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ORIGINAL PAPER

Diatom assemblage changes in lacustrine sediments from Isla de los Estados, southernmost South America, in response to shifts in the southwesterly wind belt during the last deglaciation

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Abstract Isla de los Estados (54° 45′S, 63° 10′–64° 46′W) lies east of the main island of Tierra del Fuego and is the southeastern-most point in Argentina. Because of its geographic position near the latitudes of the Southern Hemisphere Westerlies and the strong influence of the Antarctic Circumpolar Current (ACC), the area is suitable for paleoecological and paleoclimate research. The island is not far north of the Subantarctic Front, which limits the northern boundary of the ACC. Paleoenvironmental study in this geographic location can shed light on past changes in atmospheric and marine circulation patterns. Diatom analysis of the lower part of a sediment sequence from Laguna Cascada (54° 45′ 51.3″S, 64° 20′ 20.07″W) enabled inference of changing lake conditions between 16 and 11.1 cal ka BP. Between 16 and 14.4 cal ka BP fragilarioid diatom species, often a pioneer group, dominated the record. Their presence shows seasonally open-water conditions from the onset of sedimentation. In zone II (14.4–12.8 cal ka BP), the dominance of planktonic/tychoplanktonic *Aulacoseira* spp. might represent longer ice-free periods and windier conditions, which would have kept this heavy species suspended in the water column. This period corresponds to the Antarctic Cold Reversal, when the Southern Hemisphere Westerlies were possibly centered on the latitudes of Tierra del Fuego, resulting in windy and wet conditions. Zone III (12.8–11.1 cal ka BP) is dominated by benthic diatom taxa that are mainly associated with peat and wetland

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vegetation. This suggests that climate conditions had become milder and less windy, favoring aquatic productivity and terrestrial vegetation development. This change in environmental conditions may have been a consequence of the southward movement of the Southern Hemisphere Westerlies at the start of the Antarctic Holocene thermal optimum.

Keywords Diatoms · Biogenic silica · Isla de los Estados · Late glacial-early Holocene · Paleoenvironments

Introduction

During the last few decades, studies of late Quaternary paleoenvironmental records from the Southern Hemisphere have increased, particularly in southern South America (McCulloch and Davies 2001; Mayr et al. 2005; Unkel et al. 2008; Kilian and Lamy 2012; Björck et al. 2012). The area is key to assessing past changes in the southern westerly wind belt during and after the Last Glacial Maximum (*ca.* 26–19 cal ka BP).

Our study area, the Isla de los Estados (IDE) (Fig. 1a), is an island that lies in an area that is climatically sensitive to regional atmospheric and marine circulation and possesses important archives for paleoenvironmental, geomorphological and paleoclimate studies (Ponce 2009; Ponce et al. 2011a, b; Unkel et al. 2008, 2010; Björck et al. 2012). It is an area without significant anthropogenic disturbances, making it ideal for inferring natural environmental shifts. The island's climate predominantly reflects variations in the latitudinal position and/or contraction of the Antarctic Circumpolar Current (ACC) and Southern Hemisphere Westerlies (SHW). Past changes in these large-scale climate phenomena should therefore be preserved in lake sediment variables on IDE.

During the Last Termination, i.e. the time interval of the melting of the large continental ice sheets, parts of the Southern Hemisphere experienced a long warming trend between 18 and 10 cal ka BP, which was interrupted by the Antarctic Cold Reversal (ACR) around 14.5–12.8 cal ka BP (Hubbard et al. 2005).

Cooling during the ACR in Antarctica, and possibly also in large parts of the Southern Ocean, most likely in response to warming at the onset of the Bølling-Allerød interstadial in the Northern Hemisphere, is well documented by polar ice cores (EPICA 2006). A shift of the circulation fronts towards the equator during the ACR led to cooler conditions in Antarctica, but also to the expansion and re-growth of many glaciers, even on islands north of the sub-Antarctic Front (e.g. in New Zealand) (Putnam et al. 2010). Similar results have been documented from southern Patagonian glaciers (Sugden et al. 2005) and have been explained by a southward shift of the SHW from a more northerly position. Whittacker et al. (2011) proposed an intensification of the SHW during the ACR because of regionally colder conditions that forced both the polar and subtropical front farther north. Although some authors argue for a shift in the latitudinal position of the SHW during the ACR (McGlone et al. 2010; Putnam et al. 2010), others (Lamy et al. 2010) suggest that changes in terrestrial vegetation can also be explained by an expansion and contraction of the wind belt, especially at its northern edge. Such a scenario could better explain the precipitation variability recorded across different sites (Lamy et al. 2010). Although it is still not clear how far north in the Southern Hemisphere the bipolar see-saw effect (Broecker 1998) can be observed, it seems clear that it influenced the southernmost parts of South America, i.e. southern Patagonia (Sugden et al. 2005). By comparison with other parts of the Southern Ocean region, Hodgson and Sime (2010) concluded that changes in the atmosphere and ocean circulation up to 36°S could have been influenced by this effect, but whether it was primarily oceanic, atmospheric, or both, remains unknown (Putnam et al. 2010).

Our study area might thus provide good records of the large-scale circulation and climate shifts during the Last Termination. Furthermore, because of the large and shallow continental shelf area north of the island, the paleogeography of the area and the island itself changed considerably during the sea level rise following the LGM and into the mid-Holocene (Möller et al. 2010; Unkel et al. 2010; Ponce et al. 2011b).

