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Late Holocene wet/dry intervals from Fuegian steppe at Laguna Carmen, southern Argentina, based on a multiproxy record

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ABSTRACT

Late Holocene environmental conditions are reconstructed from a sedimentary core (LCTF2) retrieved from Laguna Carmen (53° 40′ 60″S, 68° 18′ 0″W, 29 m a.s.l.) in the Fuegian steppe, northern Tierra del Fuego, southern Argentina. The multiproxy study utilizes pollen/spores, algae, ostracods, palynofacies, Total Organic Carbon (TOC), carbonate content, and lithology. Findings show that grass communities developed over the landscape from 4200 to 1400 cal yr BP. After that, the plant communities fluctuated between grasses to scrubland vegetation. Changes in the lake level as indicated by the halophytes, algal content and ostracod associations, revealed alternation of wet and dry intervals. The palynofacies indicate environments close to the terrestrial source with a great input of terrigenous organic matter into the lake in agreement with the sedimentary environment. By comparison with other sites from Tierra del Fuego and southwestern Patagonia, the record of wind-carried *Nothofagus* pollen is consistent with variations in the Andean forest communities as a consequence of shifts in the latitudinal position and/or strength of the westerlies. The short-term wet/dry intervals seem to be associated with climate events of local occurrence. On the other hand, some wet intervals have been reported in lacustrine records from southern Patagonia. The last millennium showed high environmental variability. Humid conditions characterized the Medieval Climate Anomaly (MCA) event, while dryness conditions were related to the Little Ice Age (LIA) event. In particular this latter interval has been related to a northward migration of the westerlies from their present day focus.

1. Introduction

The steppe region of Tierra del Fuego is the southernmost portion of the Magellanic steppe in southern South America, that extends east of the Andes at 51°25′S, crosses northern Isla Grande de Tierra del Fuego and reaches the *Nothofagus* forests at ~54°S, in the centre of the island (Collantes et al., 2009). These windy and flat lowlands, with minor hills, tablelands and even low mountainous areas, are under the permanent influence of the southern westerly winds (SWW). The palaeoenvironmental reconstructions from this region offer a unique opportunity to add valuable information to the understanding of Late Quaternary climate history at high latitudes. Since it is located in the path of the SWW, the main source of precipitation, it conforms an important sector to address questions related to timing and scope of Holocene climate fluctuations and their subsequent effects on the biomass of this region.

Palaeoclimate studies of Quaternary terrestrial environments from Tierra del Fuego have been mainly undertaken in the forested southernmost part of the island. Postglacial palaeoecological data have been reported along the Beagle Channel area (Heusser, 2003; Markgraf and Huber, 2010; Borromei et al., 2014), on the low inner Fuegian Andes valleys (Borromei, 1995; Borromei et al., 2007, 2016; Mauquoy et al., 2004), and high-elevation Andean valleys (Markgraf, 1993; Borromei et al., 2010; Markgraf and Huber, 2010). Several palynological studies focused on central area of the archipelago (Markgraf, 1983; Heusser and Rabassa, 1995; Burry et al., 2007; Musotto et al., 2013, 2016,

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2017a, 2017b; Waldmann et al., 2014). Despite the substantial number of palaeoclimate studies, records from the northern region of Tierra del Fuego are few (Markgraf, 1980; Heusser et al., 1989–1990; Heusser, 1993). Taken together, palaeoenvironmental studies document the development of a lateglacial impoverished steppe-tundra vegetation with scattered trees after deglaciation followed by early Holocene forest expansion, and a late Holocene closed-canopy *Nothofagus* forest. Changes in the composition and distribution of these past plant communities suggested primarily variations in the amount of westerly-driven precipitation related to shifts in the latitudinal position and/or strength of the SWW, as well as changes in the Antarctic sea-ice extension, position of the Polar Front, and solar variability (Heusser, 2003; Markgraf and Huber, 2010; Kilian and Lamy, 2012).

