from unit D-1 indicating high ion concentrations due to a low lake level.

These drier conditions might have been intensified by the thermal optimum related to orbital parameters (Renssen et al., 2005). An increase in temperature and aridity in southern South America during the mid-Holocene has also been inferred from pollen records (Mancini et al., 2005). For Lago Cardiel it is concluded that the lake level fell below the present-day value from 8,490 cal. BP onward (Stine and Stine, 1990).

4.2.5. Late mid-Holocene lake level rise

Unit C (7,300-6,300 cal. BP) marks environmental changes towards moister conditions with a higher lake level observable in all proxies from Laguna Potrok Aike (Fig. 4.7). Moist conditions prevailed until 7,000 cal. BP. All proxies indicate that this phase was followed by a drier period including lake recessions with short humid pulses in between. In the sediment core from the lake level terrace (Fig. 4.1, Haberzettl et al., subm.) reworked material dated to 6,790 cal. BP was found immediately above sediments deposited during Oxygen Isotope Stage 3. Together with the presented record this indicates that there must have been a transgression starting before 7,000 cal. BP with a lake level that passed the level of this subaquatic terrace. The reworked layer seems to be the result of the proposed drier period with short humid pulses (7,000-6,500 cal. BP) resulting in lake level fluctuations. However, the record from the lake level terrace points to continuous sedimentation after 6,750 cal. BP (Haberzettl et al., subm.) indicating a further lake level rise during the humid pulses. This transgression, also indicated by the C/N- and Ca/Ti-ratio, probably was amplified by moister conditions inferred from increased minerogenic input between 6,500 and 6,300 cal. BP (Fig. 4.7). The higher lake level also resulted in more reducing conditions deduced from Fe/Mn-ratio.

For Lago Cardiel, dates reveal a maximum age for a transgression at 6780 cal. BP and evidence a high lake level thereafter (Stine and Stine, 1990).

4.2.6. Variable late Holocene conditions

Starting from moist conditions with a high lake level at 6,300 cal. BP less minerogenic input and increasing oxic conditions (Fe/Mn-ratio) show a trend towards a lower lake level. Lake level indicators (TIC, Ca, Ca/Ti-ratio and C/N-ratio) in contrast show an increased variability with periods of water abundance, which can also be traced by increased minerogenic input (Ti). The moist periods were 4,800 cal. BP, 3,900-3,700 cal. BP, around 3,000 cal. BP, 2,500 cal. BP and 1,980 cal. BP as well as around 950-750 cal. BP and 530-20 cal. BP. However, units A and B are dominated by drier conditions with lower or receding lake levels. Nevertheless, the sediment record from the lake level terrace of Laguna Potrok Aike points to a continuous deposition for this period (Haberzettl et al., subm.), which excludes a lake level lower than 30 m below present.

Attention should especially be paid to the last moist period ascribed to the Little Ice Age (Haberzettl et al., 2005). According to the TIC record, such a long duration of moist conditions has only been observed during the early Holocene and the Late Glacial prior to 8,650 cal. BP. Similar lake level fluctuations, although with less temporal resolution, were assumed for Lago Cardiel (Stine and Stine, 1990).

5. Conclusions

The presented sediment record from Laguna Potrok Aike reveals a hitherto unprecedented high resolution archive for hydrological variability in southeastern Patagonia. Based on a consistent age-depth model this maar lake record provides continuous information also around 13,120 cal. BP, when Lago Cardiel was desiccated.

The geochemical proxies TIC, Ca and Ca/Ti-ratio reflect lake level variations and are supported by the paleoshoreline proximity indicators C/N-ratio and gastropod index, by Ti as indicator for minerogenic input and by changes in redox conditions inferred from Fe/Mn-ratios assumed to react on lake level variations. All proxies cause or react on lake level changes at Laguna Potrok Aike and hence reflect hydrological changes in the Patagonian steppe. They indicate rather moist conditions starting at the beginning of the record at 16,000 cal. BP until 8,700 cal. BP only interrupted by a warm and dry phase lasting from 13,100 until 11,400 cal. BP. This gives terrestrial evidence for a warming during the Younger Dryas chronozone for southern hemispheric mid to high latitudes. Unfortunately, the Laguna Potrok Aike record does not comprise information about cold events like the Antarctic Cold Reversal or the Huelmo-Mascardi Cold Reversal (Hajdas et al., 2003). However, this study documents the potential of Laguna Potrok Aike which will be complemented by stable isotope, pollen and diatom records performed on the same samples as well as the envisaged ICDP project PASADO (Potrok Aike Lake Sediment Archive Drilling Project).

Most drastic changes of the record start with the deposition of the Mt. Burney tephra generating intensified erosion. Thereafter, from about 8,650 to 7,300 cal. BP, the lake level fell to its lowest Holocene position. After a transgression the lake level was extremely variable with a few moist periods. The last lake level high stand is ascribed to the Little Ice Age, which was the largest humid phase since the early Holocene lake level highstand before 8,650 cal. BP.

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Chapter 5:

Hydrological variability in southeastern Patagonia during Oxygen Isotope Stage 3 and the Holocene

submitted to: Palaeogeography, Palaeoclimatology, Palaeoecology

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Abstract

Seismic studies in the maar lake Laguna Potrok Aike (51°58`S, 70°23`W) revealed an erosional unconformity in a subaquatic lake level terrace. Radiocarbon dated multi-proxy sediment studies of a piston core from this location indicate that the sediment below this discontinuity has an age of 45 ka BP (Oxygen Isotope Stage 3) and was deposited during an interval of high lake level. In comparison to the Holocene section geochemical indicators of this older part of the record either point towards a different sediment source or to a different transport mechanism for Oxygen Isotope Stage 3 sediments. Holocene sedimentation above the unconformity started again before 6790 cal. BP providing a sediment record of hydrological variability until the present. Geochemical and isotopic data indicate further hydrological variations during the late Holocene. Nevertheless, the lake level did not drop to create another unconformity again. The geochemical characterization of volcanic ashes revealed a so far unknown explosive activity of the volcanoes Reclús and Mt. Burney during Oxygen Isotope Stage 3.

Keywords: geochemistry, lacustrine sediments, lake level changes, multi-proxy, tephrochronology, Argentina

1. Introduction

Especially during Oxygen Isotope Stage 3 (OIS 3) major gaps of palaeoclimatic information exist in the marine sector around South America as well as in high-resolution terrestrial records in major parts of this continent (Voelker, 2002). Such information is most notably needed, in order to compare southern hemisphere climate with the better known climate history from the tropics and the northern hemisphere. This data allows to check a possible synchrony of global climate events in the past, and to validate global climate models. Climatic information from terrestrial archives covering OIS 3, however, is limited to latitudes north of 43°S (Voelker, 2002). The southernmost sites comprise pollen records from a mire at Taiquemó (42°10`S, 73°36`W) on Isla Grande de Chiloé in Chile (Heusser and Heusser, in press; Heusser et al., 1999) and from a fen at Fundo Nueva Braunau (40°17`S, 73°05`W) (Heusser et al., 2000) as well as tree ring studies based on subfossil tree remnants found at Seno Reloncaví (40°00` to 42°30`S, 71°30` to 74°00`W) both in the southern Lake District of Chile (Roig et al., 2001). Further south, climatological information covering this time interval originates from Antarctic ice cores (Petit et al., 1999; Petit et al., 1990). Hence, a high-resolution sediment record from Laguna Potrok Aike (51°58`S, 70°23`W, Fig. 5.1) covering OIS 3 would be a critical step towards bridging the gap between these continental records.

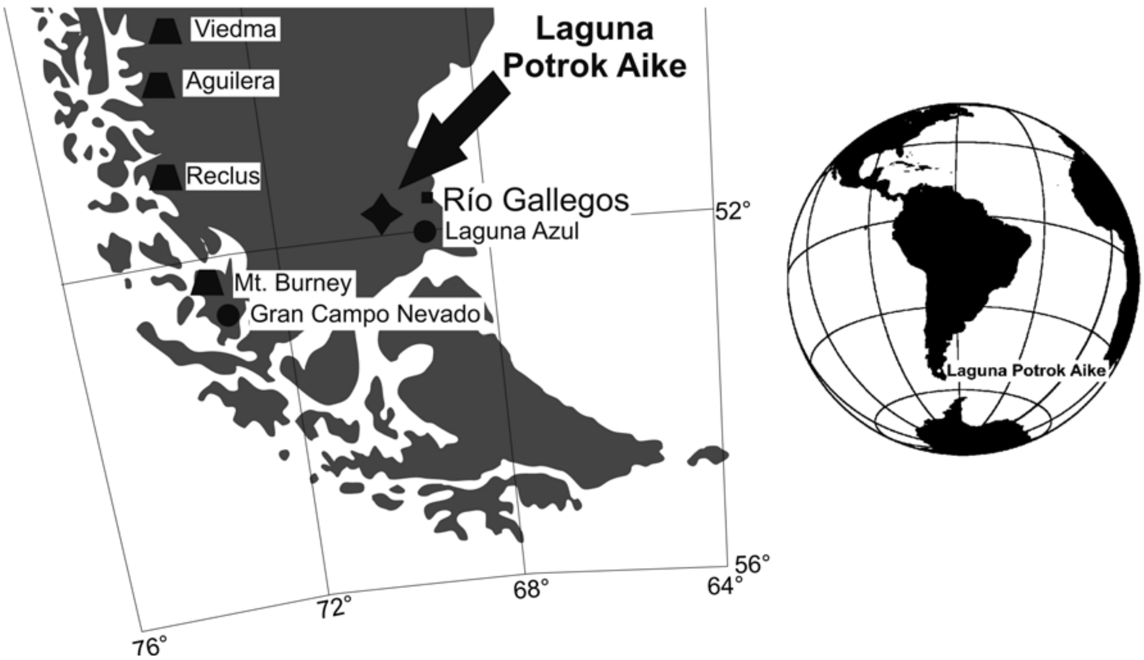

Fig. 5.1: Location of the research area in South America and other sites mentioned in the text.