Diatoms (Bacillariophyceae), our main paleoenvironmental proxy, are unicellular, photosynthetic algae that are extremely sensitive to physical (e.g. turbidity, temperature, light) and chemical (e.g. pH, nutrients, salinity) changes in water bodies. To date, analyses of diatoms in paleorecords from southern Patagonia have not been numerous or systematic (Espinosa 2008). Paleoenvironmental studies began with Frenguelli (1924), on a peat bog called La Misión (53° 30′S; 67° 50°W), located in Rio Grande (northern Tierra del

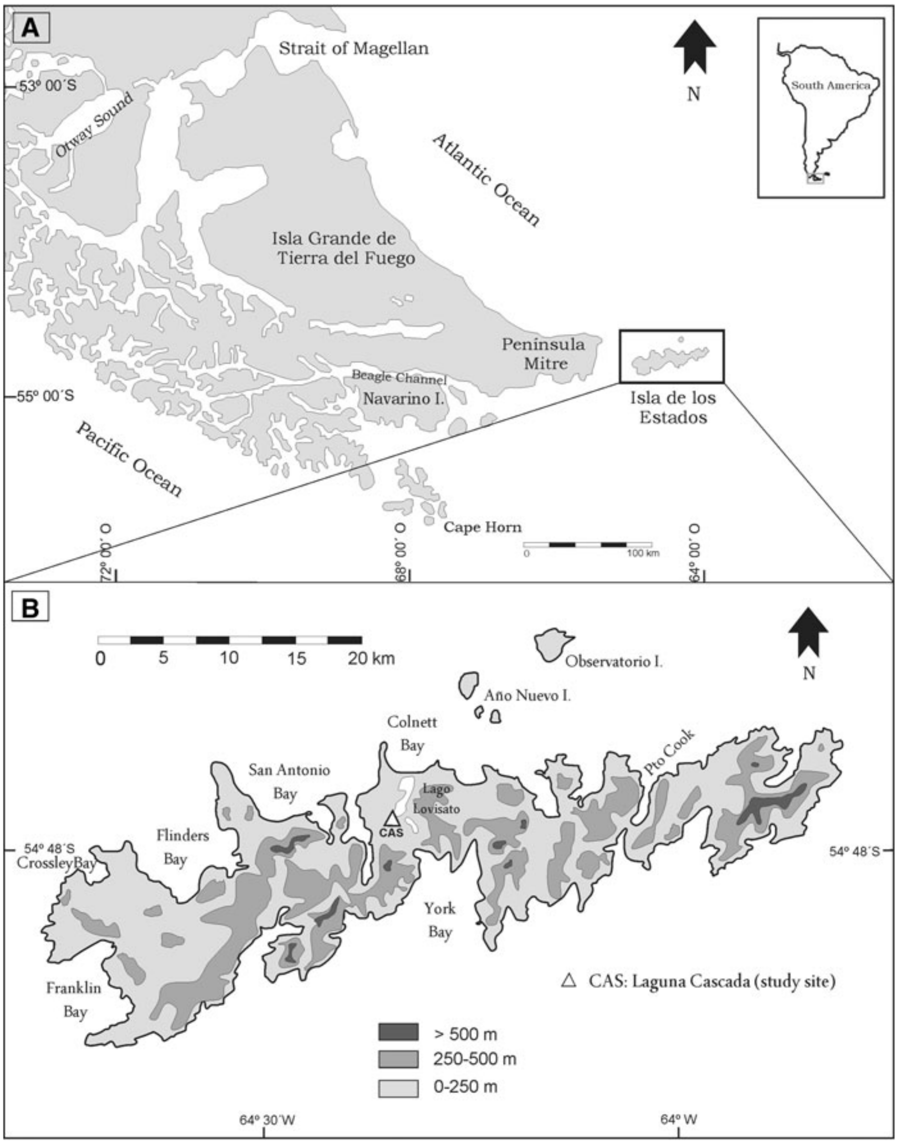

Fig. 1 **a** Map of the Fuegian Archipelago in southern Patagonia and location of Isla de los Estados. **b** Topography of Isla de los Estados showing the location of the site of the present study (Laguna Cascada) and of sites discussed in the text

Fuego), and continued with sediment analysis of Lago Fagnano, Tierra del Fuego (Bujalesky et al. 1997; Recasens 2008). More recently, diatom studies were published from Puerto del Hambre in the Magellan Straits (McCulloch and Davies 2001), the Las Cotorras peat bog on Tierra del Fuego (Borromei et al. 2010), and from other lake sediment sequences in southern Santa Cruz, such as Potrok Aike (Mayr et al. 2005; Wille et al. 2007; Fey et al. 2009).

Here we present an environmental reconstruction of the Last Termination, based on detailed diatom and biogenic silica (BSi) analysis of sediments from Laguna Cascada. Biogenic silica content provides important information about aquatic productivity (Conley and Schelske 2001). The results are compared to other environmental reconstructions from IDE based on pollen (Ponce 2009), geochemical analyses from the same peat core (Unkel et al. 2008) and a combination of aeolian sand influx and paleobotanical variables (Björck et al. 2012).

Study site

Isla de los Estados (54° 45′S, 63° 10′–64° 46′W; Fig. 1a) lies east of the larger island of Tierra del Fuego. It is separated from the rest of the Fuegian

Archipelago by the 23–36-km-wide Le Maire Strait and from the Antarctic Peninsula to the south by the 960-km-wide Drake Passage. IDE is a narrow island with a distinct glacial imprint. It is between 14 and 0.5 km wide and is 65 km long (Fig. 1b). Deeply incised fjords occur along the northern and southern coasts.

The climate is cooler, windier and more humid than on the main island of Tierra del Fuego, with the exception of the western channel area. Strong winds from the southwest and west dominate all year around (Kühnemann 1976; Garreaud et al. 2013). Summer temperatures are cooler than in the rest of the archipelago and winter temperatures are less severe. Average summer temperature ranges from 7 to 10 °C and the mean winter temperature is about 2 °C.

Permanent freshwater streams are common in the central and western mountain range. The largest water body is Lago Lovisato (3 km long) (Fig. 1b), which is located in the deeper part of an ancient basin, and is separated from the sea by an ice-marginal moraine (Möller et al. 2010). Laguna Cascada is a small lake ($\sim$13,000 m^2), situated 10 m above sea level, and is surrounded by a quagmire with a water pH of 4.5. It is located 200 m west of the southwestern-most part of Lago Lovisato (Fig. 1b) and is bordered by glacial cirques and mountain slopes in the south. We do not know the bathymetry of Laguna Cascada.