Multiproxy records from lake deposits have the potential to enhance our knowledge of past environmental changes. Despite the existence of several shallow lakes in the semiarid steppe in northern Tierra del Fuego, palaeoclimate proxy studies based on lake sediments remain scarce (Gogorza et al., 2013; Fernández et al., 2015, 2016, 2017; Laprida et al., 2014; Ramón Mercau, 2015). The study of palynomorphs in lake sediments, however, adds valuable information on changes in the aquatic environment, not available from peat sediments. Thus, remains of coccal green algae such as *Botryococcus braunii* and *Pediastrum* complex reveal hydrological changes associated with precipitation-evaporation balance (Tyson, 1995, and references quoted therein; Medeanic et al., 2003). The analysis of palynological organic matter (palynofacies) preserved in the sediment sequences is of special interest since it provides valuable information for a more accurate interpretation of depositional palaeoenvironments and palaeoclimatic conditions (Tyson, 1995; Batten, 1983). Continental ostracods are also excellent proxies in Quaternary palaeoenvironmental studies. Their distribution and abundance are controlled by the physicochemical properties (salinity, ion concentration, pH, temperature, dissolved oxygen), hydraulic conditions, and other environmental properties of the water they inhabit (Mezquita et al., 2005; Ruiz et al., 2013). Therefore, the same physical and chemical principles should also apply for the past (Forester, 1991). Although there are several ostracod studies in Patagonia (Cusminsky and Whatley, 1996; Whatley and Cusminsky, 1999; Cusminsky et al., 2005, 2011; Coviaga et al., 2017a, 2017b; Ramos et al., 2017; Ohlendorf et al., 2014; Ramón Mercau et al., 2012; Ramón Mercau and Laprida, 2016), knowledge of ostracods remains scarce for Tierra del Fuego (Laprida et al., 2014; Ramón Mercau, 2015).

Distinguishing local from regional signals of patterns of change poses important challenges for reconstructing the history of ecosystems and climate conditions. In order to generate robust centennial- to millennial-scale interpretations it is necessary to develop a large number of these studies in comparable sites (Stutz et al., 2010). In this sense, the current contribution provides new insights into the late Holocene environmental and climate changes from a multiproxy record located in a little studied area in the Fuegian steppe. Here, we present analyses of palynomorphs (pollen, spores and algae) and their associated palynofacies, ostracods, total organic carbon (TOC), and carbonate ($CO_3{}^{-2}$) content in a sedimentary core (LCTF2) retrieved from Laguna Carmen (53° 40′ 60″S, 68° 18′ 0″W, Fig. 1), northern Tierra del Fuego, spanning the last ~4200 cal yr BP. Taken together, these proxy data will allow us to decipher the vegetation dynamics and the shallow lake evolution in response to climate changes related to changes in the atmospheric circulation pattern during the late Holocene.

2. Environmental context of study site

The climate of Tierra del Fuego, southern South America, is controlled by the South Pacific and South Atlantic Polar Fronts, which result in areas of low pressure located south and southeast of the region throughout the year. Northward movement of polar air masses, particularly in the winter, often gives rise to cold southerly winds (Tuhkanen, 1992). In the lee side of the Andes and in the Fuegian steppe, winds descending to the lowlands are dry and temperate, and produce high evaporation and negative water balance during summer. At the Cape Espíritu Santo, in the northern tip of Tierra del Fuego (Fig. 1A), precipitation is 300 mm yr^{-1}, and increases southwards of the Grande river to about 450 mm/yr. Mean temperature of the coldest month (July) is 0.8 °C, and 10.1 °C of the warmest month (January) (Quiroga, 2018). In this region, an Aridity Index of 0.75 characterizes the hydric regime as Cold Subhumid Oceanic climate (Coronato et al., 2008). Meteorological information is provided by an automatic weather station located at San Julio Ranch, 80 km westwards of the Atlantic coast (Fig. 1B). Records from 2011 to 2016 showed that winds blow almost constantly from west and southwest directions with an annual average rate of 13 km/h and maximum speeds of 111 km/h; annual calms are 2.18‰ (Quiroga, 2018). The intense and strong westerlies influence over climatic parameters as well as the vegetational setting (i.e., deformation of trees) and the physiology of plants (reduced photosynthesis) (Schäbitz et al., 2013).