High-resolution seismic studies using a 3.5 kHz system in the maar lake Laguna Potrok Aike revealed an erosional unconformity in a lake level terrace located approximately 30 m below the present lake surface (Fig. 5.2). At this location

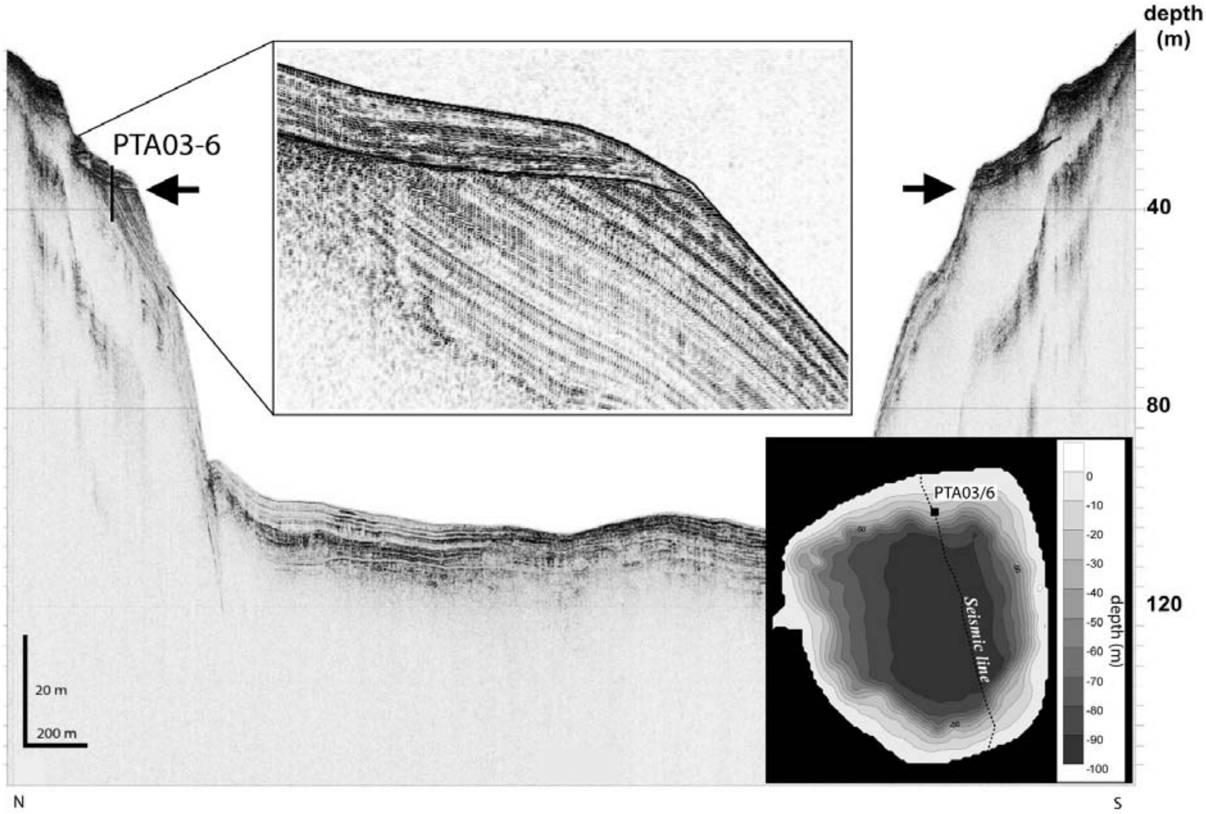

Fig. 5.2: Seismic profile of Laguna Potrok Aike performed with a 3.5 kHz system (note vertical exaggeration). The unconformity is displayed in the blow-up in the center and highlighted with arrows in the profile. The location of core PTA03/6 is indicated in the bathymetric map and the profile.

sediments follow the morphology of the ancient lake by steeply dipping towards the lake center. They are discordantly overlain by horizontally or gently lakeward dipping layered sediments. This study will show that sediments below that unconformity are much older than the base of a continuous 19 m sediment record from the center of the lake, spanning the last 13.5 ka BP (16.000 cal. BP). Moreover, there is potential to date the lacustrine transgression which enabled sediment deposition at this position. This event would be indicative for a regional hydrological change leading to wetter climatic conditions. One aim of this paper therefore is to reconstruct the hydrological variability in southeastern Patagonia on the basis of a combination of geomorphological/geophysical (e.g., lake terrace formation), sedimentological and geochemical information including stable isotope data for Laguna Potrok Aike during the Holocene and OIS 3.

Additionally, the characterization of tephra layers below the unconformity in that record will allow to refine the regional tephrochronology. During the Late Quaternary southern Patagonia was influenced by intensive volcanism that occurred along the Southern Andes in two separate volcanic zones, i.e., the Southern Volcanic Zone (SVZ) and the Austral Volcanic Zone (AVZ) (Stern et al., 1984). To the north, the Hudson volcano in the southern part of the Southern Volcanic Zone (SSVZ, ~46°S) erupted basaltic and trachyandesitic to rhyodacitic pyroclastic material. Its last explosive activity was a large phreato-Plinian eruption in 1991 (Bitschene and Fernandez, 1995; Naranjo et al., 1993; Naranjo and Stern, 1998). In the south, the stratovolcanoes of the AVZ (49°-54°S) produced many tephra eruptions of andesitic-dacitic to rhyolitic composition (Stern and Kilian, 1996). Most of those activities were confined to the Lautaro, Viedma and Aguilera volcanoes in the northern part (NAVZ) as well as to Mt. Burney and Reclús in the southern part of the AVZ (Auer, 1974; Stern, 1990). The Holocene explosive history of SSVZ and AVZ volcanoes has been substantially constrained on the basis of chemical discrimination of numerous distal tephra layers detected in terrestrial sediment records from Chile and Argentina (Auer, 1974; Haberle and Lumley, 1998; Markgraf et al., 2003; Stern, 1990; Stern and Kilian, 1996). Due to the generally widespread distribution to the east and southeast from their origin those tephras have been used as isochrones for dating and correlation of postglacial sediment records in this region. Tephra ages were estimated indirectly using numerous radiocarbon dates that are bracketing the respective tephras. Although widespread in Patagonia, volcanic ashes have not been the focus of studies in sufficient detail (Toms et al., 2004). Up to now, geochemical characterizations of tephras, erupted during OIS 3 only have been performed further north. Those investigations identified volcanic ashes from the volcano Quizapu at the northern limit of the SVZ (Toms et al., 2004) confirming the existence of volcanic activity in the SVZ during that time.

2. Site description

Laguna Potrok Aike is a maar lake located in the dry steppe of Patagonia (Fig. 5.1). This environment results from a strong precipitation gradient from west to east with ca. 200 mm a^{-1} of precipitation at the lake. The dominating climatic element of this area is the westerly wind constituting more than 50% of all wind directions and reaching mean monthly wind speeds of 9 m s^{-1} during early summer (Endlicher, 1993).

The circular lake (shoreline development: 1.1) has a maximum diameter of 3470 m. The catchment area (>200 km^2) reaches far south. Nevertheless, linear runoff only occurs episodically through a few gullies and canyons mainly after snowmelt in spring. In summer 2002 the lake level was at 100 m a.s.l. and the maximum water depth was approximately 100 m (Haberzettl et al., 2005). The lake is surrounded by well preserved subaerial as well as subaquatic lake level terraces formed by wave action. As a lake without permanent surface in- and outflow, Laguna Potrok Aike responds very sensitive to changes in the precipitation/evaporation ratio with rising lake levels in times of wetter climatic conditions and falling lake levels during drier periods (Haberzettl et al., 2005). Further details about Laguna Potrok Aike are provided elsewhere (Haberzettl et al., 2005; Haberzettl et al., accept.; Schäbitz et al., 2003; Zolitschka et al., in press; Zolitschka et al., 2004).

3. Field and laboratory methodology

A 10 m long core (PTA03/6, Fig. 5.2) was retrieved using an UWITEC piston coring system in austral summer 2003 from a lake level terrace approximately 30 m below the present lake surface, which was detected by a single-channel 3.5 kHz seismic system (Fig. 5.2). On board cores were cut into one meter sections. Field length of the entire core comprising all sections was 981 cm.

In the laboratory sediment cores were stored dark and cool at +4°C. They were split, photographed and described lithologically. Additionally, smear slides were prepared at eight centimeter intervals and at depths with macroscopically observed lithological differences for microscopic inspection.

Using a CORTEX (Corescanner Texel) XRF-scanner, which provides qualitative analyses of the chemical elements K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Sr and Pb (Jansen et al., 1998) a non-destructive core scanning method was applied to all sections. The Ca-profile obtained by XRF scanning and photographs including macroscopic marker layers were used for correlation of the overlapping core sections and for establishment of a composite sediment profile. After correlation the total subbottom depth of the core was 900 cm.

A second non-destructive method applied on the split cores was magnetic susceptibility scanning, measured with a point sensor in 1 cm resolution using a Bartington sensor (type MS2E). Subsequently, cores were subsampled continuously and volumetrically in one centimeter intervals. All volumetric sediment samples were freeze-dried for determination of dry density and water content. Dried samples were ground in a mortar and homogenized prior to measuring total nitrogen (TN), total carbon (TC) and total sulfur (TS) in 4 cm increments using a CNS elemental analyzer (EuroEA, Eurovector). Subsamples were subsequently treated with 3% and 20% HCl at 80°C to remove any carbonates and then measured with the CNS analyzer again for determination of total organic carbon (TOC). Total inorganic carbon (TIC) was calculated as the difference between TC and TOC. A preliminary screening with 8 cm increments showed that TIC was absent in all samples below 311 cm. Therefore, TOC was considered to be equal to TC for the samples from this section. At depths that show a larger variability in specific parameters, measurement resolution was increased to 1 cm intervals. Bulk mineralogy was determined for selected samples using X-ray diffraction (XRD) techniques (Philips X´Pert Pro MD equipped with an X´Celerator Detector-Array).

Grain size analyses were performed using a laser diffraction particle size analyzer (LS 200, Coulter) equipped with a variable speed fluid module which measures particles from 0.4 to 2000 µm. Subsamples taken every 5 cm were pooled for each 1 m section. In the section containing the unconformity, pooled samples were taken from above and immediately below the unconformity as well as from the lowest part of the section. Prior to analyses samples were treated with H_2O_2 to remove the organic fraction, HCl to remove carbonates and NaOH to remove biogenic silica. Chemical dispersion was performed using Calgon ($(NaPO_3)n$) .

For analyses of carbon isotope ratios of organic matter ($\delta^{13}C_{org}$) in 8 cm intervals, samples were treated with 5% HCl for 6 h in a water bath at 50°C to remove carbonates, afterwards rinsed with deionized water until pH was neutral and freeze-dried. Samples were combusted at 1080°C in an elemental analyzer (EuroEA, Eurovector) and resulting CO_2 gas was analyzed with a GC-IRMS (Isoprime, Micromass). Isotope ratios are reported as conventional δ-values (in ‰) with $\delta = (R_s/R_{st}-1)*1000$ and R_s and R_{st} as $^{13}C/^{12}C$ ratios of the sample and an international standard (Vienna-Pee Dee Belemnite, VPDB), respectively.

Plant macro-remains were picked out for AMS ^{14}C dating and gastropods for later taxonomic determination. In total five samples were selected for AMS ^{14}C age determination carried out at the Poznań Radiocarbon Laboratory, Poland. Radiocarbon analyses were performed on sieved samples containing remains of aquatic macrophytes (>100 µm). Radiocarbon ages were calibrated using the southern hemisphere calibration curve (McCormac et al., 2004) labeled as shcal., as well as with the northern hemisphere calibration curve (Reimer et al., 2004) marked as nhcal. to facilitate comparisons with other archives using the software CALIB 5.0.1 (Stuiver and Reimer, 1993; Stuiver et al., 2005).