In November 2005, a Swedish-Argentine expedition to IDE (Björck et al. 2007) retrieved a 523-cm-long sediment sequence from the quagmire surrounding Laguna Cascada (54° 45′ 51.3″S, 64° 20′ 20.07″W). The lithostratigraphy, chronology and interpretation of physical and geochemical variables in the sediments were published recently (Unkel et al. 2008). Our study used the diatom assemblages in the lower part of the sediment sequence (523–425 m depth) to assess changes in lake status and environmental conditions and to relate shifts in diatom assemblages to the geochemical and physical variables. We also compared the inferred lake status changes for Laguna Cascada to other evidence for regional climate changes.

Materials and methods

Sub-samples for diatom analysis were taken at 2–3-cm intervals between 523 and 425 m depth. In samples from a laminated clayey silt unit 1 (523–503 cm), diatom valves were too scarce to provide reliable results. Sub-samples were first treated with 10 % HCl, rinsed, and then heated with 30 % H_2O_2, at 80–90 °C for 2–3 h to oxidize the organic matter. Samples were rinsed repeatedly by suspending and dispersing the material in distilled water. The supernatant was discarded after 2 h.

Permanent slides were mounted with Naphrax® and analyzed with a light microscope at 1,000× magnification. At least 400 valves were counted on every slide. Diatom identification was primarily based on Hustedt (1930–1966), Cleve-Euler (1951, 1952, 1953, 1954, 1955), Patrick and Reimer (1966–1977), Krammer and Lange-Bertalot (1986, 1988, 1991a, b) and Rumbrich et al. (2000).

The diatom stratigraphy was plotted with the Tilia and TGview programs (Grimm 1991) and only species attaining >3 % in at least one sample were included. Diatom assemblages were grouped into three different zones using Coniss. A pH reconstruction was attempted, based on the β Index (Renberg and Hellberg 1982).

Biogenic silica analysis was run on 34 samples and is often used as a proxy for aquatic productivity. A wet-alkaline digestion technique was used (Conley and Schelske 2001). Samples were freeze-dried and ground prior to analysis. Approximately 30 mg of sample were digested in 40 ml of a weak base (0.1 M Na_2CO_3) at 85 °C for 5 h. Sub-samples of 1 ml were removed after 3, 4 and 5 h and neutralized with 9 ml of 0.021 M HCl. Dissolved Si was measured by the automated Molybdate Blue Method (Grasshoff et al. 1983). During measurement, we observed that dissolved Si was high in all except the four lowermost samples. For low dissolved Si concentrations, slope corrections for mineral Si dissolution are necessary. A linear regression between the extracted Si and the extraction time represents the contribution from mineral dissolution. Extrapolating the Si release to the intercept corrects for this and yields the total amount of BSi (DeMaster 1981). High dissolved Si concentration indicated a negligible contribution of such mineral silica and the mean of three subsamples (3, 4 and 5 h) was used to represent the amount of BSi (Conley and Schelske 2001).

Twenty samples for radiocarbon dating were taken throughout the sediment core from Laguna Cascada. Table 1 summarizes information for the 12 samples that were used to develop the age-depth model in Fig. 2 (Unkel et al. 2008, 2010). Samples for radiocarbon analysis were processed and measured at the AMS Radiocarbon laboratory in Lund. Samples that yielded dates younger than 11,000 ^{14}C years BP were calibrated with SHCal04 (McCormac et al. 2004). Samples older than 11,000 ^{14}C years BP were calibrated with IntCal04 (Reimer et al. 2004), subtracting a constant hemispheric offset of 56 ± 24 years (McCormac et al. 2004). An age-depth model for the core sequence was calculated using the OxCal 4 calibration software (Bronk Ramsey 2001, 2008). This program combines the probability distributions of the calibrated radiocarbon ages with certain assumptions about the depositional process to obtain an age–depth curve with the 1σ probability ranges of the radiocarbon ages (Unkel et al. 2008).

Methods for measuring total carbon (TC), total nitrogen (TN) and X-ray fluorescence were described in detail by Unkel et al. (2008). The XRF scanning results represent element intensities in counts per second, which mainly reflect element concentration, but also matrix effects, physical properties, sample geometry, and hardware settings of the scanner (Röhl and Abrams 2000; Tjallingii et al. 2007). In contrast to the previous presentation of the XRF data from Laguna Cascada, we now plot the data on a logarithmic scale and normalize the element counts to total counts (Cuven et al. 2011) to avoid possible bias caused by non-linear absorption or by dilution of elements outside the measuring range of the spectrometer (closed-sum effect) (Richter et al. 2006; Löwemark et al. 2011; Cuven et al. 2011). XRF data can be difficult to interpret, but some things are certain, e.g. that Rubidium (Rb) and Titanium (Ti) are often associated with clay minerals (Koinig et al. 2003), though Rb can replace K in K-feldspars (Kylander et al. 2011). Calcium (Ca) is mainly associated with Ca-carbonate in lake sediments (Cohen 2003). It has either an allogenic source, from catchment carbonate weathering, or is precipitated in the lake by biogenic and/or chemical processes. Ca and Ti can be used as proxies for atmospheric influx (dust aerosols) in peat sequences, and therefore as indicators of wind and storm activity. Strontium (Sr) can substitute for Ca in carbonate minerals (Cohen 2003; Kylander et al. 2011). The Rb/Sr ratio can be used as a proxy for chemical weathering in the catchment and thus indirectly as an indicator for wet/cold vs. warm/dry conditions (Jin et al. 2001, 2006). High Rb/Sr values in lake sediments often correspond to relatively wet and/or cold conditions, whereas low Rb/Sr values reflect warmer and/or drier conditions (Heymann et al. 2013).