The dominant vegetation community of this region is the semiarid grassy steppe, covering 5000 km^2 from the Strait of Magellan to the south of the Grande River (Fig. 1A). The plant communities are divided into two groups (acidophilous/mesotrophic and neuthrophilous vegetation) according to the landscape units, edaphic characteristics and land use (Collantes et al., 1999). In total eight communities were recognized along a floristic gradient from ericoid dwarf shrubs to forbs and grasses as soil acidity decreased (Fig. 1B). In particular, the wetland environments or 'vegas' comprise marshes of sedges and rushes sometimes with high abundance of prostrate herbs, mainly *Caltha sagittata*, and wet grasslands with cushion shrubs, especially *Azorella trifurcata* (Collantes et al., 2009). The steppe vegetation in the surroundings of Laguna Carmen (Fig. 1B) corresponds mainly to the neutrophilous vegetation (Collantes et al., 1999). It is characterized by the presence of *Festuca gracillima* tussock grasslands with short grasses (*Poa*, *Trisetum*) with less frequent forbs such as *Adesmia*, *Calceolaria*, *Cerastium arvense*, and *Vicia*. The lake littoral zone is mainly covered by grasses, sedges, cushion-type vegetation and halophytes. The hill slopes show a physiognomy of open scrublands with *Chiliotrichum diffusum*, *Empetrum rubrum*, and *Berberis*. The steppe vegetation forms a continuous ground cover except where it has been disturbed by overgrazing promoting the formation of different erosive features as deflation hollows, terraces and mushroom-shaped soils (Coronato et al., 2017).

The Laguna Carmen (~29 m a.s.l., Fig. 1C and D) is a shallow, freshwater body, located in the semiarid steppe, between the Chico and Grande rivers. It belongs to a group of shallow lakes with a maximum water depth around 1.5 m, with high salinity and turbidity, and flat bottom, defined as pans when they are dry (Villarreal and Coronato, 2017). Sub-circular in shape, 1.97 km^2 in area, Laguna Carmen is the drainage basin depocenter fed by a small number of semi-permanent water courses. The lake occupies a depression carved into the Middle to Lower Miocene marine sediments belonging to the Carmen Silva Formation (Codignotto and Malumnián, 1981; Olivero et al., 2004). The sandstone and conglomerate outcrops of this formation form coastal cliffs of 1.5 m high on its northern, eastern and southern coast, due to the erosive action of the waves generated by the permanent influence of winds from the northwest, west and southwest. Aeolian sedimentary accumulations of silty-clay in some sections of the cliffs are developed on the rocky outcrops. The western or windward coast, however, is low and receives the largest tributary to the basin, but with little or no flow during summer and winter. This area is interrupted by a rocky outcrop, which forms a spike from west to east, partially separating the lagoon into two bodies (Coronato et al., 2017) According to geomorphological data, an aeolian genesis was proposed for the depression in which this shallow lake was formed, mainly due to deflation carving alluvial deposits in a paleostream junction area. The paleostreams belonged to a former basin network, which drained towards the Atlantic coast (Villarreal and Coronato, 2017). These processes probably may have initiated during one of the cycles of aridity that occurred in the region

