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ORIGINAL PAPER

Southern hemispheric westerlies control the spatial distribution of modern sediments in Laguna Potrok Aike, Argentina

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Abstract We studied the internal lake processes that control the spatial distribution and characteristics of modern sediments at the ICDP (International Continental Scientific Drilling Program) deep drilling site in Laguna Potrok Aike, southern Patagonia, Argentina. Sediment distribution patterns were investigated using a dense grid of 63 gravity cores taken throughout the lake basin and 40 additional shoreline samples. Analysis of the surficial sediment distribution points to distinct internal depositional dynamics induced by wind-driven lake internal currents. Distribution maps illustrate that the spatial characteristics of analysed variables are linked to high erosional wave activity. Persistent wave action and littoral erosion along all shores, especially the eastern shore, is caused by prevailing Southern Hemispheric Westerlies. Several sediment variables (grain size, benthic diatoms, total inorganic carbon and calcium) indicate re-suspension of littoral sediment followed by re-distribution to profundal accumulation areas near the eastern shore. Variations within the catchment influence sediment characteristics in the north-eastern bay. That area is characterized by different mineralogical and sedimentological conditions as well as greater accumulation of pollen, inorganic carbon and diatoms. These findings are related to the influence of episodic inflow into this bay. Spatial differences in stable isotope values throughout the

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lake suggest that ephemeral tributaries around the lake basin may also contribute to the detected spatial sediment variations.

Keywords Spatial sediment distribution · Depositional dynamics · Geochemistry · Stable isotopes · Microfossils · Argentinean Patagonia

Introduction

Among the slowly emerging terrestrial climate archives in southern Patagonia, Laguna Potrok Aike is a palaeolimnological key site. Interdisciplinary multi-proxy sediment studies (Haberzettl et al. 2007; Mayr et al. 2009; Wille et al. 2007) document the sensitivity of this unique lacustrine sediment record to palaeoclimatic and palaeoecological variability in the dry steppe environment of south-eastern Patagonia. On-site monitoring (Mayr et al. 2007; Zolitschka et al. 2006) and palaeoclimatic interpretation based on single-point data from gravity (Haberzettl et al. 2005, 2006) and piston cores (Haberzettl et al. 2009, 2007; Mayr et al. 2009), geomorphological mapping, as well as climatic modelling (Wagner et al. 2007) provide detailed scientific information about climatic variability during the last 55,000 years. Comprehensive seismic surveys of the lake basin yielded further details on the geometry of the sediment infill (Anselmetti et al. 2009).

In contrast to seismic information and single-point long-term sediment core records, studies of mechanisms responsible for lacustrine sediment distribution are rare (Dehnert and Juschus 2008; Hilton and Gibbs 1984; Naya et al. 2005; Whitmore et al. 1996). Areal distribution patterns are more commonly evaluated in marine environments (Brooks et al. 2003; Vilas et al. 2005). To systematically interpret long lacustrine sediment records, it is necessary to understand the dynamic processes that control spatial sediment distributions and characteristics in the lake basin. Laguna Potrok Aike was surveyed using a dense grid of surface sediment samples to evaluate the influences of: (1) lake internal currents, (2) tributaries, (3) geology, and geomorphology on modern depositional processes. Particular attention was given to the impact of the westerly wind belt system (Mayr et al. 2007; Wagner et al. 2007) on the sediment distribution in Laguna Potrok Aike. This study will contribute to detailed interpretation of long sediment records drilled within the framework of the ICDP-project PASADO (Potrok Aike Maar Lake Sediment Archive Drilling Project) in 2008.

Site description

Laguna Potrok Aike is located in the Pali Aike Volcanic Field in south-eastern Patagonia, Argentina (51°58′S, 70°23′W; Fig. 1). The circular maar lake is estimated to have formed ~700 ka ago (Zolitschka et al. 2006). The lake bathymetry reveals a bowl-shaped morphology with a maximum diameter of 3,470 m and a maximum water depth of 100 m. The flat lake floor is separated from the littoral zone by steep slopes and a more gently dipping western flank (Fig. 2). The lake is located in the semi-arid Patagonian steppe environment where annual precipitation is <300 mm. The lake is, thus, mainly groundwater-fed. However, episodic stream runoff enters the lake through gullies and canyons, with main inflow channels located along the north-eastern, south-eastern and western shores (Fig. 2). The terminal lake Laguna Potrok Aike reacts sensitively to changes in the evaporation/precipitation ratio. Lake level rises during wet periods and lake level declines during dry periods (Haberzettl et al. 2008, 2006). Well preserved aerial and sub-aquatic lake level terraces (Anselmetti et al. 2009) document large hydrological variations during the Holocene (Haberzettl et al. 2005) due to changes in precipitation and westerly wind intensities (Mayr et al. 2007) and provide evidence for intense wave action. The predominant influence of westerly winds (Mayr et al. 2007; Prohaska 1976) in recent times promotes continuous wave action and polymictic conditions, with almost no thermal stratification of the water column throughout the year. The longest wind fetch occurs from the north-eastern to eastern shoreline of the lake. Further details about the lake are provided elsewhere (Haberzettl 2006; Zolitschka et al. 2006).

Materials and methods

Sixty-three gravity cores were recovered in 2005 (46 cores) and 2008 (17 cores) (Fig. 2) using an UWITEC corer. The cores were taken within a grid, with only 200–700 m between the individual coring