Table 1 List of radiocarbon samples taken from Laguna Cascada (CAS) which were used in the age-depth-model shown in Fig. 2

Sample No.	Analysis No.	Sample material	^{14}C age BP	1σ error BP	SHCal04*	IntCal04**	Depth cm
CAS/391	LuS 6936	gyttja	7,775	60	8,548–8,429	–	391
CAS/421	LuS 6937	gyttja	9,125	60	10,283–10,178	–	421
CAS/423	LuS 7102	gyttja	9,435	55	10,688–10,520	10,728–10,585	423
CAS/428	LuS 7293	clay-gyttja	9,730	55	–	11,225–11,125	428
CAS/433	LuS 7294	clay-gyttja	10,085	60	–	11,815–11,408	433
CAS/438	LuS 7200	clay-gyttja	10,790	70	–	12,852–12,760	438
CAS/440	LuS 6508	clay-gyttja	11,005	80	–	13,020–12,870	444
CAS/448	LuS 7295	clay-gyttja	11,505	60	–	13,401–13,286	448
CAS/457	LuS 6938	clay-gyttja	12,120	80	–	14,062–13,871	457
CAS/477	LuS 6939	clay-gyttja	12,575	80	–	15,009–14,592	478
CAS/490	LuS 6940	gyttja-clay	12,935	80	–	15,424–15,111	490
CAS/495	LuS 6507	gyttja-clay	13,285	80	–	15,949–15,545	499

All samples calibrated with OxCal 4, all ages in 1σ range. The sample numbers refer to the sampling depth before adjusting the field-based correlations between individual core sections in the laboratory

* Ages in cal BP; until 11.0 ka BP, based on McCormac et al. (2004)

** Ages in cal BP; constant correction of 56 ± 24 years based on Reimer et al. (2004) and McCormac et al. (2004)

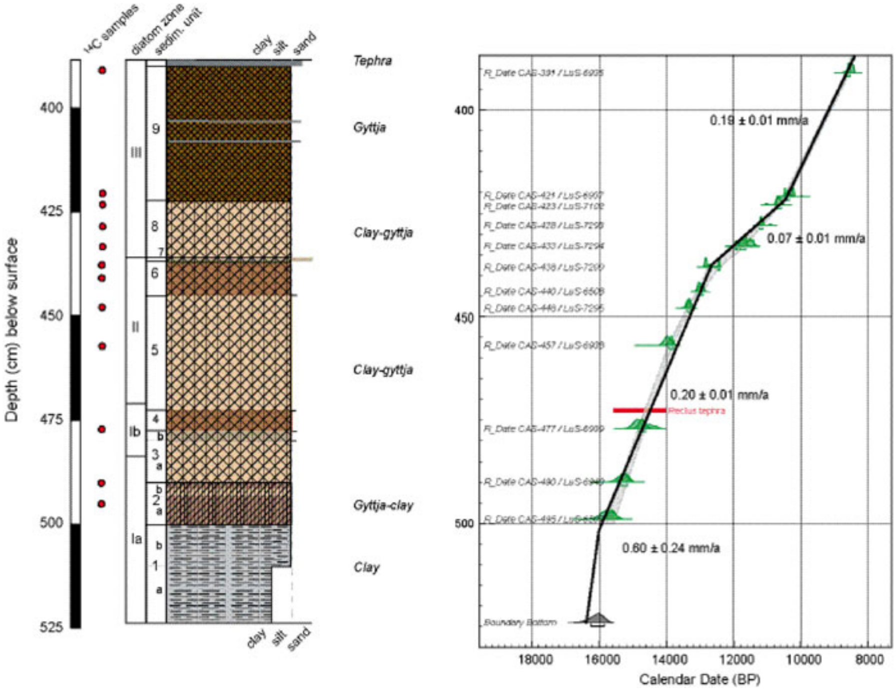

Fig. 2 Lithologic units and radiocarbon samples of Laguna Cascada (CAS). The *black line* in the diagram to the *right* shows the lithology-based age-depth model applied to the proxies discussed in the text. The *light gray* area shows the 1σ-range of the statistical age-depth model calculated with OxCal 4

Results

Diatom stratigraphy

The sediment sequence between 523 and 425 cm depth was originally divided into eight lithologic units (Unkel et al. 2008) that were comprised of glacio-lacustrine clayey silt overlain by silty gyttja clay and silty clay gyttja of varying colors. The chronology used here follows Unkel et al. (2008). Three diatom assemblage zones and two subzones were recognized (Fig. 3). The *Aulacoseira* spp. group includes *A. alpigena* (Grunow) Krammer (Fig. 4a), *A. ambigua* (Grunow) Simonsen, *A. distans* (Ehr.) (Fig. 4a) Simonsen, *A. laevissima* (Grunow) Krammer, *A. subartica* (O. Müller) Haworth, and *A. tethera* Haworth.

Zone I, Subzone Ia: 503–485 cm (16–15.2 cal ka BP)

The dominant diatoms in this subzone are the benthic fragilarioids *Pseudostaurosira brevistriata* (Grunow) Williams and Round, *Staurosira construens* Ehr., *S. venter* (Ehr.) Cleve and Möller (Fig. 3), *Stauroforma exiguiformis* (Lange-Bertalot) Flower, and *Staurosirella pinnata* (Ehr.) Williams & Round. Two unidentified fragilarioids named "morph 1" and "morph 2" also occur in this subzone (Figs. 4b, c). Species present at less than 5 % include the planktonic *Brevisira arentii* (Kolbe) Naguno & Kobayasi (1977) (Fig. 4d), and the benthic *Eunotia* sp., *Pinnularia interrupta* Smith and *Frustulia rhomboides* (Ehr.) De Toni. By the end of the subzone, the planktonic/tychoplanktonic *Aulacoseira* spp. group becomes dominant (up to 25 %).