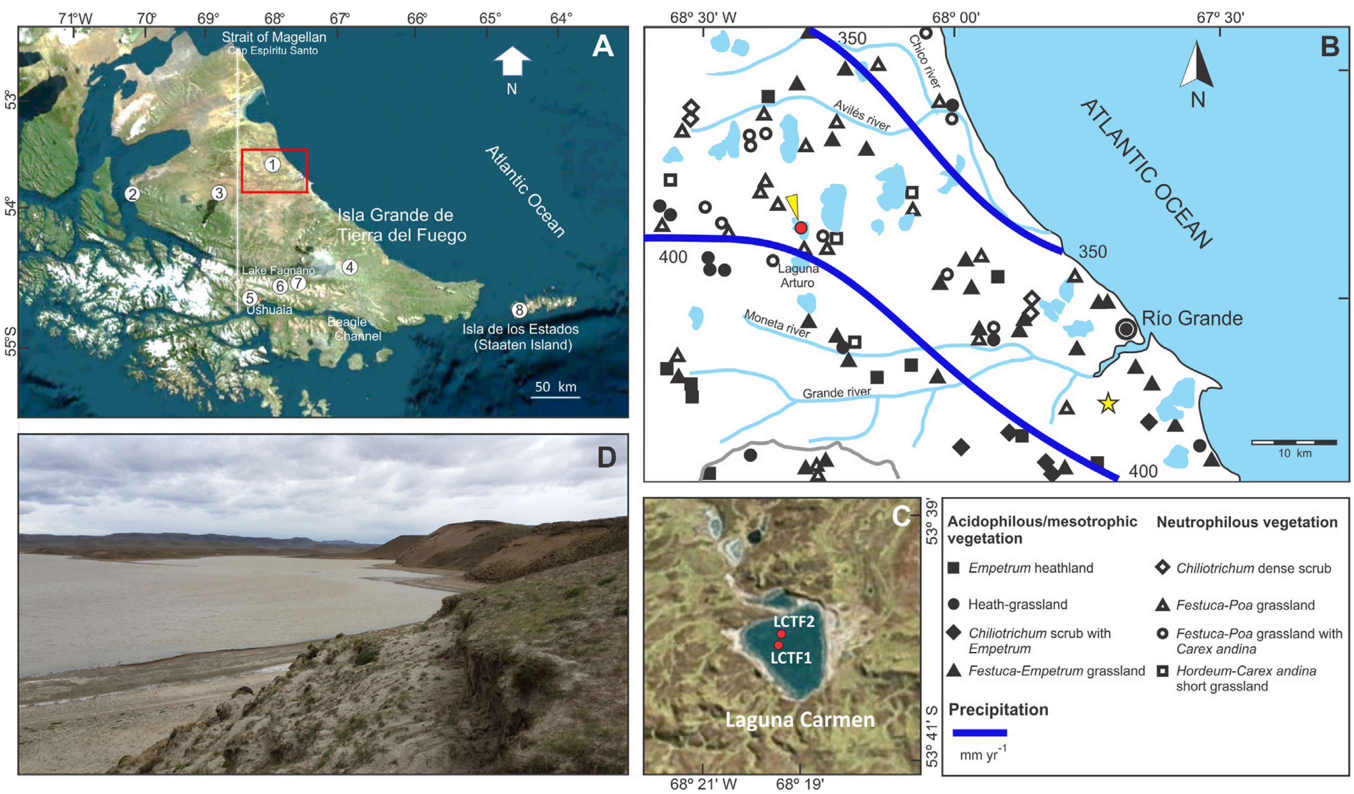

Fig. 1. (A) Satellite image of the Fuegian Archipelago showing the location of the sites cited in the text: 1. Laguna Carmen; 2. Punta Yartou; 3. Onamonte; 4. La Correntina; 5. Cañadón del Toro; 6. Las Cotorras; 7. Terra Australis; 8. Isla de los Estados (downloaded from SAS Planet, free version). (B) Present vegetation map of northern Isla Grande de Tierra del Fuego with the mean annual precipitation isohyets (modified from Collantes et al., 1999). The location of sedimentary core LCTF2 (red circle), and the meteorological station (yellow star) are shown as well. (C) Aerial photograph of Laguna Carmen showing the two sedimentary cores (LCTF1 and LCTF2) (taken from Google Earth, free version). (D) Ground photograph of Laguna Carmen facing to the NW. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

during the mid-Holocene (Orgeira et al., 2012; Coronato et al., 2017). A period of intense wind activity for the region has been reported from Laguna Arturo (Fig. 1B), distant 2 km south of the studied site (Coronato et al., 2011), where a 6.49 m thick of a dune stratum had been deposited between paleosols radiocarbon dated at 5800 ± 64 yr BP (6557 cal yr BP) and 4871 ± 59 yr BP (5545 cal yr BP) (Coronato et al., 2011, 2017).