Tephras have been characterized geochemically and microscopically in order to define the volcanic sources. For comparison, tephra samples from Hudson, Reclús and Aguilera/Lautaro (Gilli, 2003; Gilli et al., 2001; Gilli et al., 2005; Markgraf et al., 2003) obtained from the sediment records of Lago Cardiel (48°57`S, 71°26`W) were analyzed as well. Tephra samples were carefully cleaned with 30% H_2O_2 to remove organic matter and surface coatings, and dried with Ethanol. Major-element chemistry of single glass shards was determined on the basis of polished thin sections by electron probe micro analyses (EPMA) using a CAMECA SX100 instrument at GFZ Potsdam. The operating conditions for measurements were 15 kV accelerating voltage, 20 nA beam current, a defocused beam of 15 µm diameter and peak counting times of 20 s except for Na (10 s). Instrumental calibration used interlaboratory natural mineral and glass (Lipari obsidian) reference materials (Hunt and Hill, 1996). At least ten glass shards per tephra were measured according to the homogeneity of samples. Individual analyses of glass shards with total oxide sums lower than 95 wt.% have been excluded. The data of accepted analyses of individual tephra layers were recalculated to 100 wt.% and given as a mean with 1σ standard deviation of n glass shards. Petrological classification is based on the Total-Alkali-Silica diagram (Le Bas et al., 1986).

4. Results

4.1. Seismics

High resolution seismic studies revealed an unconformity in a subaquatic lake level terrace of Laguna Potrok Aike. This unconformity in the terrace located approximately 30 m below the present lake surface, can be traced all around the lake. The unconformity is characterized in the seismic lines by three to four meters of almost horizontally layered sediment above and sediments dipping towards the lake center below (Fig. 5.2).

4.2. Lithology

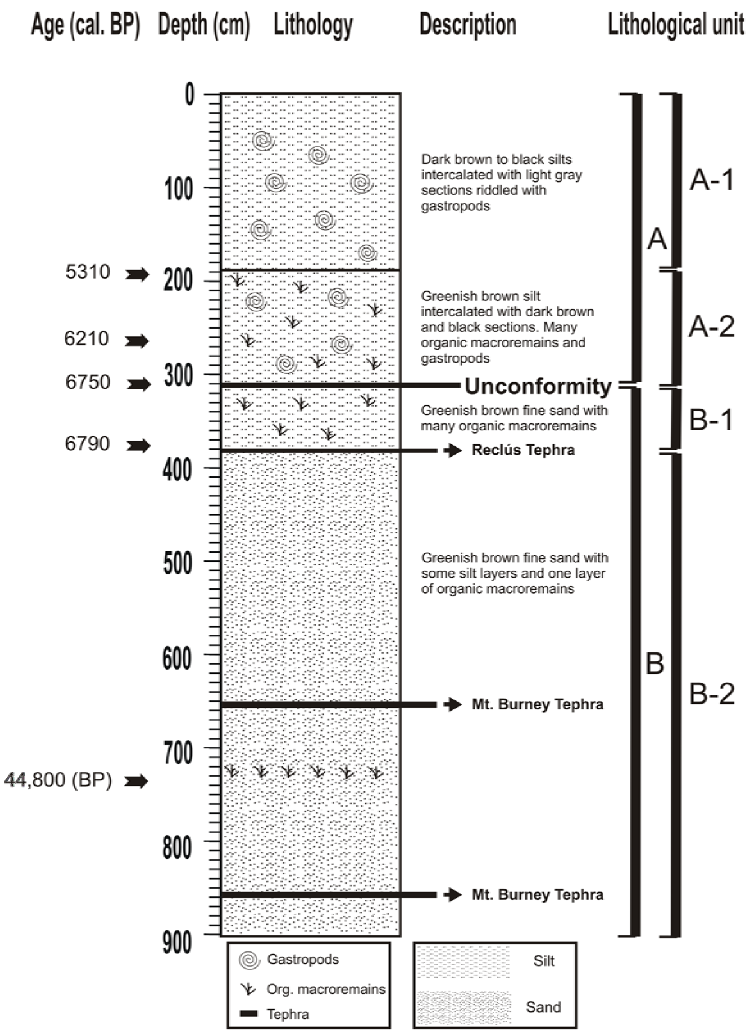

Fig. 5.3: Lithology of core PTA03/6 from Laguna Potrok Aike including ages derived from age model.

In the core PTA03/6 (Fig. 5.2) two major lithological units can be distinguished which are separated by the unconformity at 311 cm (Fig. 5.3). Unit A (above the unconformity, 0-311 cm) consists of dark brown to black silts, whereas unit B (below the unconformity, 312-900 cm) is composed of greenish brown fine sands (Fig. 5.3 and 5.7). Both lithological units can be subdivided into two separate subunits A-1, A-2 and B-1, B-2 (Fig. 5.3). A-1 (0-190 cm) consists of silt with abundant gastropods and A-2 (191-311 cm) of silt with gastropods and, in addition, plenty of plant debris. Unit B-1 (312-378 cm) is characterized by the absence of gastropods but presence of many organic macroremains (moss shoots and plant debris), whereas in unit B-2 (379-900 cm) macroremains only occur in one layer at a depth of 728 cm (Fig. 5.3). The boundary between subunits B-1 and B-2 is marked by a white tephra layer at 379 cm sediment depth. Further downcore, within B-2, two other volcanic ashes have been detected in sediment depths of 643 cm and 859 cm (Fig. 5.3).

4.3. Chronologies

4.3.1. Radiocarbon dating

The AMS ^{14}C datings of sediment core PTA03/6 reveal ages between 4680 and 44,800 BP (Tab. 5.1, Fig. 5.4). The oldest radiocarbon date therefore was not calibrated as it is beyond the calibration curves of CALIB 5.0.1 (McCormac et al., 2004; Reimer et al., 2004; Stuiver and Reimer, 1993; Stuiver et al., 2005). Hence, the oldest dating is displayed uncalibrated in years BP (Fig. 5.3, 5.4, Tab. 5.1). The absence of a hard water effect in the sediments of Laguna Potrok Aike has been demonstrated in an earlier study (Haberzettl et al., 2005).

Tab. 5.1: AMS radiocarbon dating carried out on stems of acquatic mosses. Radiocarbon ages were calibrated with the southern hemisphere calibration curve (shcal., McCormac et al., 2004) as well as with the northern hemisphere calibration curve (nhcal., Reimer et al., 2004) for comparative reasons using the software CALIB 5.0.1 (Stuiver and Reimer, 1993; Stuiver et al., 2005). The ages derived from the age model are given in cal. BP and are used for interpretation.

Lab. No.	Sediment depth	^{14}C Age (BP)	Error	shcal. median age (BP)	error to present	error to past	nhcal. median age (BP)	error to present	error to past	age derived from age model used for interpretation (cal. BP)	Sediment depth
Poz-6096	191 cm	4680	±40	5390	315	185	5400	85	175	5310	191 cm
Poz-6166	266 cm	5320	±50	6050	130	130	6100	150	170	6210	266 cm
Poz-6167	311 cm	6040	±40	6820	125	140	6890	120	105	6750	311 cm
Poz-6097	372 cm	5910	±50	6670	120	165	6730	95	150	6790	372 cm
Poz-6098	728 cm	44,800	±2000							44,800 (years BP)	728 cm

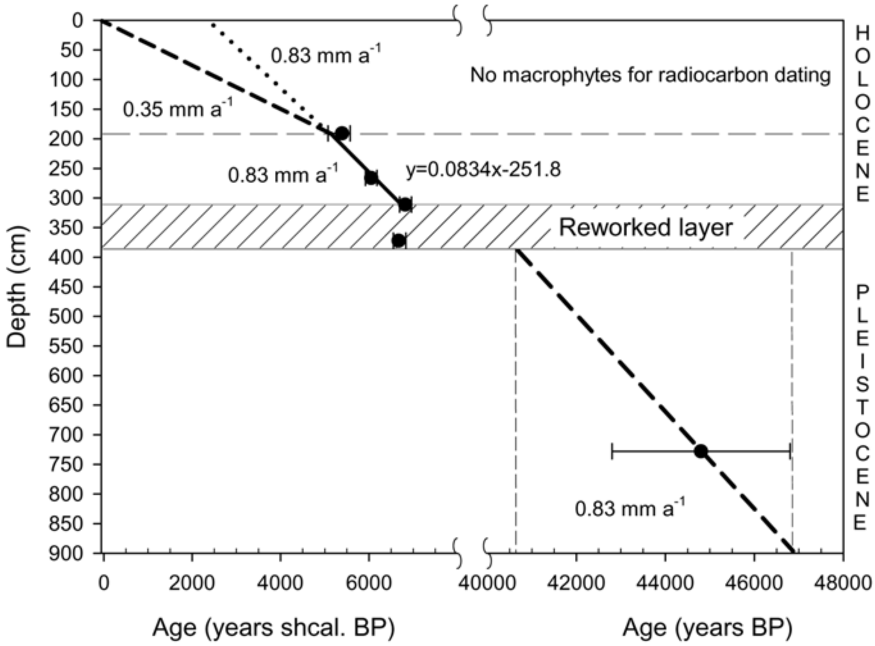

Fig. 5.4: Age model based on radiocarbon dates. If applicable these are calibrated with CALIB 5.0.1 (Stuiver and Reimer, 1993; Stuiver et al., 2005). Each date of the Holocene section was calibrated with the southern hemisphere calibration curve and is displayed as median of the 2σ-probability distribution with error bars. In order to get an idea about the time span covered by the lower section of the record the same sedimentation rate as obtained between 191 and 311 cm was applied as an approximation.

4.3.2. Tephrochronology

Three previously unknown tephra layers have been identified in the lower part of the recovered section of PTA03/6 (Fig. 5.3). The youngest tephra at 379 cm sediment depth is a 1.5 cm thick, fine grained (maximum grain size $d_{max} \leq 100$ µm) white ash layer that directly underlies lithological unit B-1. Glass shards forming the essential phase of tephra components reveal two different major-element chemistries: the main glass population is dacitic in composition showing relatively high aluminum concentrations (> 15 wt.%), while the secondary phase displays a rhyolitic composition with relatively high potassium values (Tab. 5.2). Minerals are rare and comprise plagioclase, orthopyroxene, amphibole and apatite phenocrysts. Sporadically, corroded xenocrysts of quartz, biotite and clinopyroxene occur displaying remaining components of granodioritic rock fragments.

Tephra layers at 643 cm and 859 cm sediment depth are both white ash deposits of 1 cm thickness each. The upper is mainly made up of fine grained ($d_{max} \leq 100$ µm) vitric components which are characterized by a homogenous low-K-rhyolitic chemistry (Tab. 5.2). Its mineral assemblage comprises plagioclase, orthopyroxene and rare amphibole phenocrysts. The lower tephra, in contrary, is a coarser grained pumice deposit ($d_{max} \leq 300$ µm) that additionally bears rare biotite and Fe-Ti-oxide phenocrysts. Vitric components (microcrysts-bearing pumices and low vesicular glass shards) show a similar but slightly more silicic low-K-rhyolitic composition than the tephra at 643 cm (Tab. 5.2).

Tab. 5.2: Mean major oxide concentrations of glass shards extracted from the tephra layers of core PTA03/6. n = number of shards analyzed. 1σ standard deviations are shown as numbers in parentheses.