Zone 1, Subzone Ib: 485–470 cm (15.2–14.4 cal ka BP)

This sub-zone is characterized by a dominance of *Pseudostaurosira brevistriata, Staurosira venter, Stauroforma exiguiformis*, whereas *Fragilaria* sp. and *Aulacoseira* spp. have lower values than in subzone Ia. *Staurosirella pinnata*, *Eunotia* sp., *Pinnularia interrupta* and *Frustulia rhomboides* occur in lower numbers (Fig. 3). Absence of *Staurosira construens* in the lower part of the zone, and of *Staurosira venter* in the upper part of zone Ib is noteworthy.

Zone II: 470–437 cm (14.4–12.8 cal ka BP)

Aulacoseira spp. reaches its highest abundance in the entire profile, attaining values ~80 %, whereas *Stauroforma exiguiformis* decreases (5 %) (Fig. 3).

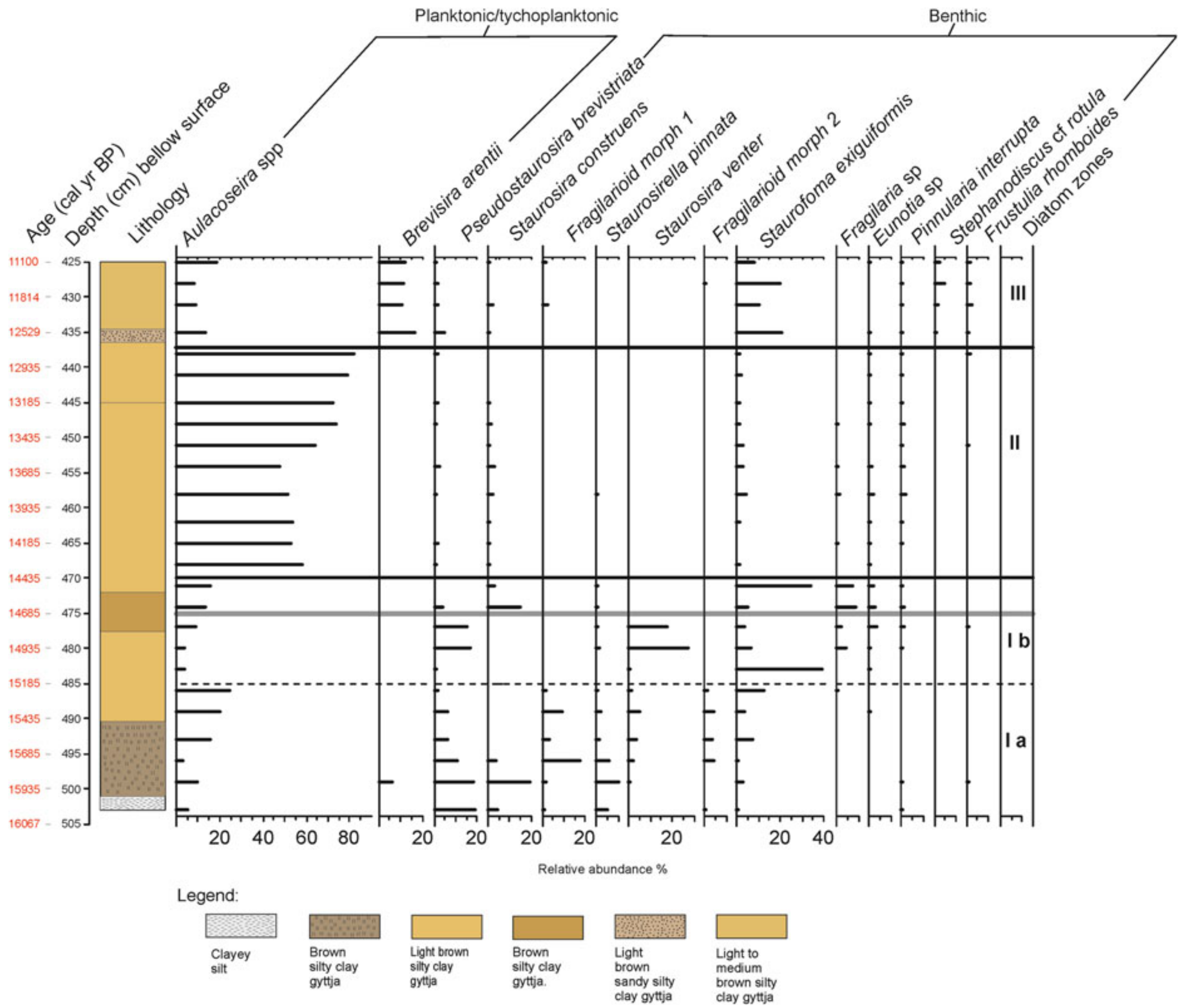

Fig. 3 Diatom diagram and lithology-based age-depth model of the lower 78 cm from Laguna Cascada. The *grey line* marks the position of a tephra layer. The lithology-based age-depth model is also shown

Pseudostaurosira brevistriata, Staurosira construens, Stauroforma exiguiformis, Fragilaria sp., *Eunotia* sp. and *Pinnularia interrupta* are present throughout the zone, but at low frequencies.

Zone III: 437–425 cm (12.8–11 cal ka BP)

Aulacoseira spp. percentages decrease sharply at the beginning of zone III and remain below 20 %. *Stauroforma exiguiformis* and *Brevisira arentii* become the dominant taxa (Fig. 3). Sub-dominant taxa are: *Pseudostaurosira brevistriata, Staurosira construens,* fragilarioids "morph 1" and "2", *Eunotia* sp., *Pinnularia interrupta, Stephanodiscus cf. rotula* (Kützing) Hendey and *Frustulia rhomboides.*

Biogenic silica

With the exception of the four lowermost samples that have low BSi (1–2 %), the content of BSi is fairly high in our sequence (Fig. 5), with a conspicuous rise starting at 16 cal ka BP. This rise persists until 15.2 cal ka BP (24 %) after which there is a slightly fluctuating pattern (20–25 %) for *ca.* 1,000 years. A first peak in BSi (27–28 %) occurs between 14.2 and 13.8 cal ka BP, followed by a decline and fluctuating values (16–25 %), reaching a minimum *ca.* 12.5 ka cal BP. This is followed by a sharp rise, reaching a peak (29 %) 200–300 years later, followed by high but slightly lower values (27–23 %) into the Holocene.