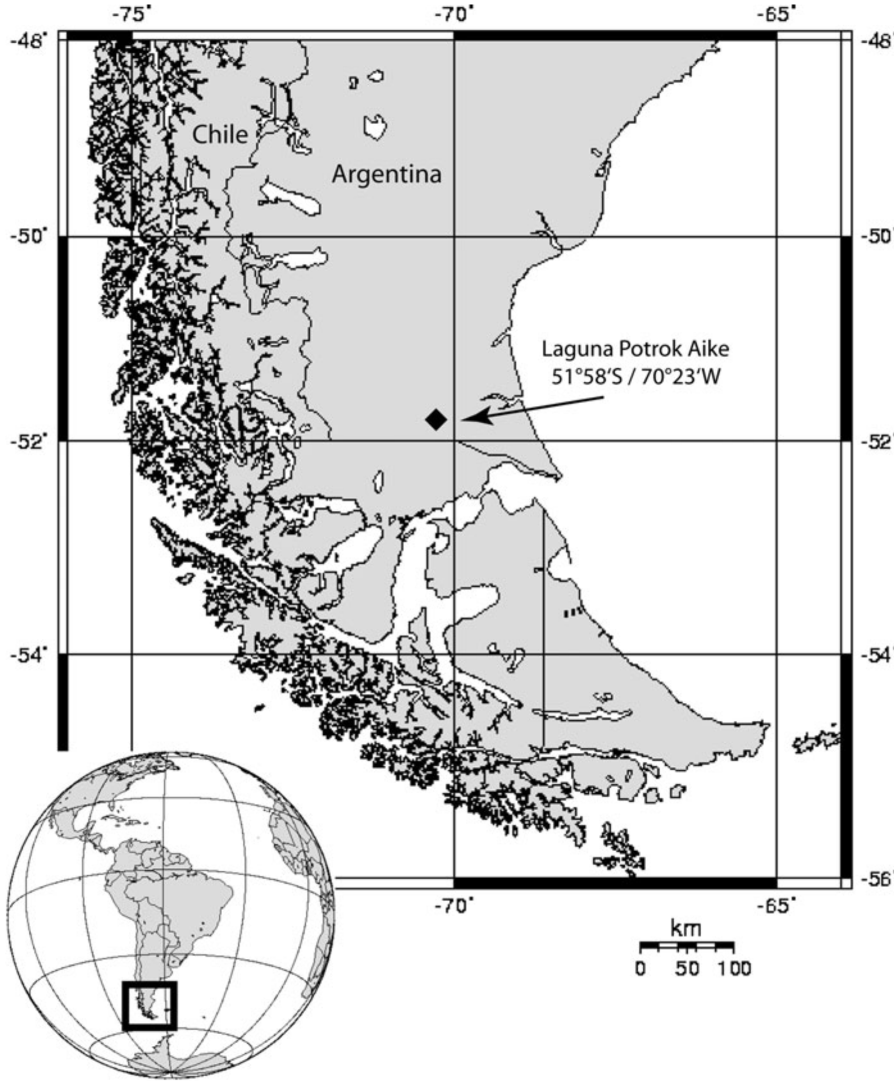

Fig. 1 Location of Laguna Potrok Aike, southern Patagonia, Argentina. Maps were created with Online Map Creation (OMC; http://www.aquarius.geomar.de/omc/)

sites, to achieve equal area coverage of the basin. Ranging up to 49 cm in length, the cores were collected in water depths from 9 to 100 m. This investigation was based on bathymetric and seismic data obtained from Laguna Potrok Aike during four field surveys since 2002 (Anselmetti et al. 2009). Additionally, 40 surface samples were collected along the lake shoreline in 2008 (Fig. 2). All surface sediment samples are considered to represent "modern" deposits.

In the laboratory, sediment cores were stored at +4°C in the dark until they were split, photographed and described lithologically. Non-destructive scanning (Mo tube, 1,000-μm step size) of the split cores for X-ray fluorescence (XRF) was carried out at 1-mm resolution with an ITRAX XRF core scanner (Cox Analytics, Sweden) (Croudace et al. 2006). Ground shoreline samples were measured as separate samples with the same device. Element count rates are given as total counts (cnt). Magnetic susceptibility (MS) measurements were performed with a Bartington point sensor MS2F at 4-mm resolution on split cores. Each value represents the difference between a sediment measurement and the mean of an air measurement prior to and after the sediment measurement to eliminate a possible temperature trend and to account for sensor drift during the measuring time. Values are given as volume specific magnetic susceptibility (κ) in 10^{-6} SI.

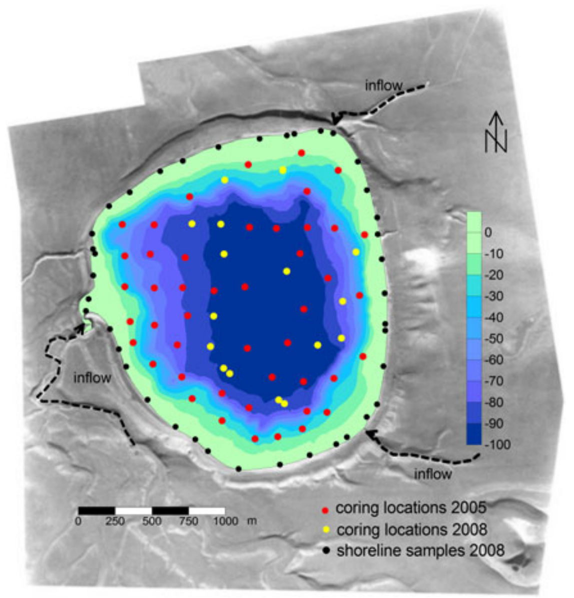

Fig. 2 Bathymetry and aerial photograph of Laguna Potrok Aike with highlighted positions of gravity cores recovered in 2005 and 2008, shoreline sample positions collected in 2008 and marked inflows

Scanning data, photographs and lithology were used to correlate all 63 cores. Only 3 cores, which were missing an intact sediment water interface, could not be correlated. The uppermost centimetre (0–1 cm) from the other 60 cores, representing the last ~10 years, i.e. modern times, was sampled. An overview of the number of cores and samples recovered in 2005 and 2008 and all analysed variables is given in Table 1.

All sediment samples were freeze-dried for determination of water content (WC) and dry density (DD). Furthermore, a ground and homogenized aliquot of each core and shoreline sample was used for determination of total carbon (TC), total nitrogen (TN), and total sulphur (TS) with a CNS analyser (EuroEA, Eurovector). Total organic carbon (TOC) was measured with the same device after samples were treated with 3 and 20% HCl at 80°C to remove carbonates. Total inorganic carbon (TIC) was calculated as the difference between TC and TOC.

For determination of total phosphorus (TP), ~70 mg of each ground and homogenized sample were digested with 6 ml HNO_3 and 2 ml HCl (modified *aqua regia*) in a microwave digestion system (speedwave MWS-3+, Berghof). Samples were heated to 180°C for 25 min. After cooling, the solution was filtered and photometrically analysed with the vanado molybdo-phosphoric acid method (DIN EN 1189).

Grain sizes of all samples were analysed with a laser counter (Coulter Laser Counter LS 200). Samples were sieved to <2 mm, pre-treated with 30% H_2O_2, 10% HCl and NaOH to remove organic material, carbonates and diatoms and thereafter dispersed with $(NaPO_3)_n$.

Another aliquot of the sub-samples was investigated for stable isotopes of organic matter. The sediment was sieved to <200 µm, freeze-dried and homogenized prior to analyses of the carbon and nitrogen isotope signatures of bulk organic matter at the Research Centre Jülich. For total nitrogen isotope ratios ($\delta^{15}N$), the bulk sediment was weighed into tin capsules and combusted at 1,080°C in an elemental analyser (EuroEA, Eurovector) linked to an isotope ratio mass spectrometer (Micromass, Isoprime). Analytic precision was 0.12‰. For carbon isotope ratios of organic matter ($\delta^{13}C_{org}$) samples were decarbonised with 5% HCl for 5 h in a water bath at 50°C. Afterwards, samples were rinsed with

Table 1 Number of sampled cores and near-shore samples in 2005 and 2008 and analyses carried out for each year of sampling: CNS (carbon, nitrogen, sulphur), TP (total phosphorus), XRF-scanning (X-ray fluorescence-scanning), MS-scanning (magnetic susceptibility-scanning)

Sample year	Sample type	Amount of cores/samples	Amount of sediment samples	Conducted analyses								
				Grain size	CNS	TP	Organic matter isotopes	Carbonate isotopes	Diatoms	Pollen	XRF scanning	MS scanning
2005	Core	46	46	x	x	x	x	x	x	x	x	x
2008	Core	17	14	x	x		x				x	x
2008	Near-shore sediment	40	40	x	x						x	

deionised water to neutral pH, freeze-dried and combusted at 1,080°C in an elemental analyser (Euro EA, Eurovector). The resulting CO_2 gas was analysed with a mass spectrometer (Isoprime, Micromass). Analytic precision was 0.1‰. Isotope ratios are reported as conventional δ-values in per mil (‰) according to $\delta = (R_s/R_{st} - 1) * 1000$, with R_s and R_{st} as isotope ratios ($^{13}C/^{12}C$, $^{15}N/^{14}N$) of the sample and the international VPDB standard.