Tephra	379 cm		643 cm	859 cm
	Glass type A	Glass type B		
SiO_2	70.19 (0.59)	74.52 (0.69)	72.69 (0.80)	74.26 (1.33)
TiO_2	0.56 (0.03)	0.12 (0.02)	0.34 (0.03)	0.23 (0.02)
Al_2O_3	15.23 (0.36)	12.43 (0.17)	13.39 (0.18)	12.99 (0.24)
FeO	2.79 (0.14)	0.99 (0.01)	1.94 (0.09)	1.39 (0.09)
MnO	0.05 (0.03)	0.03 (0.01)	0.05 (0.02)	0.04 (0.02)
MgO	0.84 (0.06)	0.14 (0.00)	0.49 (0.02)	0.37 (0.03)
CaO	3.08 (0.24)	1.17 (0.04)	2.26 (0.07)	1.79 (0.09)
Na_2O	3.59 (0.13)	3.01 (0.18)	3.54 (0.20)	3.79 (0.30)
K_2O	2.24 (0.07)	3.16 (0.12)	1.48 (0.02)	1.65 (0.11)
P_2O_5	0.11 (0.05)	0.04 (0.03)	0.06 (0.03)	0.05 (0.03)
Cl	0.13 (0.01)	0.17 (0.01)	0.19 (0.02)	0.17 (0.03)
Total	98.81	95.76	96.42	96.72
	n = 10	n = 2	n = 11	n = 8

4.4. Sediment analyses

4.4.1. Lithological unit B (below unconformity)

Below the unconformity at 311 cm values, for magnetic susceptibility and dry density are much higher (Fig. 5.5) than above. Water content, TN, TOC, TIC, TS and Ca reveal only minor variations with low intensities. C/N-ratios are oscillating around 6. $\delta^{13}C$ values vary little around -26‰ but show two minima at 434 cm and at 415 cm followed by a shift to more positive values at 407 cm (Fig. 5.5). Ti, Fe, K and Co show a prominent shift to higher values around 770 cm. Decreasing values from 770 to 645 cm are followed by a re-increase (646-397 cm). Mn only shows minor fluctuations around 200 cps in the whole record except for two distinct maxima at 854 cm and 538 cm (Fig. 5.5).

4.4.2. Unconformity

The most prominent shift in most parameters occurs at a sediment depth of 311 to 312 cm (Fig. 5.5). This shift is best visible in magnetic susceptibility, water content, dry density, TN, TOC, TIC and Ca (Fig. 5.5). Below 311 cm values of magnetic susceptibility and dry density are much higher than above. The opposite is observable for water content, TN, TOC, TIC, $\delta^{13}C$ and Ca with higher and oscillating values above 312 cm (Fig. 5.5). The other data obtained by XRF-scanning do not show any anomalous features at the level of the unconformity but TS, $\delta^{13}C$ and C/N exhibit a major peak there.

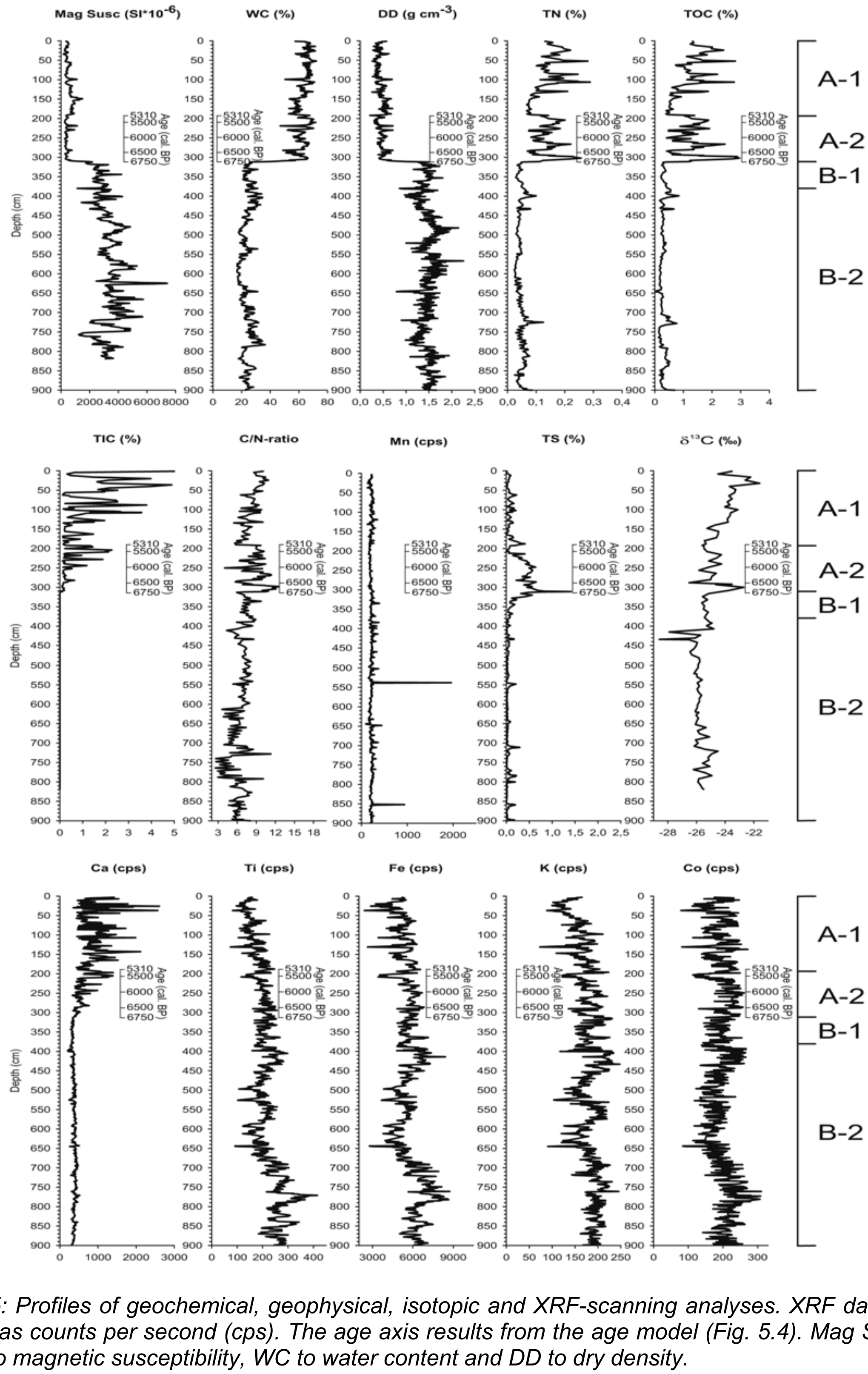

Fig. 5.5: Profiles of geochemical, geophysical, isotopic and XRF-scanning analyses. XRF data is plotted as counts per second (cps). The age axis results from the age model (Fig. 5.4). Mag Susc refers to magnetic susceptibility, WC to water content and DD to dry density.

4.4.3. Lithological unit A (above unconformity)

At 308 cm sediment depth an XRD analysis shows the presence of calcite, chamosite, illite-montmorillonite, plagioclase, pyrite and quartz. Going further up the record, TS and C/N-ratio continue to show high values (TS until 164 cm, C/N-ratio until 190 cm). At 290 and 250 cm minima occur in C/N-ratio. Towards the top of the record values are significantly lower but C/N-ratios rise again in the uppermost 50 cm. TIC and related Ca show much higher variations than in unit B increasing more and more to the top of the core (Fig. 5.5). A similar pattern is observed for water content, TN and TOC, though the latter two parameters show low values between 190 and 120 cm. Magnetic susceptibility and dry density show slightly higher values at the same depth, although in general values between 311 and 0 cm are low. Ti, Fe, K and Co are decreasing very slowly from 311 cm sediment depth to the top. $\delta^{13}C$ decreases to lowest values at 293 cm, followed by a slight increasing trend from 290 cm to 132 cm. From there values begin to rise more rapidly to the highest values of the record between 32 and 16 cm sediment depth (Fig. 5.5).

5. Interpretation and discussion

5.1. Chronology

The age model above the unconformity (lithological unit A-2) is based on three AMS ^{14}C-dates using the medians of the 2σ-probability distribution calculated with the southern hemisphere calibration curve (McCormac et al., 2004). As a line connecting the medians of the dates at 191 and 311 cm sediment depth would not intersect the 2σ-probability of the date at 266 cm, a linear regression (y=0.0834x-251.8) of the three medians was calculated to form the age model (R^2=0.97). This intersects the 2σ-ranges of all three dates (Fig. 5.4). The calculated ages derived from that age model for the respective depths are given in Tab. 5.1 as cal. BP. Based on this approach the sedimentation rate between 191 and 311 cm is 0.83 mm a^{-1}.

Above 191 cm no organic macroremains for radiocarbon dating were found (Fig. 5.3, 5.4). If sedimentation would have continued with the same rate (0.83 mm a^{-1}) until the top of the core, about 3000 years or 3.6 m would be missing. However, according to observations in the field the sediment/water-interface was well preserved and forms the top of the sediment record (i.e., the coring date in March 2003). Therefore, either the sedimentation rate decreased after 5310 cal. BP (191 cm) to less than 0.35 mm a^{-1} (Fig. 5.4) or there is one large or several smaller hiatuses due to erosion or non-deposition.

A date obtained at 372 cm is in the same age range as the date at 311 cm (Fig. 5.3, 5.4, Tab. 5.1). However, proxy data suggest that lithological unit B-1 already belongs to the lower part of the core (Fig. 5.5) which apparently is much older. The dated stems of aquatic mosses yielded only 0.23 mg of carbon for AMS-dating, instead of the normally necessary 1 mg carbon. Nevertheless, the age of the sample might be correct as in most cases a lower carbon content only affects precision, i.e., the error increases (Goslar, 2005) but not the accuracy of dating. For that reason, the date at 372 cm was accepted and perturbation of the sediment during deposition is assumed for the section between 311 and 372 cm (Fig. 5.4), resulting in a reworked layer. In the reworked layer younger plant remains were incorporated into older minerogenic sediment with similar properties as the sediment below the unconformity. The reworked layer was probably deposited very rapidly during a lake transgression as the shoreline passed the coring location. This means the reworked layer was formed before more pelagic Holocene sediment deposition started.

The idea that unit B-1 consists completely of a palaeosoil was abandoned due to the fact that the datings at 311 cm and 372 cm show only slightly different results though they are 61 cm apart and the dating at 372 cm was performed on stems of aquatic mosses and not on roots. Therefore, the cover of 61 cm also containing organic macro remains (detritus) which was not in situ had to form very rapidly. As the 2σ-probabilities of the dates at 311 and 372 cm are overlapping and a clear boundary is visible in the proxy data (Fig. 5.5) and in the lithology (Fig. 5.3), the law of superposition is applied, which means that the lower dating is older than the upper. Therefore, for 372 cm (Tab. 5.1) the median of the maximum age of that dating and the calculated age (i.e., cal. BP in Tab. 5.1) of the dating at 311 cm was chosen (6790±40 cal. BP). The reworked layer is delimited to the top by the marked shifts in all data above 312 cm and to the base by an undisturbed tephra layer at 379 cm.