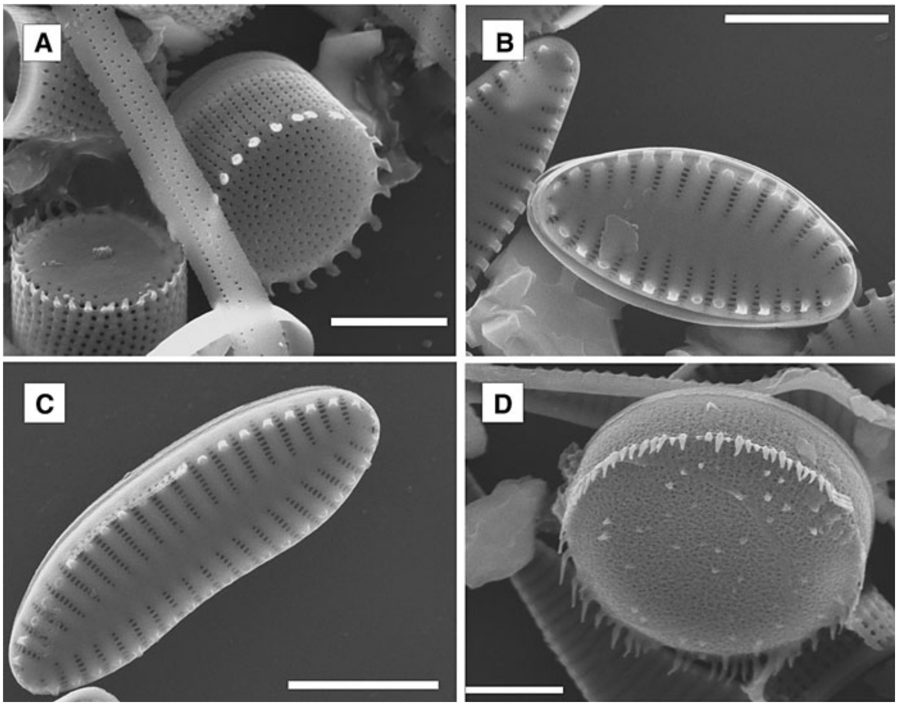

Fig. 4 **a–d** SEM photographs. **a** *Aulacoseira distans* valve face and mantle. *Aulacoseira alpigena* external valve view. **b** Unidentified fragilarioid morph 1. **c** Unidentified fragilarioid morph 2. **d** *Brevisira arentii*, external valve view. *Scale bar* 5 µm

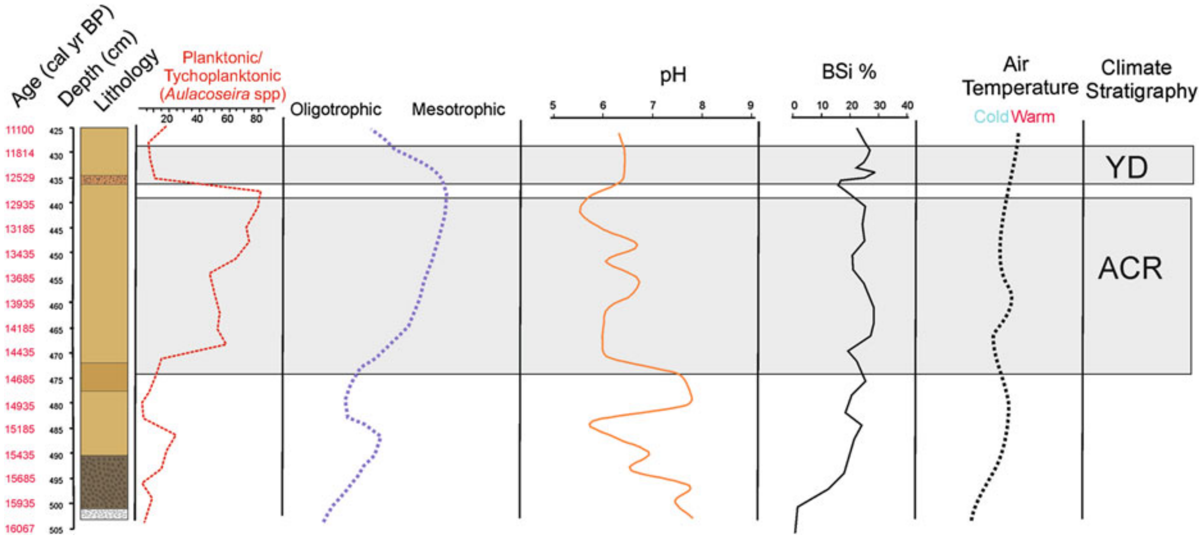

Fig. 5 Lake status changes in Laguna Casacada during the deglacial period. The *grey intervals* mark the Antarctic Cold Reversal (ACR) and the Younger Dryas (YD) climate events in the Southern and Northern Hemispheres, respectively. The qualitative air temperature diagram is based on the results of Unkel et al. (2008) and the *curve* represents the estimated mean annual climatic trend. The lithology-based age depth model applied is also shown