Pollen samples of 20 surface samples cored in 2005 were analysed at the University of Cologne (Hering 2008). Samples were treated following standard procedures (Haberzettl et al. 2005; Wille et al. 2007). Two tablets of *Lycopodium* spore markers (Stockmarr 1971) were added to each sample for calculation of pollen percentages. Samples were then treated with HCl and KOH, rinsed and sieved through a 100-µm mesh. After acetolysis, samples were stored in glycerine. Pollen slides were mounted with paraffin. Due to the low pollen concentration in most surface samples, 200 instead of the normal 300 grains were counted, except for three samples that contained a sufficient number of grains. Pollen concentration is given in absolute pollen frequency (APF, grains * 10^3 cm^{-3}).

Diatom analyses of all surface samples cored in 2005 were performed at the University of Buenos Aires, Argentina. The sample material was heated with H_2O_2 to oxidize organic material following standard procedures (Battarbee 1986). Permanent slides were prepared with Naphrax® after adding a known volume of polystyrene microspheres to the final suspension (Battarbee and Kneen 1982). A minimum of 400 valves was counted under a light microscope and relative frequencies were calculated. To calculate relative abundances (in %) of life forms, all species with an abundance of >3% were classified as benthic, planktonic or epiphytic diatoms.

A subset of 40 shoreline surface samples recovered in 2008 was analysed for CNS and grain size. Furthermore, an aliquot of each sample was ground in an agate mill, placed into plastic cubes ($\sim$3 cm^3) and scanned with an ITRAX XRF Unit. For each sample cube, a mean value was calculated from 15 measurements.

The sedimentological, geochemical, scanning, pollen and diatom data were used to create distribution maps of each variable (Surfer 8.0, Golden Software), including bathymetric information and coring positions (Figs. 3, 4, 5). Interpolation of data points was calculated with a point kriging method. Prior to kriging, the absolute values of CNS, XRF and isotope measurements were standardised by a Z-transformation to enable better comparison. Values are reported in a range from −5 to 5 (without dimension), where 0 is equal to the mean of each distribution.

Results

Distribution maps

Grain size

The interpolated percentage values of sand and clay of all shoreline and core samples are shown in Fig. 3a, b. The littoral areas of the lake are dominated by sandy material, whereas the profundal region is characterized by silts. However, local sand maxima are also detected in the profundal zone. A clay maximum is obvious in the deep central plain and along the steep slope of the north-eastern bay. The silt and clay fractions are strongly positively correlated ($r = 0.99$, $p < 0.05$), while both grain size classes are strongly negatively correlated with sand (clay $r = -0.99$, silt $r = -1$; Table 2). Statistical significance is given at the 95% level (*t*-test) with $p < 0.05$.

Pollen

The distribution pattern of the APF (absolute pollen frequency; Fig. 3c) follows the lake bathymetry, with a distinct maximum in the central basin (15.6×10^3 g^{-1}) and lower concentrations in littoral areas (minimum 1.84×10^3 g^{-1}). A second local accumulation maximum is detected along the north-eastern shore. The littoral pollen concentration at the eastern shore (2.78×10^3 g^{-1}) is lower than that on the western shore (8.82×10^3 g^{-1}).

Diatoms

Absolute diatom abundance for all species shows a heterogeneous distribution across the lake (Fig. 3d). Concentrations of benthic, epiphytic and planktonic diatoms vary between 163 and $1{,}653 \times 10^4$ valves g^{-1}. Diatom abundance maxima are obvious at the eastern and south-eastern central areas and along

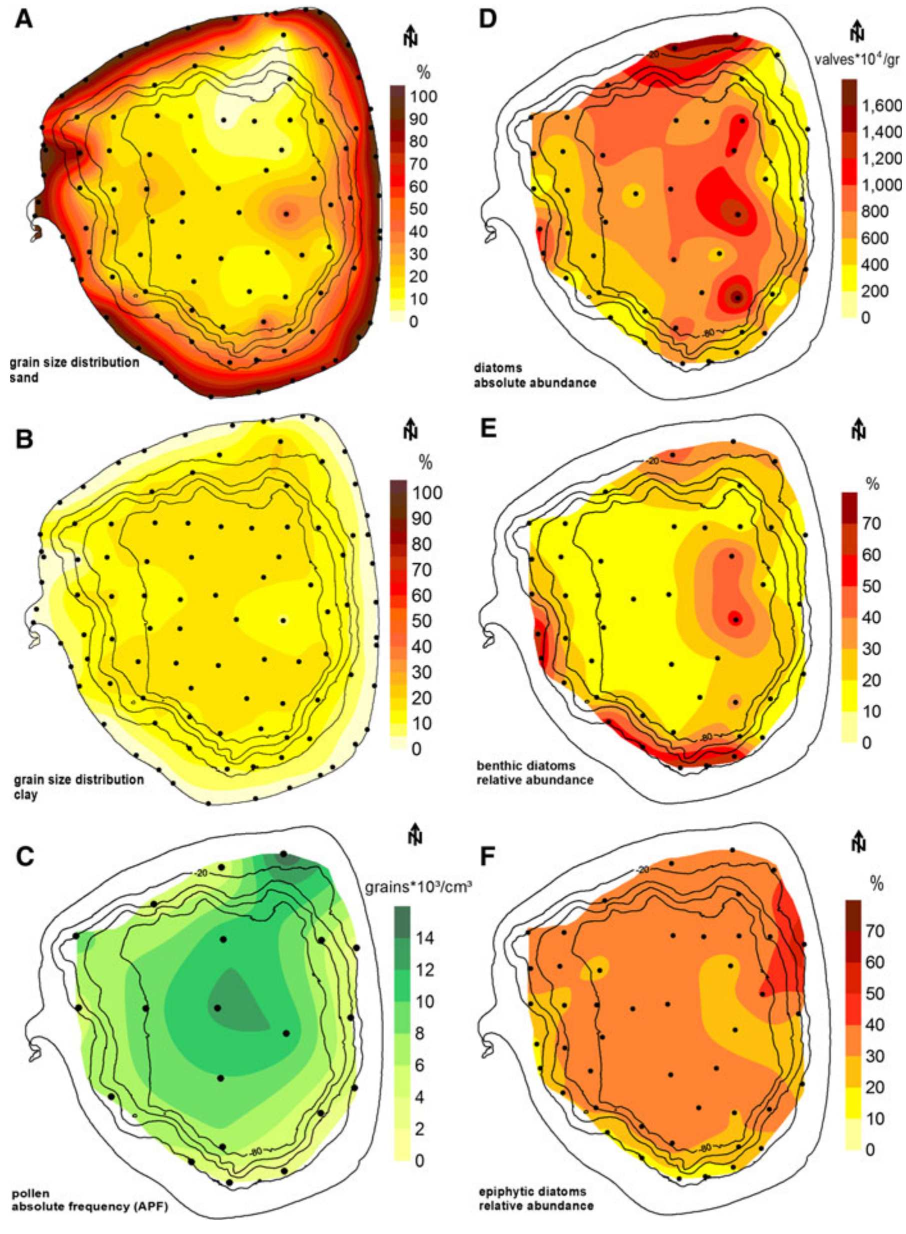

Fig. 3 Distribution maps combined with bathymetric information and core positions (*black dots*) of sedimentological, pollen and diatom data. Note the different number of samples used for interpolation. **a** Percent distribution of sand ($n = 100$); **b** percent distribution of clay ($n = 100$); **c** pollen information ($n = 20$); **d** absolute diatom abundance ($n = 46$) and relative abundance of **e** benthic and **f** epiphytic species

the northern shore. Minimum concentration values occur at the eastern and western to south-western shores and in the south-western profundal areas.