Below 379 cm sediment depth material suitable for radiocarbon dating was only found at 728 cm depth. To get an idea of the age of the whole section below 379 cm, a similar sedimentation rate as calculated for the age modeled section between 191 to 311 cm (0.83 mm a^{-1}) was assumed as a first approximation. Based on the uncalibrated age of 44,800 BP at 728 cm and the assumed sedimentation rate of 0.83 mm a^{-1} the theoretical time span covered by the section from 379 to 900 cm reaches from 40,610 BP to 46,860 BP (Fig. 5.4). This first approximation might overestimate this time span as sediment is much coarser than in the Holocene section. Hence, the sedimentation rate might be higher and consequently the time span shorter. However, a similar tephra as the one at 379 cm is not contained in a core from the center of Laguna Potrok Aike, continuously spanning the last 13.5 ka BP. Therefore the transition between lithological unit B-1 and B-2 is definitively older.

Based on this chronology the record can be divided into four parts (Fig. 5.4) which are consistent with the lithological units (Fig. 5.3):

B-2: Pleistocene (OIS 3) section with a dating of 45 ka BP at 728 cm (900-379 cm),

B-1: reworked layer (378-312 cm),

A-2: mid-Holocene section of continuous sedimentation (311-191 cm),

A-1: late Holocene section of either low sedimentation rate (0.35 mm a^{-1}) or discontinuous sedimentation (190-0 cm).

5.2. Tephrochronology

The age of the tephra deposited at 379 cm sediment depth has been roughly constrained by extrapolation at approximately 40 ka BP. The bimodal glass chemistry and the mineralogy in combination strongly support a correlation with an eruption of the Reclús volcano, even though potassium values were slightly lower for Late Pleistocene and Holocene tephra products (Fig. 5.6).

The major-element chemistry of the tephras deposited at 643 and 859 cm sediment depth clearly clusters within the Mt. Burney pyroclastic field evidencing an origin from this volcano (Tab. 5.2 , Fig. 5.6). According to the preliminary age estimation described above both tephras were erupted shortly before and after 44.8 $\pm$ 2 ka BP.

Even though independent datings of tephra layers for improvement of the sediment chronology are not available at the moment, the correlations of Laguna

Potrok Aike tephras to distinct volcanic sources help to increase the knowledge of the explosive activity of southern Patagonian volcanoes during OIS 3. The results of tephrochronological investigations, for instance, imply that at least Reclús and Mt. Burney were explosively active between 40 and 50 ka BP. According to the thicknesses of tephra layers in the Laguna Potrok Aike sediment core and the maximum grain sizes of their components, large volumes of tephra have been erupted and dispersed to an easterly direction suggesting a predominance of westerly winds similar to today during the last Glacial/Interglacial cycle in this region. Even the petrological features of erupted magmas – particular from the Mt. Burney volcano - did not change significantly during this time period.

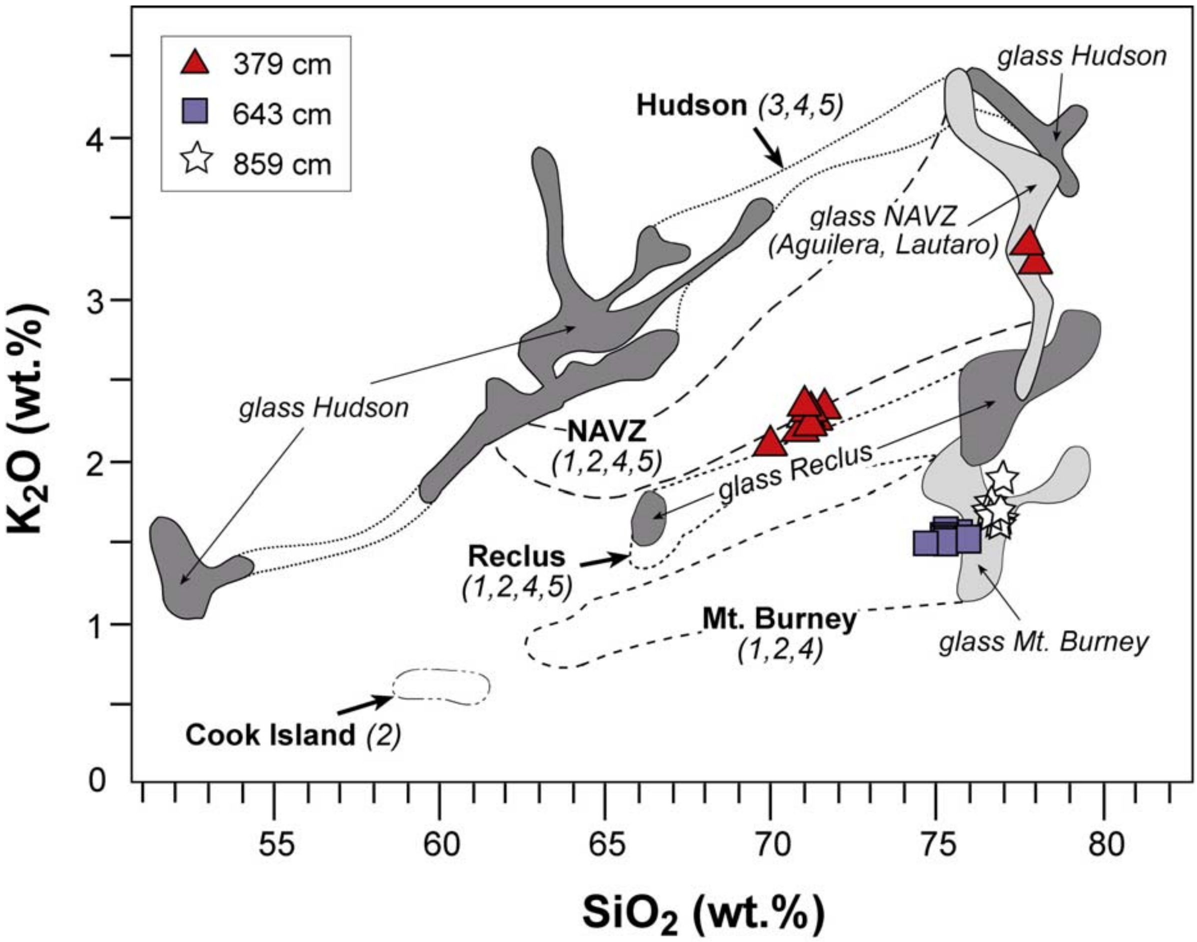

Fig. 5.6: Biplot of SiO_2 vs. K_2O for single glass shards extracted from Laguna Potrok Aike tephras at 379 cm (triangles), 643 cm (rectangles) and 859 cm (stars) compared to the mean oxide concentrations of tephras derived from southern Patagonian volcanoes (geochemical envelopes = EPMA data of juvenile glass; dashed lines = whole rock XRF data). Data are from: (1) (Stern, 1990); (2) (Stern and Kilian, 1996); (3) (Naranjo and Stern, 1998); (4) (Kilian et al., 2003b); (5) (Bitschene and Fernandez, 1995).

5.3. Hydrological variability

The interpretation and discussion starts with lithological unit A-2, 311-191 cm, for which a good age control is available in order to explain the interdependence of some proxies on the basis of continuous deposition. This becomes essential for sections without continuous age control which will subsequently be discussed. Hence, lithological units A-2 and A-1 (Holocene) will be discussed prior to the lithological units B-2 (OIS 3) and B-1 (Reworked Layer).

5.3.1. Lithological unit A-2

Lithological unit A-2 represents the first continuously deposited Holocene sediment at the coring position. This means that the lake level after the transgression above the terrace was high enough to prevent disturbances at the sediment surface, i.e., wave erosion at the shoreline as well as disturbance at the base of waves in the littoral zone. Thus, the lake level should have been at least 3 to 5 m above the coring location as erosion of beach sediments usually starts at the base of the wave which theoretically can reach 5 m (Sly, 1994) if preconditions given at Laguna Potrok Aike are taken into account. Today aquatic macrophytes start to grow at a water depth of 2 to 3 m suggesting recent disturbances to that depth. As indicated by higher TIC, TOC, TN and C/N-ratios, the lake level was still quite low in comparison to lithological unit B and the lower part of A-1.

The high C/N-ratios, which were used as an indicator of palaeoshoreline proximity for a short core from the center of Laguna Potrok Aike (Haberzettl et al., 2005) as well as for Lake Victoria, East Africa (Meyers and Teranes, 2001) point to the closest distance of the coring location to the shoreline of the entire recovered record (Fig. 5.5). C/N-ratios allow to distinguish between higher plant (aquatic macrophytes, terrestrial vegetation) and algal and soil material (Mayr et al., 2005). For Laguna Potrok Aike this assumption is based on the knowledge that terrestrial and littoral aquatic plants show high C/N-ratios above 24 (Haberzettl et al., 2005) and can therefore be distinguished from planktonic algae which typically have C/N-ratios between 4 and 10 (Meyers, 1997, 2003; Meyers and Teranes, 2001). Similar observations were made for Laguna Azul (Fig. 5.1), located approximately 60 km further to the east (Mayr et al., 2005). In Laguna Potrok Aike, C/N-ratios between

312 and 290 cm (6750-6500 cal. BP) are highest (Fig. 5.5) and reflect higher contributions of terrestrial and aquatic macrophytes, i.e., a rising lake level still close to the coring location. Peaks in TN and TOC during that time (Fig. 5.5) point towards erosion of plants at the littoral belt by wave action and accumulation at the coring location, which is easier to perform if the shoreline is not too far away. Further evidence for this is given by the higher amount of plant debris in this core section (Fig. 5.3). This interpretation is supported by the $\delta^{13}C$-values (Fig. 5.5), which were also identified as a sensitive parameter for palaeoshoreline proximity for Laguna Potrok Aike (Haberzettl et al., 2005) and Laguna Azul (Mayr et al., 2005). Most positive $\delta^{13}C$-values are observed between 311 cm and 290 cm (6750-6500 cal. BP) possibly indicating higher contributions of organic matter from aquatic macrophytes, which have $\delta^{13}C$ values between -10 and -16‰ at Laguna Potrok Aike. Thus, shallow water habitats (in which the aquatic macrophytes live) still were close to the coring location (Fig. 5.5).

TIC and Ca representing autochthonously precipitated $CaCO_3$ which was identified as a sensitive lake level (water volume) indicator (Haberzettl et al., 2005), support a rising lake level (Fig. 5.5) in this interval. Due to concentration and dilution processes the relationship between those proxies and lake level is simple: high TIC/Ca values point to a low lake level and vice versa (Haberzettl et al., 2005). This is based on calcite precipitation during concentration (=lake level lowering/low lake level) and no precipitation during times of dilution (=lake level rise/high lake level). In this case low values probably indicate a lake level rise with minor stagnations or lake level lowerings which cause brief intervals of low $CaCO_3$ precipitation.