Discussion

Unkel et al. (2008) characterized the sediments in the lowermost part of the Laguna Cascada sequence as glacio-lacustrine clays, which were deposited during deglaciation of the catchment. We interpret the changes in sediment lithology and geochemical variables around 16 cal ka BP to be the effects of increased organic productivity, increased influence from the terrestrial biosphere and a decrease in clastic input to the lake as glacial influence ceased. Moreover, the increase in C/N ratio suggests that terrestrial organic material contributed to the pool of organic matter in the lake (Fig. 6). The diatom assemblage in subzone Ia (16–15.2 cal ka BP) is characterized by a dominance of fragilarioid taxa (Fig. 3), which are primarily benthic and common in shallow waters and in littoral areas of deeper lakes. They occur in circumneutral to alkaline and oligotrophic to mesotrophic environments (Douglas and Smol 2010). Their ability to tolerate a wide variety of environmental conditions is demonstrated by their abundance and dominance in many aquatic systems (Wilson et al. 1997). Indeed, fragilarioid taxa have been described from extreme environments, such as polar ponds and lakes (Stoermer 1993) and have also been reported from early postglacial sediments in temperate and alpine regions (Haworth 1988). The relationship between the amount of planktonic and periphytic diatoms, especially fragilarioids, has been used to reconstruct the duration and extent of lake ice cover (Smol and Douglas 2007; Rühland et al. 2008; Ampel 2008; Douglas and Smol 2010). Dominance of fragilarioid taxa between 16 and 15.2 cal ka BP suggests a flora typical of environments characterized by fairly long seasonal lake-ice cover, physical disturbances and overall harsh conditions (Denys 1990; Anderson 2000). In the middle of sub-zone Ia, around 15.6 cal ka BP, there is an increase in planktonic/tychoplanktonic *Aulacoseira* spp. This suggests shorter ice-cover periods, increased thermal stratification and increased aquatic productivity, supported by the steeply rising BSi values (Fig. 5) (Smol and Douglas 2007; Douglas and Smol 2010). Such a scenario is in agreement with the sediment stratigraphy and geochemical variables (Fig. 6), which show a change from a proglacial environment to a lake with increased organic productivity shortly after 16 cal ka BP. According to the C/N ratio, the lake sediments possess a mix of aquatic and terrestrial organic material. BSi values imply that glacial influence ceased shortly after 16 cal ka BP, and a clear peak at the end of zone Ia (Fig. 5) shows that the lake had undergone a shift from oligotrophic to mesotrophic conditions (Fig. 5).

The combined changes in diatom assemblages, BSi and geochemical variables suggest a change in lake status around 15.2 cal ka BP (beginning of subzone Ib) (Fig. 6). Alkaliphilous species and lower BSi values indicate a return to more oligotrophic conditions, and the increase in small, benthic fragilarioids points to longer ice-cover periods and possibly colder climate conditions. The slight increase in BSi, *Aulacoseira* spp. and taxa such as *Eunotia* sp. and *Pinnularia interrupta* around 14.8 cal ka BP (Fig. 3) implies a return to warmer climate conditions. Another possibility, however, is that deposition of the tephra at 475 cm depth, which likely corresponds to Reclus 1 (McCulloch et al. 2005; Stern 2008; Unkel et al. 2008), enriched the trophic state of Laguna Cascada. The epiphytic taxa, which dominate the end of subzone Ib, suggest the presence of aquatic vegetation (macrophytes) in the littoral zone of the lake.

The dominance of *Aulacoseira* spp. in zone II, which dates to between 14.4 and 12.8 cal ka BP and thus corresponds in time to the Antarctic Cold Reversal (ACR) (Hubbard et al. 2005), indicates a remarkable change in environmental conditions. The dominance of these taxa suggests an increase in water level by more than 3 m. They prefer slightly acidic to circum-neutral and oligotrophic to mesotrophic waters (van Dam et al. 1994), and are also indicative of increased nutrient cycling and thermal mixing (Kilham et al. 1996; Rühland et al. 2008). Moreover, heavily silicified *Aulacoseira* spp. require re-suspension through turbulence to maintain their position in the water column (Kilham et al. 1996). Thicker snow cover in the mountains and consequent increased meltwater discharge into the lake during spring and early summer (Sterken et al. 2008), and perhaps most importantly, strong winds, could have kept the water column turbulent (Ti and Ca, Fig. 6). Such a scenario is supported by the geochemical data, especially TC, but also the BSi record. Whereas TC shows that aquatic productivity may have already decreased by 14.5 cal ka BP and remained stable for more than 1,500 years (Fig. 6), BSi shows a decline at 14.4 cal ka BP (Fig. 5). Moreover, relatively low C/N ratios (Fig. 6) show that the deposited organic material was not dominated by terrestrial organic matter. Other studies on Isla de los Estados (Unkel et al. 2008; Ponce 2009; Ponce et al. 2011a) indicate that this period was characterized by windy and possibly fairly wet conditions.

Diatom assemblages between 12.8 and 11.1 cal ka BP are co-dominated by *Aulacoseira* spp., *Brevisira arentii* and *Stauroforma exguiformis* (Fig. 3), indicating more acidic conditions in the Laguna Cascada basin. Some other species (*Pinnularia interrupta*,