The mean relative abundance for species with >3% of total abundance in all samples was 32% planktonic, 28% benthic, and 32% epiphytic diatoms. Generally, benthic diatoms are dominant in the shallow water sediments and have no in situ abundance in profundal zones. Exceptions are a minimum in the eastern shallow-water zone, which is negatively correlated with a minimum of planktonic species, and a relative benthic maximum in the eastern profundal (Fig. 3e). Epiphytic diatoms show a more homogenous distribution over the lake, with a slight dominance in the south-western basin and north-eastern bay (Fig. 3f).

Bulk organic and inorganic matter variables

Total inorganic carbon (TIC) values range between 0 and 3.7% (mean: 0.76%) with a distinct local maximum in the northern littoral zone. The profundal zone shows a homogenous distribution of TIC

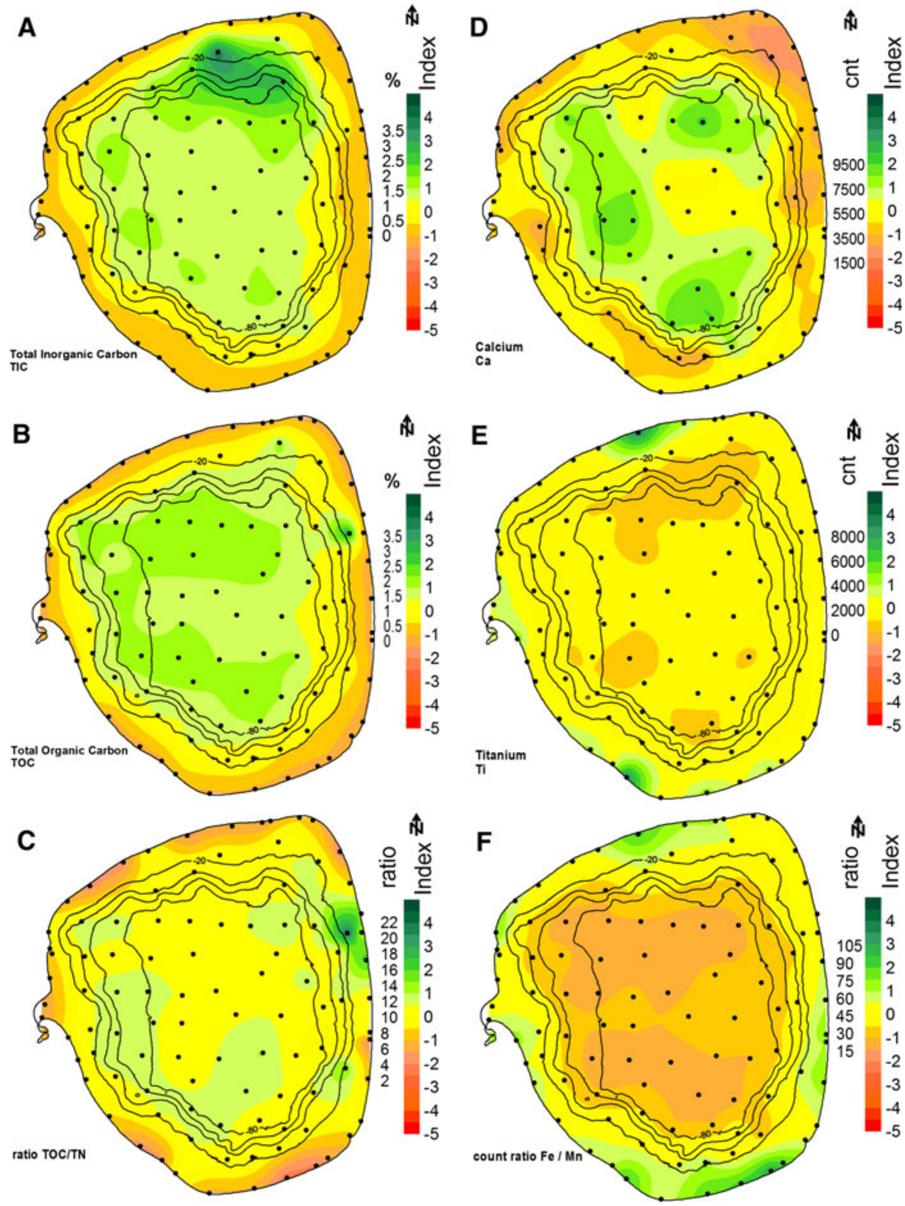

Fig. 4 Distribution maps combined with bathymetric information and core positions (*black dots*) of geochemical analyses and XRF-scanning data. For all analyses, 100 samples were used for interpolation ($n = 100$). All data are standardised by a Z-transformation represented by index values of -5 to $+5$. Absolute values are plotted on the *left side* of the colour scale. The plots show **a** total inorganic carbon (*TIC*), **b** total organic carbon (*TOC*) and **c** TOC to TN molar ratio, and XRF scanning data of **d** calcium, **e** titanium and **f** the iron to manganese count ratio

(Fig. 4a). Minimum values are detected for all shoreline samples. Total organic carbon (TOC) ranges between 0 and 3.5% (mean: 1.06%) with minimum values along the shoreline and in the littoral zone and a homogenous distribution in the profundal area (Fig. 4b). Surface sediments show TOC/TN molar ratios between 3.6 and 22 with lowest values at the northern, western and southern shores and littoral zones. A local maximum occurs at the north-eastern shore. In the deep basin, the ratio is relatively uniform (Fig. 4c). Distribution maps of total carbon (TC), total nitrogen (TN) and total sulphur (TS) are not illustrated. The signal of TC is better represented by differentiation between TOC and TIC. The TN signal is represented by the TOC/TN ratio. Furthermore, TS has a heterogeneous distribution with a mean concentration of 0.04%.

The total phosphorus distribution map is presented in Fig. 5c. Values range from 0.57 to 1.83 g kg^{-1} with lowest values at the northern profundal to littoral area and along the western to southern shallow-water areas. Maximum values are obvious in the southern