Around 290 cm (6500 cal. BP) all mentioned parameters indicate a distinctly higher lake level than before (Fig. 5.5). Above 290 cm, until 191 cm (6500-5310 cal. BP) all proxies are oscillating rapidly indicating a variable lake level (Fig. 5.5).

In many aquatic systems allochthonous clastic input is characterized by higher Ti and Fe contents (Haug et al., 2003; Haug et al., 2001). For Laguna Potrok Aike correlations of Ti with Fe, K and Co (R^2=0.69, 0.65 and 0.50) allow the same conclusion for K and Co. At this lake the allochthonous input is associated with run-off and hence hydrological variability (Haberzettl et al., 2005). In lithological unit A-2 the highest values of the entire Holocene for all four elements occur. Decreasing values from 311 cm to about 200 cm (ca. 5500 cal. BP), where they have a distinct minimum (Fig. 5.5), indicate a tendency to reduced fluvial detrital input and hence either stagnancy in transgression or a dropping lake level. Nevertheless, the other parameters point to a variable lake level during this interval. Ca and TIC support a lake level lowering or stagnation at ca. 5500 cal. BP.

Elevated TS values indicate oxygen-poor to anoxic conditions in the sediment of this unit (Fig. 5.5). This assumption is based on an XRD analysis at 308 cm sediment depth, which reveals the presence of pyrite (FeS_2). Therefore, it is assumed that the sulfur present in this section is mainly incorporated into pyrite, which forms under oxygen-restricted conditions (Wignall et al., 2005) in association with organic matter decomposition (Gore, 1988). This does not imply that the lake water above the sediment was anoxic (Gore, 1988). Pyrite can also form below the sediment/water interface in organic-rich sediments deposited in oxygenated water (Cohen, 2003; Gore, 1988). By rapid deposition of minerogenic matter (indicated e.g., by Ti) an oxygen impermeable layer might develop. The impermeable layer leads to anaerobic decomposition of deposited organic matter in interstitial waters, resulting in reducing anaerobic conditions (O´Neil, 1998) that can induce pyrite formation (Degens, 1968; Wignall et al., 2005). Therefore, as Ti, Fe, K and Co and hence minerogenic input decrease, e.g., around 200 cm (ca. 5500 cal. BP), TS decreases as well.

5.3.2. Lithological unit A-1

There are two possible reasons for the distinct change in sedimentation rate above 191 cm (Fig. 5.4): (1) sediment supply was significantly reduced, either due to a higher lake level enlarging the distance to the shore and thus leading to less deposition or due to less input to the lake. Alternatively, (2) there were regressions of the lake level causing the formation of unconformities. Considering a constant sedimentation rate and interruptions in sedimentation (non-deposition) without significant phases of erosion the sum of the breaks would have lasted approximately 3000 years. This value is derived from the intersection of the extrapolated regression of the dated Holocene section (unit A-2) with the sediment surface (Fig. 5.4). Accordingly, if erosion is considered as well, this time span would be shorter.

However, neither lithology (Fig. 5.3) nor seismic investigations (e.g., Fig. 5.2) yielded evidences for unconformities in this lithological unit. Low TS values indicate a lower sedimentation rate than in lithological unit A-2. Attempts to correlate this section with cores from the center of the lake (Mayr et al., unpublished data) with respect to $\delta^{13}C$ reveal a similar trend. Nevertheless, the absence of unconformities cannot be excluded completely.

The low values of TIC, C/N-ratio, TOC, TN and $\delta^{13}C$ (Fig. 5.5) at the bottom of this unit and the trend to higher values towards the top, beginning at 132 cm sediment depth, point to an initially high lake level followed by a regression. A lower lake level close to the top of the core especially becomes evident if $\delta^{13}C$ is regarded (Fig. 5.5): at 311 cm, the depth where undisturbed Holocene sedimentation initiated, values for this palaeoshoreline proximity indicator are very high. At that time the lake shore was close to the coring location causing those high $\delta^{13}C$-values due to deposition of aquatic macrophytes. At a depth of 16 to 32 cm values for $\delta^{13}C$ are even higher (Fig. 5.5) implying that the lake shore was also very close to the coring location and aquatic macrophyte debris was deposited. Towards the top of the core, Ti, Fe, K and Co also point to less minerogenic sediment supply and hence less fluvial input and drier conditions (Fig. 5.5). This is in agreement with the absence of glacier extensions larger in extend than the “Little Ice Age” moraines during the last 5000 years at Gran Campo Nevado (53°S, Fig. 5.1) located southwest of Laguna Potrok Aike (Kilian et al., 2003). Due to the lack of datable material it was impossible to present the course of the regression in greater temporal detail. Finally, a lower sedimentation rate due to a high lake level enlarging the distance to the shore and hence leading to less deposition followed by a regression with less minerogenic input might be most conceivable.

5.3.3. Lithological unit B-2

Assuming that during glacial times $\delta^{13}C$, TIC, Ca and C/N-ratio can be used as lake level indicators in the same way as in the Holocene, the lake level was high during OIS 3 (Fig. 5.5). The high lake level during that time may point to a less arid climate or less evaporation (due to e.g., higher relative humidity, less wind or seasonal ice cover). A high lake level of Laguna Potrok Aike at this time coincides with a dust minimum of the Vostok ice core, where the source of the dust was ascribed to Patagonia (Basile et al., 1997; Petit et al., 1999). In the Vostok and Epica records dust mobilization is more prevalent during OIS 2 and 4 whereas lower concentrations and fluxes of dust occur in interglacials and interstadials (Delmonte et al., 2004; Petit et al., 1999; Petit et al., 1990).

The generally higher values of Ti, Fe, K and Co in Laguna Potrok Aike produce further evidence for this hypothesis and might be explained by the fact that during colder conditions vegetation cover was markedly reduced. Therefore, material in the catchment was eroded and transported to the lake. The reduced plant cover might also be responsible for high values of dry density and magnetic susceptibility (Fig. 5.5), both commonly associated with allochthonous input (Geiss et al., 2003; Thompson et al., 1975).

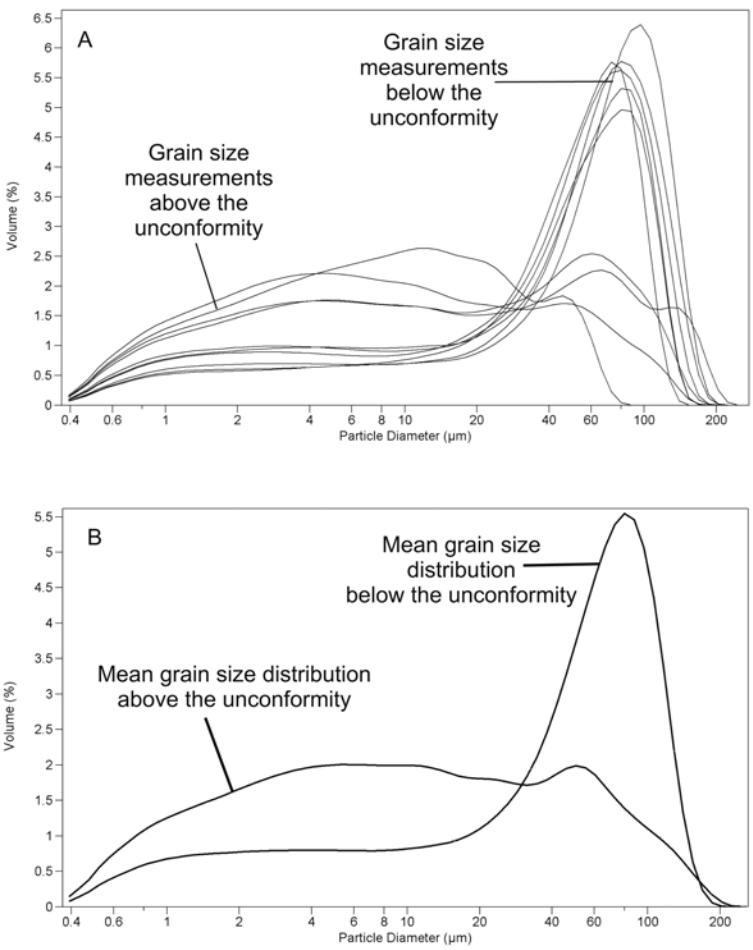

Fig. 5.7: Differences in grain size distribution above and below the unconformity. In A all measurements are displayed, B shows the mean grain size distribution. Note different scaling in A and B.

At Laguna Potrok Aike OIS 3 sediments consist of coarse silt and fine sand (Fig. 5.7). Those sediments are the first to be moved by wind and kept in suspension (Tucker, 1991). Magnetic susceptibility varies with the magnetite grain-size usually showing distinct maxima at around 0.02 µm and between 25 and 100 µm (Dearing, 1994). The latter spectrum matches with the peak of the grain-size distribution of the OIS 3 section in Laguna Potrok Aike (Fig. 5.7). Between the two areas of increased magnetic susceptibility values are rather low. This is in agreement with the mean grain-size distribution above the unconformity in Laguna Potrok Aike, which is almost equally distributed from 0.4 to 200 µm (Fig. 5.7). Though the interval between 25 and 100 µm is also contained in the grain-size distribution above the unconformity, there is some kind of diluting effect of material of smaller grain-sizes (Fig. 5.7). Due to the reduced vegetation cover higher amounts of dust compared to the Holocene should have been transported to the lake. This would be in agreement with a higher amount of dust during OIS 3 than today in the Vostok record (Petit et al., 1999; Petit et al., 1990). Comparisons between the Vostok ice core record and magnetic susceptibility measured on a loess sequence in China showed similar results with high magnetic susceptibility values during glacial periods with loess accumulation (=dust maxima in ice core) and low magnetic susceptibility values in intercalated interglacial soils (Petit et al., 1990). If the origin of the sediments deposited during OIS 3 could mainly be attributed to aeolian transport of loess-like material, this would explain the higher values of magnetic susceptibility as this parameter may register changing sediment sources for lake sediments (Dearing, 1994) or a different transport mechanism. In this case magnetic susceptibility might be used as a dust indicator. Unfortunately, neither sediments from the Last Glacial Maximum (OIS 2) nor from OIS 4, when dust fluxes were even higher in the Vostok record (Petit et al., 1999; Petit et al., 1990), have been recovered from Laguna Potrok Aike so far to test whether magnetic susceptibility values were higher during those times.

5.3.4. Lithological unit B-1

The thickness of the reworked layer is hard to determine. As far as $\delta^{13}C$, C/N-ratio, TOC, TN, Ca, Ti, Fe, K and Co are concerned, it seems to proceed from 312 to 407 cm. At this depth a distinct change takes place in those parameters. Above values are almost constant (Fig. 5.5). However, at 379 cm a tephra layer was found. If the sediment was already in a state of mixing, this tephra would have been reworked and probably been diluted. Furthermore, below the tephra no organic macrophytes were detected whereas there were plenty above (Fig. 5.3). Therefore, the tephra is regarded as lower boundary of the reworked layer. The change in the proxies at 407 cm sediment depth hence has to be addressed to some other event. After this event, sedimentation went on until the tephra was deposited. Due to erosion, mixing and (re)deposition the homogeneity, visible in almost all proxies of lithological unit B-1 can be explained (Fig. 5.5).