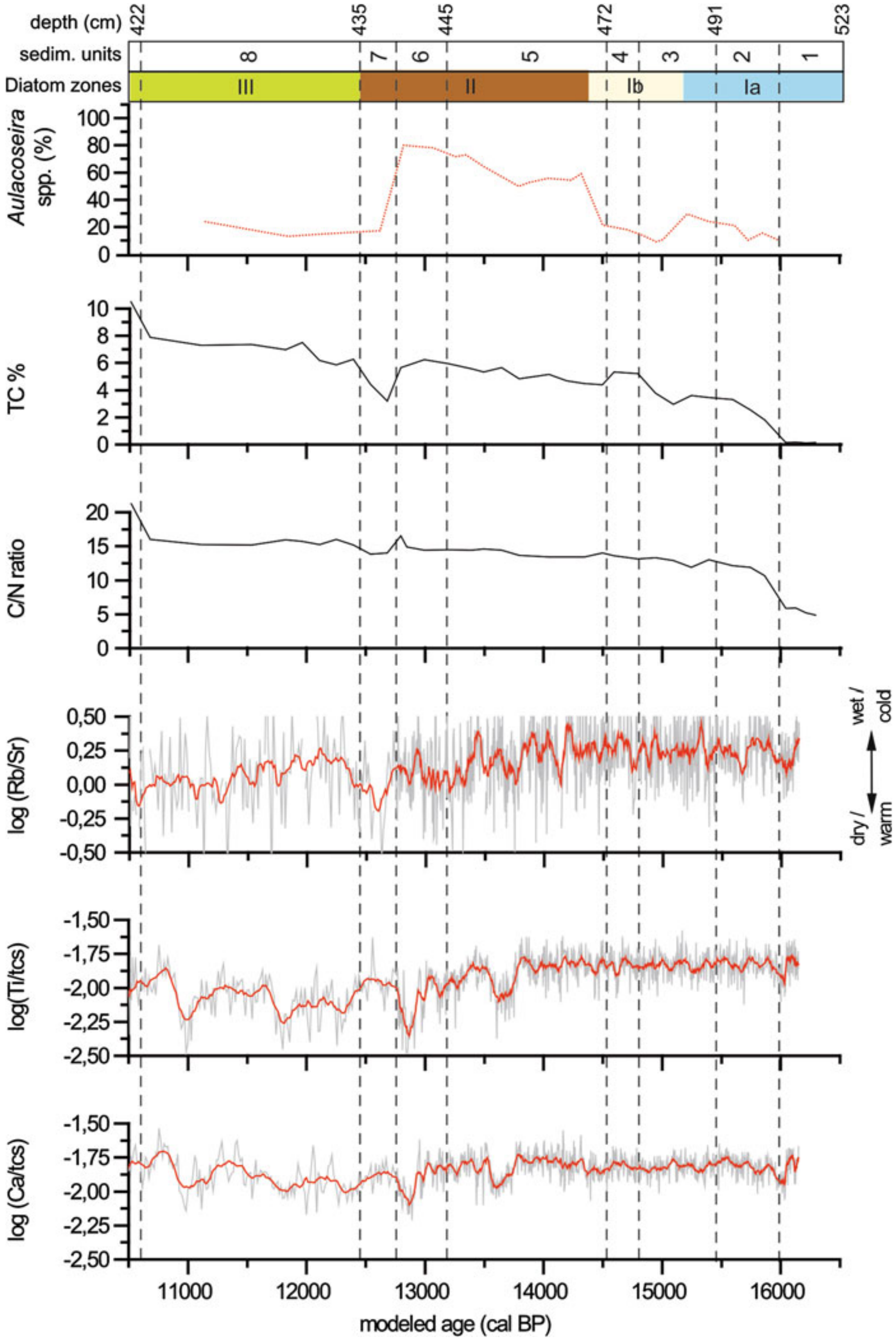

Fig. 6 *Aulacoseira* spp. percentages compared to some of the geochemical analyses plotted on a logarithmic scale. Lithologic units and depth (cm) below surface are shown to the *right*. Partly modified from Unkel et al. (2008)

Stephanodiscus cf. *rotula*, *Frustulia rhomboides*, and *Eunotia* sp.) are associated with peat bogs and damp surfaces (Krammer and Lange-Bertalot 1986), suggesting a new phase in the lake's development (Fig. 5). The lithologic and geochemical records suggest increased aquatic productivity, gradually warmer temperatures and fairly arid conditions (Unkel et al. 2008; Fig. 7) without glacial influence. Also, falling Rb/Sr ratios indicate warmer and drier conditions (Fig. 6). Warmer temperatures could have led to an expansion of the wetland surrounding the lake and to increased growth of aquatic plants, which would have provided suitable habitats and substrates for diatoms (Douglas and Smol 1995). BSi values, however, display a short-duration minimum between 12.9 and 12.7 cal ka BP, at the onset of the Younger Dryas cooling in the Northern Hemisphere, followed by higher values. The reason for this minimum may have been drier conditions and falling lake level, which led to reduced lake extent and *Aulacoseira* productivity, resulting in an ecosystem shift. With a new ecosystem in place, reflected by a shift in the diatom assemblage to dominance of benthic diatom species, aquatic productivity (BSi) could have once again been high.

Glacier retreat and warmer temperatures are reported for the Strait of Magellan between 12.6 and 11.8 cal ka BP (McCulloch and Davies 2001; McCulloch et al. 2005), which corresponds temporally to the GS-1/Younger Dryas (YD) cool event in the Northern Hemisphere. Furthermore, the multi-proxy study of Björck et al. (2012) shows that calm and dry conditions on IDE began a few centuries into the YD. Together with our diatom results, this implies a partly anti-phase behavior between Patagonia and the Northern Hemisphere at the end of the last deglaciation. This conclusion is supported by a lack of consensus regarding evidence for a cooling episode in southernmost South America, equivalent to the Northern Hemisphere YD event (Rabassa 2008).

Conclusions

The diatom record from Laguna Cascada on Isla de los Estados provides insights into lake status changes between 16 and 11 cal ka BP. Dominance of benthic fragilarioid species between 16 and 15.2 cal ka BP suggests oligotrophic conditions, long seasonal lake-ice cover and harsh environmental conditions. The marked increase in *Aulacoseira* spp. after 14.4 cal ka BP and high percentages of planktonic diatoms until 12.8 cal ka BP suggest higher nutrient input to the lake and more mesotrophic conditions, but also a turbulent water column. The increase in aquatic productivity is also shown by high values of BSi after 14.2 cal ka BP. This interval, which corresponds in time to the ACR, was characterized by less lake ice cover and higher water levels and was, in comparison with results from other studies, apparently wetter and windier. At around 12.8 cal ka BP air temperatures increased, whereas precipitation and wind strength decreased. This shows that warming during the Holocene Epoch in Tierra del Fuego began approximately 1,000 years before its defined age in the Greenland NGRIP ice core. This warming also marks the onset of the Antarctic Holocene climate optimum and continues to the top of our studied sequence. According to other authors, it persists until 10 cal ka BP in the southern Tierra del Fuego region.

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