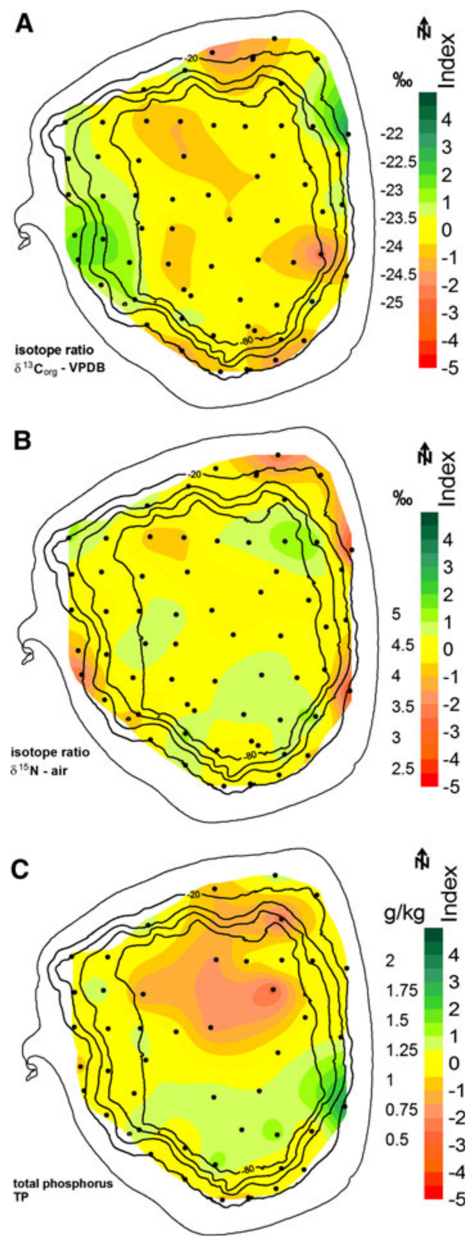

Fig. 5 Distribution maps combined with bathymetric information and core positions (*black dots*) of isotope analyses and total phosphorus. Note the different number of samples used for interpolation. All data are standardised by a Z-transformation represented by index values of −5 to +5. Absolute values are plotted on the *left side* of the colour scale. **a** carbon isotope signal of bulk organic matter ($\delta^{13}C_{org}$, $n = 60$); **b** total nitrogen isotope signal ($\delta^{15}N$, $n = 60$); **c** total phosphorus ($n = 46$)

profundal zone as well as in the south-eastern littoral zone. Therefore, differentiation between the northern and southern profundal is greater than that between the littoral and profundal. Phosphorus shows no significant correlation with any of the other analysed variables.

Major elements

Distinct spatial variations with respect to relative concentrations detected with XRF scanning are observed for Ca, Ti, Fe and Mn (Fig. 4d, e, f). Significant positive correlations ($p < 0.05$) exist for Ca count rates and water depth ($r = 0.70$), Mn count rates and water depth ($r = 0.61$) and between Ti count rates and Fe/Mn count ratios ($r = 0.72$). Significant negative correlations are obvious for Fe/Mn count ratios and water depth ($r = -0.84$), Ti count ratios and water depth ($r = -0.53$), Ca count rates and Fe/Mn count ratios ($r = -0.60$), for Ca and Ti count rates ($r = -0.29$) as well as for Ti count ratios and TIC values ($r = -0.53$; Table 2).

The maxima of Ca counts (Fig. 4d) occur below 80 m water depth. Ca values in the eastern profundal zone are low, similar to the eastern littoral zone. The lowest Ca counts are detected in the north-eastern bay. Highest Ti contents (Fig. 4e) are observed in the littoral, as opposed to profundal sediments. At the eastern to north-eastern shore, Ti contents are lower than in the other littoral areas. The profundal area has medium Ti values with a local minimum close to the north-eastern tributary. Highest Fe/Mn ratios (Fig. 4f) were detected within littoral zones while the profundal shows a homogenous distribution of low count ratios, with higher ratios only in a lobe extending from the eastern steep flank into the profundal.

Stable isotopes

The $\delta^{13}C_{org}$ values range between −22.0 and −25.0‰, with more positive values at the eastern littoral and western littoral to profundal areas (Fig. 5a). Local minima are recorded in the northern and southern littoral areas and spots in the profundal zone.

Nitrogen isotope ratios ($\delta^{15}N$) range between 2.8 and 5.0‰ (Fig. 5b). Western, north-eastern and eastern littoral areas are characterized by minimum values. The profundal area is characterised by comparably enriched values, with maxima in the north-eastern profundal and the southern profundal to littoral area.

Table 2 Correlation matrix of selected sediment parameters with respective *p*-values

	TOC %	TIC %	TOC/TN molar	$\delta^{13}C_{org}$	$\delta^{15}N$	Ti cps	Ca cps	Mn cps	Fe cps	Fe/Mn ratio	TP g/kg	Clay	Silt	Sand
Water depth	0.80	0.78	0.54	*−0.14*	0.44	−0.53	0.70	0.61	−0.64	−0.84	*−0.14*	0.80	0.83	−0.83
p-values	0.0	0.0	0.0	*0.30*	0.0	0.0	0.0	0.0	0.0	0.0	*0.30*	0.0	0.0	0.0
TOC %	1	0.76	0.78	0.37	*−0.20*	−0.56	0.59	0.44	−0.71	−0.80	*−0.01*	0.88	0.89	−0.89
p-values		0.00	0.00	0.00	*0.13*	0.00	0.00	0.00	0.00	0.00	*0.94*	0.00	0.00	0.00
TIC %		1	0.53	*−0.19*	0.28	−0.53	0.64	0.34	−0.66	−0.72	*−0.26*	0.80	0.83	−0.83
p-values			0.00	*0.15*	0.03	0.00	0.00	0.00	0.00	0.00	*0.09*	0.00	0.00	0.00
TOC/TN molar			1	0.65	−0.44	−0.52	0.34	0.29	−0.58	−0.66	*0.19*	0.66	0.67	−0.67
p-values				0.00	0.00	0.00	0.00	0.00	0.00	0.00	*0.20*	0.00	0.00	0.00
$\delta^{13}C_{org}$				1	*−0.12*	*0.10*	*0.03*	*0.07*	*0.16*	*−0.13*	*0.07*	*−0.10*	*−0.09*	*0.10*
p-values					*0.39*	*0.47*	*0.84*	*0.63*	*0.25*	*0.34*	*0.64*	*0.47*	*0.49*	*0.48*
$\delta^{15}N$					1	*−0.20*	0.47	0.38	*0.02*	−0.36	*−0.24*	*0.22*	*0.21*	*−0.21*
p-values						*0.15*	0.00	0.00	*0.91*	0.01	*0.13*	*0.11*	*0.12*	*0.11*
Ti cps						1	−0.29	*−0.14*	0.91	0.72	*0.24*	−0.55	−0.57	0.57
p-values							0.00	*0.18*	0.00	0.00	*0.12*	0.00	0.00	0.00
Ca cps							1	0.68	−0.30	−0.60	*−0.05*	0.53	0.56	−0.55
p-values								0.00	0.00	0.00	*0.76*	0.00	0.00	0.00
Mn cps								1	*−0.07*	−0.59	*−0.04*	0.31	0.32	−0.32
p-values									*0.51*	0.00	*0.79*	0.00	0.00	0.00
Fe cps									1	0.78	*0.15*	−0.70	−0.73	0.72
p-values										0.00	*0.34*	0.00	0.00	0.00
Fe/Mn ratio										1	*0.10*	−0.73	−0.75	0.75
p-values											*0.51*	0.00	0.00	0.00
TP g/kg											1	*−0.11*	*−0.22*	*0.20*
p-values												0.45	0.15	0.19
Clay												1	0.99	−0.99
p-values													0.00	0.00
Silt													1	−1.00
p-values														0.00

Non-significant correlations are given in italics with a statistical significance at the 95% level (*t*-test; $p < 0.05$)

Correlation was performed with $n = 100$ for CNS, grain size and XRF scanning values, $n = 60$ for isotope and MS scanning values, and $n = 46$ for TP values

Discussion

Westerly winds, lake water currents and sediment availability

The year-around prevailing wind direction at Laguna Potrok Aike is from the SW (Mayr et al. 2007; Shulmeister et al. 2004). The influence of the Westerlies generates strong wave action and is assumed to drive internal lake water circulation in Laguna Potrok Aike. Endlicher (1993) provided a value for the mean monthly wind speed of 9 m s^{-1} during early summer for southern Patagonia. Our own onsite wind measurements (Mayr et al. 2007) support these observations. The longest wind fetch for typical west winds, and therefore the strongest influence of wave action likely influences the eastern to north-eastern lake shore. However, no direct measurements of water current flow direction nor speed are available and, thus, no modelling of wind driven circulation (Beletsky et al. 2003; Bennett 1974; Simons 1985) has been done yet at Laguna Potrok Aike.