The radiocarbon date of 6790±40 cal. BP in lithological unit B-1 gives an idea when climate became more humid (hydrological change). This resulted in a significant lake level rise leading to erosion of a mixture of mid-Holocene plant macro remains and eroded OIS 3 minerogenic sediments and deposition onto much older OIS 3 material as the lake shore passed by during transgression. The date 6790±40 cal. BP is a minimum age of the onset of transgression, because the lake level was probably lower than the -30 m level of the coring site. During the previous dry phase, the lake level either dropped at or below the lake level terrace and eroded parts of the previously deposited sediment forming the erosional unconformity.

The occurrence of this dry phase prior to 6790±40 cal. BP is in agreement with analyses of sediment cores (Gilli, 2003; Markgraf et al., 2003) from Lago Cardiel (49°S) which yield evidence for an increased influx of freshwater between 7100 and 5500 cal. BP (Gilli, 2003).

6. Conclusions

The sediment record from the subaquatic lake level terrace of Laguna Potrok Aike can be divided into 4 lithological units. A Pleistocene section (OIS 3, B-2) with an age of about 45 ka BP, a reworked layer (B-1), a dated mid-Holocene section (A-2) covering the time interval from 6750 to 5310 cal. BP and a section without a confirmed age control due to a lack of aquatic macrophytes suitable for dating above (late Holocene, A-1). Results of a multi-proxy study of sediment core PTA03/6 display sediment deposition at more than 70 m above the recent lake floor during OIS 3 giving evidence for a high lake level. The latter extends the sediment record from the center of Laguna Potrok Aike covering the last 13.5 ka BP (16.000 cal. BP) further back in time and emphasizes the potential of Laguna Potrok Aike for long-term palaeoclimate reconstructions. In comparison to the Holocene section, however, geochemical indicators of dominant allochthonous material point towards a different sediment source or to a different transport mechanism probably triggered by a less dense vegetation cover during OIS 3. Between OIS 3 and 6790 cal. BP the lake level either remained lower than the lake level terrace or deposited material was eroded. The radiocarbon date of 6790 cal. BP in the reworked layer gives a minimum age for a hydrological change, leading to a higher lake level again, as the rising lake level needed some time to reach the elevation of the coring location. This event is marked by an unconformity in a seismic profile showing sediments dipping towards the lake center below and horizontally laminated sediments above. This geomorphological/ geophysical evidence is extremely helpful for the interpretation of the hydrological parameters measured on the sediments from the center of Laguna Potrok Aike. The lake level remained near the coring location or was slowly rising until 6500 cal. BP. Then it rose considerably. Subsequently, conditions were unstable. Some time after 5310 cal. BP the climate becomes drier again. After that date no material suitable for radiocarbon dating was found which inhibits a precise dating of the regression. Proxies indicate less minerogenic sediment supply to the lake after 5310 cal. BP which might be an explanation for the low sedimentation rate.

The three tephra layers recovered from PTA03/6 are restricted to the Pleistocene. Geochemical and petrophysical data indicate that these tephras are derived from Mt. Burney and Reclús. None of them has been previously described. These results imply that at least the mentioned AVZ volcanoes were explosively active between 40 and 50 ka BP. Thus, there is a high potential for tephrostratigraphical studies in southern Patagonia and the western part of the South-Atlantic Ocean that requires further volcanological and tephrochronological efforts.

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Chapter 6:

Conclusions and Outlook

Conclusions

The presented studies on sediments from Laguna Potrok contain hitherto unprecedented continuous high-resolution information of paleoenvironmental change in southern Patagonia. Investigations on a one meter short core gave an insight to natural and anthropogenically induced paleoenvironmental variations during the last two millennia (Chapter 2, 3). A 19 m long core from the center of Laguna Potrok Aike extended the covered time span to the last 16,000 years (Chapter 4). Further information was inferred from a 9 m long core from a subaquatic lake level terrace. Here, sediments below an erosional unconformity enabled insights into paleoenvironmental conditions during Oxygen Isotope Stage 3 (Chapter 5).

Studies of the maar lake Laguna Potrok Aike demonstrate that this lake presents an outstanding archive for hydrological variations in southeastern Patagonia with excellent dating opportunities. Though the first dating results performed on the short core showed only moderate results, they demonstrate that bulk samples are not suited for dating sediments from Laguna Potrok Aike. In contrast, dates of TIC turned out to be valuable. Omitting bulk samples, the age-depth models of all cores analyzed in this study are consistent.

The geochemical and sedimentological studies of sediment cores from Laguna Potrok Aike reveal numerous climatic as well as anthropogenic changes in the steppe environment of Patagonia during the last 16,000 cal. BP and Oxygen Isotope Stage 3. The multi-proxy approach of SALSA helped to prevent misinterpretation and contributed significantly to the understanding of individual parameters. In the course of analyses and interpretation of the short core from Laguna Potrok Aike TIC, Ti, $\delta^{13}C$ and C/N-ratio turned out to be lake level indicators reflecting hydrological changes in southern Patagonia. During further studies Fe/Mn-ratio, Ca/Ti-ratio, gastropods, differences in sedimentation rate and occurrence of monohydrocalcite also demonstrate to be interpretable with respect to the hydrological regime. The results of those proxies were confirmed by age determinations of subaerial and subaquatic lake level terraces. The latter were investigated with various seismic systems.

Based on these results, the following climatic/hydrologic scenarios have been inferred: A high lake level is suggested for Oxygen Isotope Stage 3 for southeastern Patagonia. Unfortunately, no information is available between Oxygen Isotope

Stage 3 and 16,000 cal. BP as the recovered sediment cores do not encompass this time span. During the Late Glacial the lake level was very high, probably resulting in surface outflow. First evidences of a lake level recession are identified between 13,100 and 11,400 cal. BP. From 12,800 cal. BP until 11,400 cal. BP a major warm(ing) phase is recorded in Laguna Potrok Aike giving terrestrial evidence from southern South America for a potentially southern hemisphere-wide phenomenon. Unfortunately, the record of Laguna Potrok Aike does not comprise information about cold events like the Antarctic Cold Reversal or the Huelmo-Mascardi Cold Reversal.

From 11,400 cal. BP to 8,650 cal. BP conditions are humid (high lake level). Afterwards, the lake level dropped to the lowest position hitherto manifested in the investigated sediments. Since 6,750 cal. BP there is evidence for a pronounced lake level rise. Afterwards, the lake level was extremely variable but comparatively low with a few distinct wet periods in between. The last humid time span ascribed to the Little Ice Age was the temporally most extended since the early Holocene lake level highstand before 8,650 cal. BP. The record also suggests that Medieval drought conditions (Medieval Climate Anomaly) commenced much later than proposed before for southern South America, i.e., from the mid 13th to the 15th century.

In addition to hydrological variations the record also gives an idea about the anthropogenic impact in the vicinity of Laguna Potrok Aike. European influence is detectable in the sediment composition (with respect to pollen, charcoal and various geochemical parameters) of Laguna Potrok Aike a long time before the first sheep farmers arrived in the late 19th century. However, after their arrival the impact increased distinctively.

The different studies performed also contain information about the past explosive activity of volcanoes of the Patagonian Andes. In addition to the already known eruptions of Hudson, Mt. Burney and Reclús which were used for the age-depth model of the long core from the deepest part of Laguna Potrok Aike, three hitherto undescribed tephra layers, one from Reclús and two from Mt. Burney were found below an erosional unconformity in the core from a subaquatic lake level terrace. Those were roughly dated to Oxygen Isotope Stage 3 and give evidence for explosive activity of those volcanoes during the last glacial period.

Comparisons of the presented sediment records from Laguna Potrok Aike to other terrestrial archives from the Patagonian steppe, especially to Lago Cardiel, point to a uniform climatic behavior, perhaps slightly shifted in time. Due to the multi-proxy approach of SALSA, and especially due to the high-resolution of geochemical analyses as performed here, it was possible to obtain climatic information in an unprecedented resolution for southern Patagonia.

Comparisons with Andean archives reveal an opposite hydrological pattern. This is probably based on the fact that intensification of the Southern Hemisphere Westerlies results in increased precipitation in the Andes and drier conditions to the east due to an enhanced lee effect. In contrast, periods with less strong westerly winds allow precipitation carrying easterly wind from the South Atlantic Ocean to proceed to the inner steppe area of Patagonia where Laguna Potrok Aike is located.

Outlook

Based on the promising results of the multi-proxy approach of SALSA applied to the sediments of Laguna Potrok Aike and confirmed by various seismic studies deploying 3.5 kHz, 2 cu-inch airgun and sparker seismics as well as refraction and multi-channel reflection seismics with a 40 cu-inch airgun system a proposal for an ICDP (International Continental Scientific Drilling Program) deep drilling project is in preparation. Within the project PASADO (Potrok Aike Sediment Archive Drilling Project) this proposal aims to employ the GLAD800 coring device which is able to recover sediments from a depth of up to 800 m below the lake surface (including the water column). A workshop about PASADO will be held in Río Gallegos (80 km east of Laguna Potrok Aike, Argentina) in March 2006. This workshop brings together more than 50 international scientists to fine-tune analytical strategies and to develop the time schedule and outline for the full drilling proposal. In case of realization of PASADO, Laguna Potrok Aike will, with the exception of Lake Titicaca, be the hitherto only ICDP deep drilling location for South

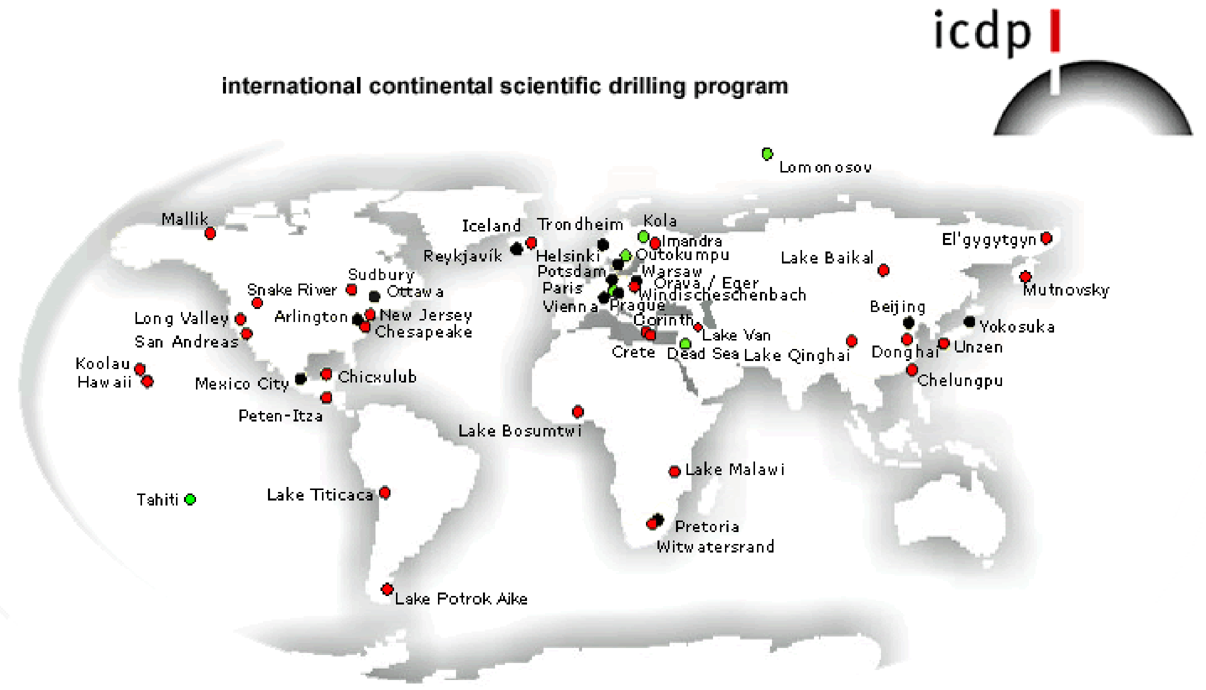

Fig. 6.1: Distribution of ICDP drilling sites (www.icdp-online.de - last access 25.01.2006, modified).