3. Methodology

3.1. Sampling and sediment analyses

A 117 cm-deep sedimentary core (LCTF2) was obtained from the centre of the lake using a Livingstone piston corer during the 2011 southern autumn. The core was stored at 4 °C in the Laboratorio de Sondeos de Ambientes Continentales y Marinos (SACMa, FCEyN-Universidad de Buenos Aires, Argentina). Samples for palynological and associated palynofacies analyses were taken at 2.5-cm intervals from top to 18.75 cm depth, and at 1.25-cm intervals from 18.75 cm depth to the base. Ostracod analysis, total organic carbon content and carbonate content were performed from contiguous samples taken at 2.5-cm intervals. Determination of total carbon (TC) was performed by dry combustion with a LECO (CR12) automatic analyzer at the Laboratorio de Servicios Analíticos de Suelos, Plantas y Ambiente (LABSPA, CERZOS-Universidad Nacional del Sur, Argentina). The percentage of total organic carbon (TOC) was measured by difference between the amount of total carbon (TC) and total inorganic carbon (TIC) in the sediments calcined at 450 °C for 24 h. The percentage of carbonate (CO_3^{-2}) was calculated from the TIC data using the following equation: CO_3 (wt%) = TIC (wt%) × 5.

3.2. Chronology and age-depth model

The chronology of the core LCTF2 is based on three AMS radiocarbon dates performed on organic matter contained in the lacustrine sediments. They were obtained at the AMS Facility Laboratory of the University of Arizona, USA. Radiocarbon ages (Table 1) were calibrated against the Southern Hemisphere curve SHCal13 (Hogg et al., 2013) using the program Calib 7.1 software (Stuiver et al., 2015). The age-depth model was constructed by the OxCal 4.2.4 (Bronk Ramsey and Lee, 2013). Ages are reported as calendar years before 1950 CE (cal yr BP). The sediment accumulation rate was calculated jointly with the age-depth model using the same software.

3.3. Palynomorph analysis

Palynological samples were prepared following the standard techniques of Faegri and Iversen (1989). No oxidation and no acetolysis were applied in order to preserve the more fragile non-pollen

Table 1
Summarized sedimentary description of the LCTF2 core (modified from Coronato et al., 2017).

Depth (cm)	Unit	Sediment characteristics
16–0	a	Silt with sandy-silt lenses and silt-sand layers. Carbonate content (5.7%) reaches maximum values. TOC (< 1.7%).
51–16	b	Silt with sandy-silt layers and lenses. TOC (< 2%) and carbonate content (< 2%).
117–51	c	Silt with sand grains, sandy layer and sandy-silt lenses. TOC (up to 2.3%). Carbonate content (up to 2.8%).