As lake internal circulation patterns at Laguna Potrok Aike have not been studied directly, mechanisms of sediment transport are inferred from knowledge about other basins. Investigations at Lake Michigan (Lou et al. 2000) proposed sediment re-suspension by waves and turbulence, while the transport depends on currents (Beletsky et al. 2003; Vilas et al. 2005). Commonly, uniform wind stress is responsible for long-shore, downwind currents and upwind return flows in deeper waters (Beletsky et al. 2003; Bennett 1974; Dyck and Peschke 1995). Influences of the Coriolis force on internal currents can be disregarded for relatively small lakes like the study site (Imboden 2005). For Laguna Potrok Aike, waves at the eastern shore have the largest energy available for re-suspension of near shore sediments. Consequently, reverse currents may lead to downward transport of the re-suspended sediment load to profundal areas.

Spatial sediment distribution is correlated with water depth, while sediment accumulation is mainly restricted to deeper parts of the lake, i.e. profundal and less turbulent littoral zones (Håkanson and Jansson 1983). Moreover, sediment transport is affected by internal currents as well as by allochthonous sediment input and strongly controls lake internal sediment distribution as shown by Girardclos et al. (2003) for Lake Geneva. Inflows deposit their coarsest sediments close to the lake shore, while finer sediment fractions are transported to deeper zones. Less turbulence in deepwater zones provides the best conditions for accumulation (Beletsky et al. 2003; Rea et al. 1981). In addition to sediment availability, inflows affect lake internal currents, as differences in temperature and density between runoff and lake waters prevent homogeneous sediment distribution (Dyck and Peschke 1995). Presently, there is an episodic inflow at the western lake margin of Laguna Potrok Aike (Fig. 2). Ephemeral tributaries at the north-eastern and south-eastern lake margins may also contribute to sediment input during modern times.

The amount of sediment accumulation is furthermore influenced by autochthonous production and atmospheric deposition. Sources of material as well as transport processes by currents and turbulence can be recorded by stratigraphic variations and spatial sediment distribution (Bradbury and Winter 1976). Distinct areal sedimentation patterns can be correlated to external factors such as wind direction, influence of tributaries, geologic setting and internal currents. Knowledge about modern processes, patterns and causes of spatial sediment distribution in Laguna Potrok Aike can facilitate interpretations of palaeoclimate proxies in long sediment records (Haberzettl et al. 2009, 2007).

Spatial patterns of sedimentological, diatomological and palynological data

The sedimentation of coarse-grained material in the eastern lake profundal zone, as well as higher benthic diatom occurrence towards the deep-water zone (Fig. 3a, e), point to transport of sediments from the eastern littoral zone to the profundal. Percentage grain size distribution indicates sandy material at the lake margins and silty to clayey sediments at water depths >50 m (Fig. 3a). Local patterns of a sand minimum and clay maximum along the north-eastern slope to profundal may be explained by a combination of interpolation artefacts due to missing data points and the strong influence of the north-eastern inlet transporting more fine-grained material into the lake. Disregarding this area, the profundal exhibits areas of more sandy material in the east, south and west. The pattern in the eastern profundal area can probably be attributed to wind- and wave-induced down-slope transport processes of re-suspended littoral sediments. As no ice cover has been observed during modern times for Laguna Potrok Aike, we suggest that wind-driven waves and currents are the main mechanisms for sediment re-distribution. Coarser material in the western profundal zone seems to be transported by inflow currents of the main western tributary while coarser material at the southern margin may also originate from down-slope transport.

Diatoms are extensively used for climate reconstructions within closed basins (Battarbee 2000), whereas modern diatom distributions in sediments can be used to infer lake internal currents and sediment transport (Bradbury and Winter 1976). Benthic diatoms commonly live in the photic littoral zones, while planktonic species live in the photic zone across the entire lake and are more readily deposited in deep water. The accumulation of diatoms at the northern littoral bay is possibly due to less turbulent situations there (Fig. 3d). The distinct accumulation of diatom valves in the eastern profundal zone in contrast to low abundances of diatoms in the eastern littoral zone is possibly caused by littoral-to-profundal transport of diatom-size particles at the eastern slope, as was already argued for grain-size distribution patterns. This lake-internal transport is further supported by the distribution patterns of the different living diatom forms. The relative distribution of benthic diatoms reflects a shift from their littoral habitat to the profundal area (Fig. 3e). Patterns for relative valve abundance of epiphytic (Fig. 3f) diatoms complement this benthic diatom pattern. The epiphytic maximum in the profundal zone may be related to drifting plant remains. In contrast, the maximum in the north-eastern bay seems to be related to observed in situ plant growth.

Palynological information points to distribution mechanisms somewhat different from the previously assumed littoral to profundal transport (Fig. 3c). Pollen input at Laguna Potrok Aike is controlled by fluvial and aeolian processes (Wille et al. 2007), while pollen sedimentation patterns seem to be controlled by wind and individual requirements for preservation. Inferred from the analysed samples, APF (absolute pollen frequency) is highest in deep-water areas with little water turbulence and no erosion. Low APF values occur in the littoral zones due to oxidative processes and strong erosion. Especially at the eastern shore, erosion as a result of the longest wind fetch seems to be the main reason for low APF values. A second local pollen accumulation area at Laguna Potrok Aike is represented by one sample from the north-eastern shore associated with a canyon structure. The bay-like structure may provide less turbulent conditions and thus have fostered recent pollen accumulation. Additionally, wind fetch causes concentration and later accumulation of pollen grains at this site.

Areal patterns of geochemical data

Total inorganic carbon (TIC) is produced by autochthonous chemical precipitation and occasional occurrence of molluscs in Laguna Potrok Aike. Therefore it is used as a qualitative lake level indicator in palaeoclimate studies. During the Holocene, high TIC values indicate low lake levels and low values indicate high water levels (Haberzettl et al. 2005). Shoreline samples from Laguna Potrok Aike show no TIC at all (Fig. 4a). A TIC maximum in the north-eastern profundal to littoral area could be due to samples enriched in mollusc shells, as radiographic images show accumulated molluscs in these upper core sections. It is possible that the environment at the shallow terrace, without frequent turbulence or re-suspension, creates a suitable habitat for molluscs. The profundal TIC distribution pattern (Fig. 4a) suggests a connection between profundal values and low values at the eastern shore. Again, this points to near-shore erosion of "TIC-free" littoral sediments at the eastern lake shore followed by down-slope transport and accumulation of the re-suspended material in deep-water areas. This confirms the assumed wind-induced internal currents.

The relatively homogenous distribution of TOC (Fig. 4b) over the deep basin area may reflect the almost continuous mixing of organic material within the water body and accumulation in deep-water areas. Nonetheless, preservation of organic material may also be better in deep-water zones. Near-shore samples are mostly depleted in organic compounds due to permanent wave action. At the eastern lake site the interpolated distribution pattern of TOC values tends to document reworking from the lake shore and down-slope transport.