America (Fig. 6.1). Furthermore, it will be the southernmost ICDP project worldwide. Obtained data, subsampled with high-resolution, will provide ideal means of linking this record to other long terrestrial archives like ice cores from Antarctica (EPICA community members, 2004; Gabrielli et al., 2005; Petit et al., 1999; Petit et al., 1990) and marine records (Kaiser et al., 2005; Lamy et al., 2001; Lamy et al., 1999; Lamy et al., 2004) from the southern oceans in an inter-archive comparison.

Further studies on the sediments already recovered from Laguna Potrok Aike will concentrate on the evaluation of OSL dates sampled in 2004 (analyses are still in progress), on the identification of chironomids in collaboration with J. Massaferro (Natural History Museum, London) and alkenones in collaboration with S. Hanisch (AWI, Bremerhaven), on the interpretation of grain-size analyses performed during this study as well as on the examination of more than 50 short cores (ca. 30-50 cm each). The latter ones have been sampled in a grid during austral summer 2005 and will yield spatial information about recent depositional processes inside the lake. This information will be completed by ongoing monitoring activities (sediment traps, thermistors, a pressure sensor, water profiles and a weather station) which already started in 2002 (Mayr et al., subm.; Zolitschka et al., in press). Further studies of the SALSA team will concentrate on Lago del Desierto, Laguna Cháltel, Laguna las Vizcachas and Laguna Azul in order to obtain a more regional idea of the paleoenvironmental history in southern Patagonia.

Fig. 6.2: Sites with future perspectives for the SALSA team.

A similar approach with the aim of a regional understanding was submitted by the author to the German Science Foundation (DFG). This project is called EAGLES (East Andean Glacial Lake Sediments) and is pending. In case of funding a short core survey will be performed in glacial lakes located on a N-S-transect along the eastern side of the Andean Cordillera. The aim of this project is to obtain archives with high, ideally annual resolution to further understand the climatic history in southern Patagonia on a supra-regional scale for the last millennium.

In the framework of the MIDHOL project statistical downscaling models have already been formulated and applied for Laguna Potrok Aike for the recent climate and transient climate simulations with a coupled general circulation model for the Mid-Holocene. Future investigations are intended to focus on numerical downscaling methods including regional model simulations for southern South America that also allow to investigate extent and magnitude of climate change at (sub-)regional scales.

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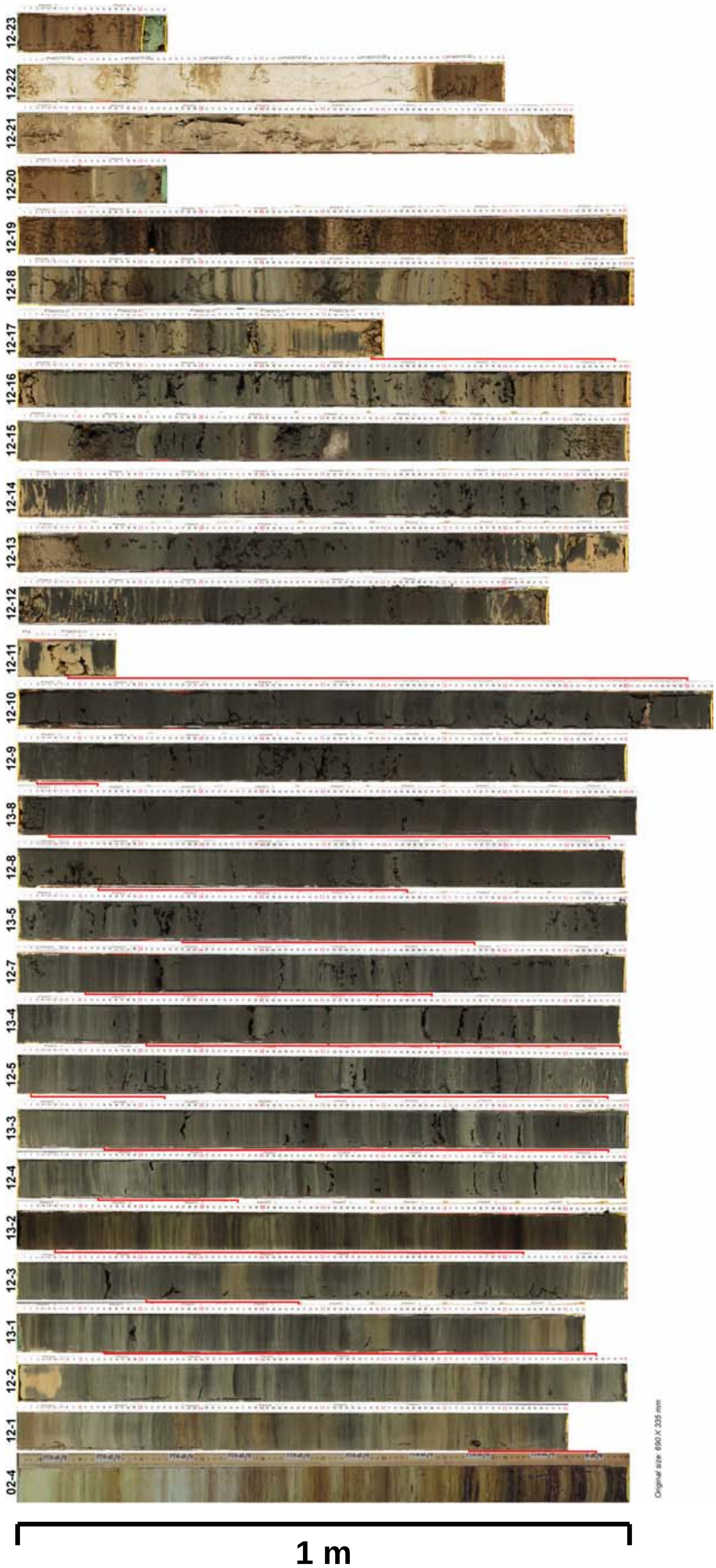
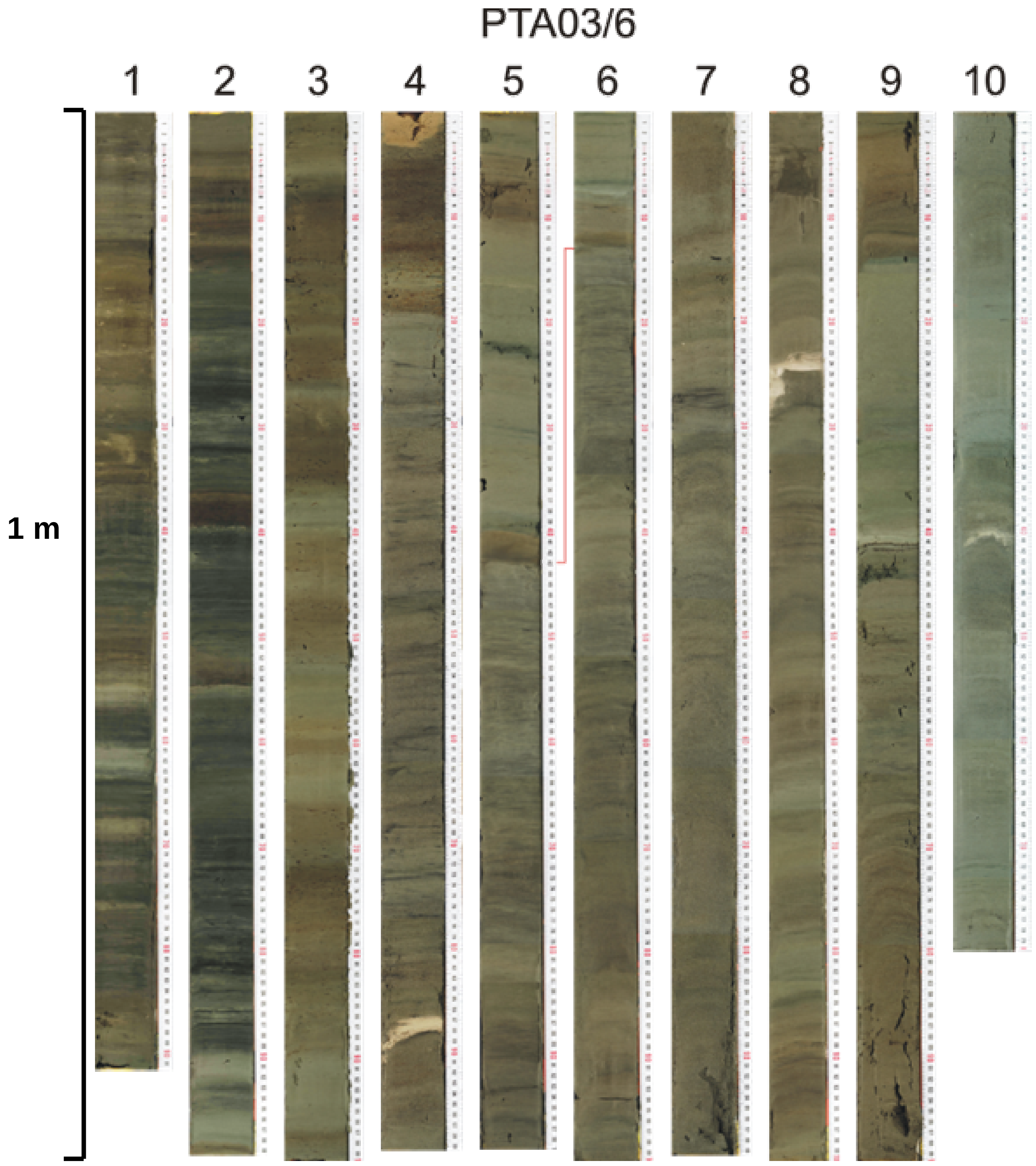
Appendix

A-1: *Composite of cores PTA02/4, PTA03/12 and PTA03/13 from the center of Laguna Potrok Aike.*



A-2: Core PTA03/6 from a subaquatic lake level terrace.



A-3: Data presented can be obtained from the author on request.