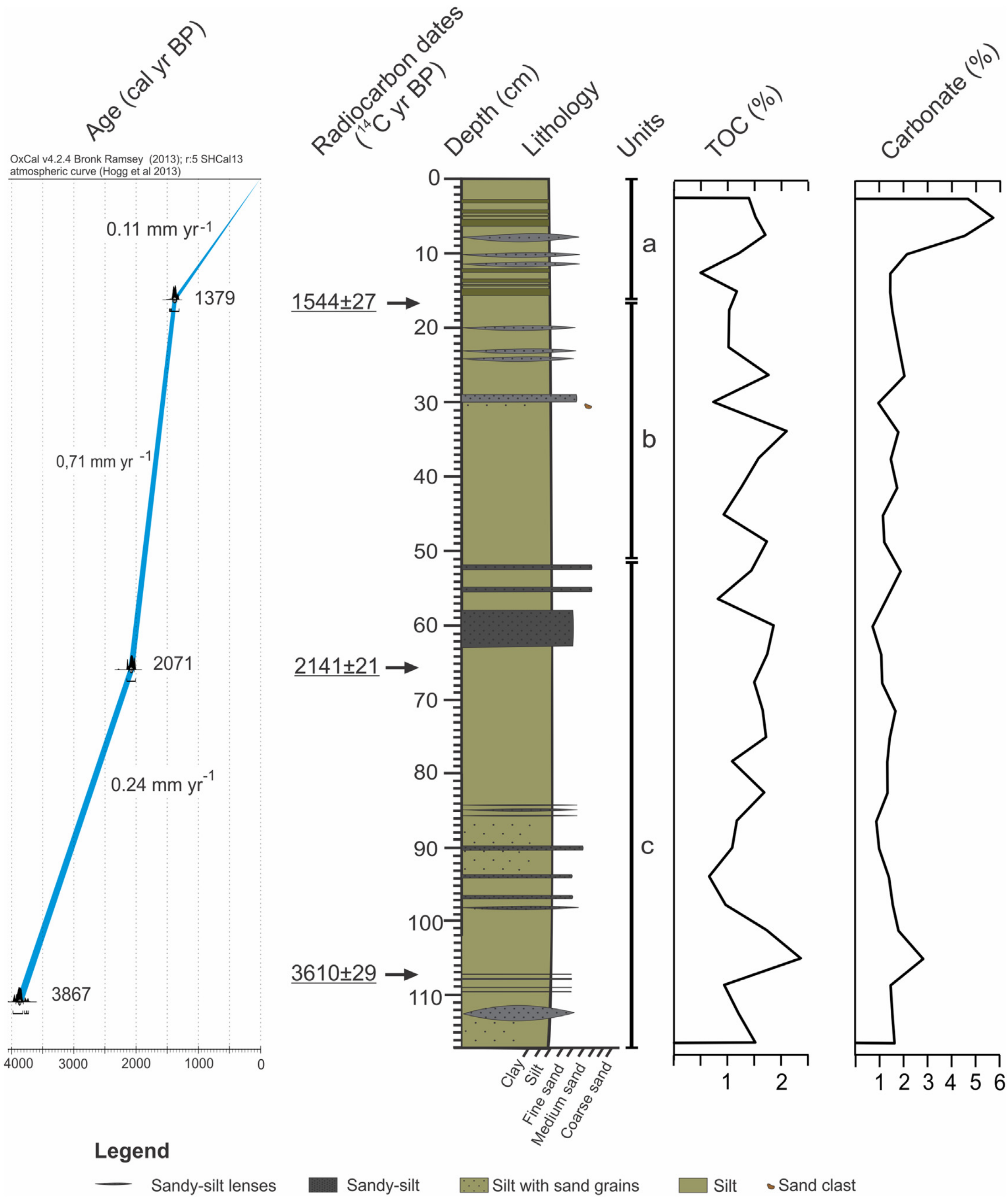

Fig. 2. Age–depth model curve, radiocarbon dates, sediment description, organic matter and carbonate content on sediments plotted against depth, from LCTF2 sedimentary core at Laguna Carmen site (modified from Coronato et al., 2017).

palynomorphs and the palynological organic matter. All samples were stained with Safranin-O (Stanley, 1966). Two *Lycopodium clavatum* spore marker tablets were added before the treatments in order to calculate palynomorph concentrations per gram of dry weight of sediment (Stockmarr, 1971). Identified non-pollen palynomorphs (NPPs) included spores of bryophytes (*Phaeoceros*, *Anthoceros*, *Sphagnum*), pteridophytes (*Lycopodium*, Polypodiaceae), and colonies of green algae (*Pediastrum*, *Botryococcus braunii*). The pollen sum of terrestrial and aquatic vascular plants ranged between 314 and 901 grains. Each taxon was expressed as a percentage of the total pollen sum. Frequencies of bryophytes and pteridophytes were calculated as percentage of the total pollen sum plus spores sum. Algae frequencies were calculated in relation to the total pollen sum plus algae sum.

Pollen zones were defined based on visual inspection of the pollen record and stratigraphically constrained cluster analysis using Edwards & Cavalli-Sforza's chord distance square-root transformation (CONISS). Pollen types selected for this analysis were those whose percentages were ≥2% after recalculating sums and percentages. Diagrams were drawn using TGView 2.0.1 program (Grimm, 2012). In order to interpret the fossil pollen assemblages, we used the modern pollen datasets from surface soil samples (Heusser, 1989; Trivi de Mandri et al., 2006; Musotto et al., 2012) and the present-day vegetation on Tierra del Fuego (Pisano, 1977; Moore, 1983).

The rarefaction technique, applied to fossil pollen sequences for analyzing palynological richness, is a method to interpret the changes in the biological diversity of landscapes and vegetation (Berglund et al., 2008). It has been used in the present study to evaluate the dynamic changes in the steppe vegetation structure through the late Holocene. Thus, the estimation of the number of pollen types was carried out using Psimpoll 4.27 (Bennett, 2009). It is based on the lowest pollen

Table 2
Radiocarbon dates and calibrated ages of selected samples from LCTF2 and LCTF1 sedimentary cores at Laguna Carmen site.