TOC/TN ratios and $\delta^{13}C_{org}$ values are frequently used to determine the origin of organic matter (OM). Due to rare rainfall events and thus low input of terrestrial material, allochthonous OM is largely negligible. Following this approach, the TOC/TN molar ratios (Fig. 4c) of Laguna Potrok Aike surface samples are in the range of phytoplankton and aquatic macrophytes (Mayr et al. 2005; Meyers 1994). Detailed analyses of aquatic and terrestrial OM in Laguna Potrok Aike are described by Haberzettl et al. (2005) and Mayr et al. (2009). As a TOC/TN ratio >11 indicates the influence of non-planktonic OM (Meyers and Teranes 2001), high values in the eastern littoral zone provide evidence of accumulated submersed aquatic plant debris due to wave-induced erosion. Minor influence of terrestrial OM from grasses was also suggested (Mayr et al. 2009, 2007). The homogenous distribution of TOC/TN molar ratios in the deep basin points to a mixture of phytoplankton, aquatic macrophytes and terrestrial OM. Low TOC/TN ratios (<11) detected in the northern, western and southern littoral zones are interpreted as reflecting soil- or algae-dominated OM.

Phosphorus in lake sediment cores is sometimes used to reconstruct past lake productivity (Boyle 2001), as it commonly limits biological production

(Wetzel 2001). Total phosphorus concentrations of 1,300–3,600 μg l^{-1} for Laguna Potrok Aike water samples measured during 2002 and 2004 indicate that phosphorus probably does not limit lacustrine production (Zolitschka et al. 2006). As nearby lakes and a spring also showed high TP values similar to Laguna Potrok Aike, Zolitschka et al. (2006) assumed that the regional geology and groundwater contribute to the elevated phosphorus values. Dissolved phosphorus in the water column is rapidly precipitated and sedimented. During oxic conditions the sediment is an efficient trap for phosphorus stripped from the water column (Boyle 2001) and sediments are enriched in TP relative to surface waters (Engstrom and Wright 1984). Phosphorus in lake sediments is bound to inorganic or organic compounds (Engstrom and Wright 1984; Wetzel 2001). Highest TP variability is found in surface sediments as a result of variations in inorganic phosphorus. Organic phosphorus is mostly bound to carbon as it is precipitated with calcite (Engstrom and Wright 1984). The map reveals a heterogeneous pattern of TP distribution (Fig. 5c). In contrast to other sedimentological, geochemical and mineralogical analyses, the TP values show a north–south trend, with minimum values at the northern littoral to profundal zones. Highest TP values are possibly related to the geologic setting, with sources near the southern basalt cliff. Without analyses of the different phosphorus fractions, a detailed study of sources and processes of retention and release of phosphorus cannot be done.

Areal patterns of organic carbon and total nitrogen isotope data

Stable isotope values of organic matter were previously used as palaeo-shoreline indicators (Haberzettl et al. 2005; Mayr et al. 2009). Thus, $\delta^{13}C_{org}$ variations in combination with TOC/TN ratios were interpreted to reflect the input of different types of sediment organic matter as mentioned above. In the first study, organic matter of Laguna Potrok Aike was regarded as a mixture of algal matter and aquatic macrophytes (Haberzettl et al. 2005; Meyers and Teranes 2001). Later, Mayr et al. (2009) applied an advanced geochemical fingerprint approach, using $\delta^{13}C_{org}$, bulk $\delta^{15}N$ and TOC/TN ratios of a more complete environmental sample set, to better characterize the bulk organic matter (OM) sources to Laguna Potrok Aike sediments. This approach suggested the origin of modern sediment OM is mainly from diatomaceous ooze (29%), cyanobacteria (26%) and soil OM (44%) during present time. Multiple factors may control the nitrogen isotope signal (Hodell and Schelske 1998; Meyers and Teranes 2001). Input of nitrogen compounds occurs via the atmosphere and by surface and sub-surface runoff (Leng et al. 2006).

Here, high organic carbon isotope values ($\delta^{13}C_{org}$) in the surface sediments at the western, northern and eastern littoral zones (Fig. 5a), along with increased TOC/TN ratios (Fig. 4c), reveal the occurrence of macrophyte debris in the surface sediments. The OM-rich spots correlated with higher $\delta^{15}N$ values of ~5‰ on the steep flanks, and the southern and north-eastern profundal zones are located near ephemeral inflows (Fig. 2). Thus, OM at these locations seems to be influenced by input of terrestrial OM (i.e. soils) via the tributaries. Nonetheless, influences of sediment re-location due to internal currents must be considered.

The isotopic signature of organic matter sources in and around Laguna Potrok Aike (Mayr et al. 2009) suggests that the combination of low $\delta^{15}N$ values and low $\delta^{13}C_{org}$ values at the northern and southern to south-eastern shores indicates input of terrestrial vascular plant OM (i.e. grass). In combination with $\delta^{13}C_{org}$ values of up to −22.0‰ at the western and eastern littoral, the $\delta^{15}N$ values of ~3 ‰ are interpreted to be more influenced by aquatic macrophytes and/or cyanobacteria. Soils and incorporated organic matter are characterized by nitrogen isotope values of 5–7‰ (Mayr et al. 2009) and thus cannot explain such low $\delta^{15}N$ values. The input of soil organic matter is the most likely explanation for the mentioned spots of increased $\delta^{15}N$ in the profundal, even if the concentration of OM and thus the weighted effect to the total sediment is low compared to plant debris. Differences in the types of transported OM are probably related to the morphodynamics and transport capacities of ephemeral channels reaching the lake. Some spots of comparably low $\delta^{13}C_{org}$ values in the profundal point to contributions of planktonic algae above the average pelagial input.

Areal patterns of element concentrations

The Ca counts mainly represent the amount of TIC and thus the content of autochthonously precipitated

$CaCO_3$, which varied with Holocene lake level changes at Laguna Potrok Aike (Haberzettl et al. 2007, 2005). Calcium released from weathered basaltic rocks in the catchment area is assumed to be the main source for dissolved Ca^{2+} within the lake (Haberzettl et al. 2005). The positive correlation between Ca and water depth may indicate that Ca is mostly bound to fine-grained fractions. The local Ca minimum at the shallow eastern lake site (Fig. 4d) and in the eastern profundal zone may be caused by sediment re-distribution related to wind-induced counter currents. Enriched Ca counts at the southern shore may reflect direct influence of the basalt cliff, while lower Ca values in the north-eastern littoral zone represent mineralogical differences in the catchment area.

In Laguna Potrok Aike, titanium is associated with allochthonous clastic input via tributaries, during times of weakened westerly winds (Haberzettl et al. 2007). This interpretation is supported by higher Ti values in front of the main tributary in the western part of the lake. Ti-rich basaltic and phreatomagmatic deposits surrounding the lake may be the sources (D'Orazio et al. 2000). Shoreline samples show an accumulation of Ti-bearing sediments around the lake (Fig. 4e). Only the north-western, north-eastern and eastern shores, farthest from the basaltic cone, exhibit sediments with lower Ti counts. This may be explained by the local geological differences, dilution effects by strong erosion of shoreline sediments or grain-size effects. Furthermore, low Ti values reflect dilution by TIC (Haberzettl et al. 2005) as suggested by the negative correlation between Ti and TIC (Table 2).

The Fe/Mn ratios (Fig. 4f) indicate oxic conditions at the sediment/water interface or in the sediment (Haberzettl et al. 2007, 2006; Schaller and Wehrli 1996). The relatively low present-day lake level and continuous westerly winds currently cause polymixis and oxic conditions throughout the water column. With increasing water depth, Fe/Mn ratios decrease as more oxidized MnO_2 is fixed at the sediment surface (Cohen 2003; Sigg and Stumm 1996). This is also shown by the significant correlation between Mn and water depth. A shift to slightly higher Fe/Mn ratios at the eastern profundal is indicative of sediment re-distribution from the littoral zone as described above for other sediment variables. The strong correlation between Fe and Ti ($r = 0.91$) implies a minerogenic origin from a titano-magnetite, and suggests that both elements are indicators of erosion and clastic sediment input to Laguna Potrok Aike.

Conclusions

Bradbury and Winter (1976) and Whitmore et al. (1996) suggested using caution when interpreting single-point sediment cores as their studies showed the influence of wind stress, sediment redistribution by wave action, currents and turbulence on spatial sediment distribution. Sedimentation in Laguna Potrok Aike is not only sensitive to lake level changes, as demonstrated by multi-proxy studies of long sediment cores, but is also controlled by strong westerly winds that cause internal lake currents, littoral erosion and littoral to profundal sediment re-distribution. Furthermore, episodic inflows, sub-aquatic groundwater springs and the surrounding geology may influence the spatial distribution of some sediment variables.

Observations during field trips to Laguna Potrok Aike and the discussed information about modern spatial sediment distribution with respect to sedimentology, geochemistry, stable isotopes, mineralogy, pollen and diatoms, yields a coherent picture of lake internal depositional dynamics. Distribution patterns of grain size, benthic diatoms, elements and elemental ratios indicate polymictic conditions in the water body, and strong wind-induced west-to-east surface currents, which cause wave erosion and re-suspension of sediment along the lake margins, particularly along the eastern lake shore (Fig. 6a). The resulting east-to-west sub-surface return currents are believed to transport and re-distribute the eroded sediment. Consequently, the eastern profundal zone serves as a sediment accumulation area (Fig. 6b).

The north-eastern bay is apparently more affected by local morphometry and an ephemeral inflow (Fig. 6a). This area promotes accumulation as shown by grain-size distribution, absolute diatom abundance, pollen and the TIC record. Mineralogical information and observations during field trips point towards the influence of glacial tills in the catchment area and enhanced sediment input during snowmelt via the north-eastern tributary. The isotope values of total nitrogen clearly identify points of organic matter input via the north-eastern and south-eastern tributaries into

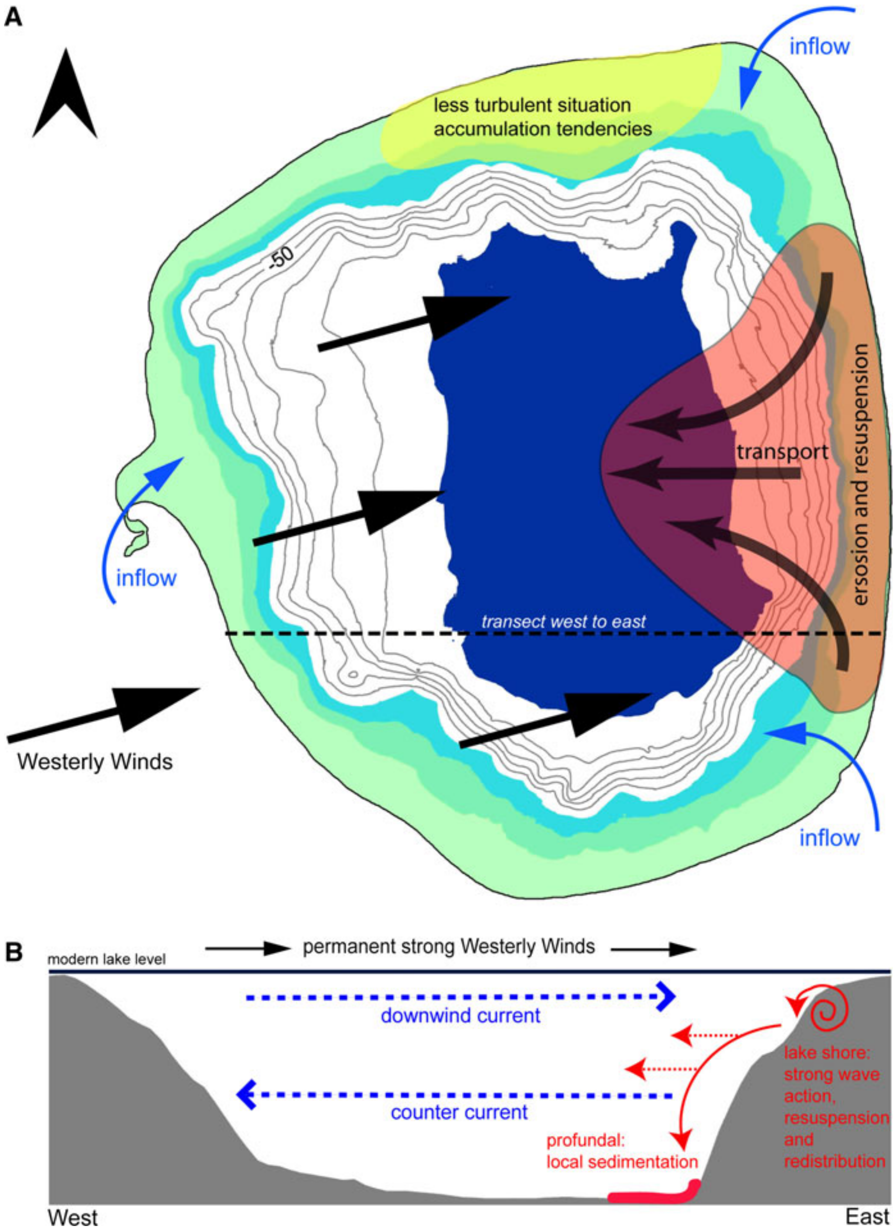

Fig. 6 Interpretation of areal sediment distribution data in terms of modern internal lake processes. **a** The littoral area is highlighted in greenish colours, the deep basin in blue, and areas of high erosion dynamics and downward slope transport are coloured in red. An additional accumulation area is marked as *yellow* in the north-eastern bay. Wind direction and transport are indicated by *arrows*. **b** A west-to-east transect (**a**) depicts lake currents and sediment transport pathways induced by westerly winds during modern climate and lake level conditions. The eastern profundal describes a local re-sedimentation area

the deep lake basin, despite the strong wave action and internal distribution patterns. Furthermore, the influence of the surrounding geology is inferred from the titanium distribution and spatial variations of total phosphorus.

Beyond already existing single point source information, areal patterns of sediment distribution presented here will improve interpretations of long sediment records recovered within the ICDP deep drilling project PASADO. Results and implications of the modern spatial sediment distribution of Laguna Potrok Aike are intended to be used to better understand stratigraphic changes in sediment cores spanning the Late Holocene, a time of varying lake level and related climate conditions. Knowledge of modern spatial variability in sediment components will enable us to interpret temporal shifts in Fe/Mn ratios related to changes in redox conditions and/or erosion, shifts in the types and amounts of phosphorus in cores, and implications of changing isotope values in organic matter, related to the source of OM and lake stage.

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