Sample depth (cm)	Lab. code	Uncalibrated age (^{14}C years BP)	$\delta^{13}C$ (‰)	Calibrated years BP (median probability)	1σ range	2σ range
LCTF2-16.25.5	AA104695	1544 ± 27	−27.3	1379	1353–1411	1310–1432
LCTF2-65.7	AA107270	2141 ± 21	−28.4	2071	2041–2095	2010–2116
LCTF2-107.5	AA104696	3610 ± 29	−31.2	3867	3829–3924	3818–3974
LCTF1-13.75	Beta-343,218	1220 ± 30	−28.2	1087	999–1012	982–1032
LCTF1-113.75	Beta-343,219	3300 ± 30	−28.3	3485	3447–3512	3397–3568

sum of the group of samples being compared, of 314 grains ($E_{(T314)}$).

The lake-level fluctuations were estimated from the palynomorph salinity index (PSI) (modified from Vilanova et al., 2006). PSI represents halophytic palynomorph types (Chenopodiaceae, Plumbaginaceae, and *B. braunii*) as a percentage of halophytic plus hydrophytic palynomorphs types (Cyperaceae, *Myriophyllum*, and *Pediastrum*). Poaceae pollen is not included as it does not correspond exclusively to halophytic taxa. Higher percentages of PSI represent times of low water level in the lake.

3.4. Palynofacies analysis

Samples for palynofacial analysis were mounted using a glycerine-based jelly, after chemical removal (HCl and HF) of the mineral matrix and sieving through a 10 μm mesh screen. The palynological matter was systematically examined under normal transmitted light. According to Tyson (1995), the palynological organic matter was grouped into four main categories: 1) phytoclasts (translucent and opaque), 2) amorphous organic matter (AOM), 3) palynomorphs (pollen, spores and algae), and 4) zooclasts (fragmentary material of animal derivation). In order to quantify the relative amount of particulate organic matter, a minimum of 500 particles larger than 10 μm were counted for each sample (Tyson, 1995). The cluster analysis was performed with using the PAST 3.14 program (Hammer et al., 2001) to test the group consistency. The palynofacies were recognized by measurement of the Euclidean distance with the UPGMA-Unweighted pair groups with arithmetic averages (Hammer et al., 2001).

3.5. Ostracod analysis

Dry sediments were processed and disaggregated using tap water, and washed through a 63 μm mesh and dried at room temperature. Ostracod valves and carapaces, both adults and juveniles, were picked and counted under binocular microscope. In order to identify the species and to perform the statistical analysis, only adult individuals have been used. The species were identified following Cusminsky and Whatley (1996), Cusminsky et al. (2005), Karanovic (2012), Coviaga (2016), and Ramos et al. (2017). Due to the small numbers of individuals recovered in some samples, and in order to have enough ostracods for statistical analysis, the quantity recovered was presented as weight in 10 g of sediments. The ostracod data were plotted using TGView 2.0.1 program (Grimm, 2012). To distinguish different assemblages along the sequence, a stratigraphically constrained sum-of-squares cluster analysis (CONISS) was applied to the percentage values of ostracod species. Based on the modern ostracod datasets published in Ramón Mercau and Laprida (2016) and Coviaga et al. (2017a), a conductivity reconstruction (μS/cm) was performed using a weighted averaging (WA) regression (C2 software, Juggins, 2003).

4. Results

4.1. Sedimentology and chronology

The sedimentary core LCTF2 is mainly composed of massive silt with thin sandy-silt levels and sandy lenses (Fig. 2). Coronato et al. (2017) divided the core LCTF2 into three lithologic units based on granulometric analysis and sedimentological visual descriptions. From base to top, they are: Unit c (117–51 cm depth), Unit b (51–16 cm), and Unit a (16–0 cm) (Table 1). Lithological details are fully described by Coronato et al. (2017). In general, the core shows massive silty-clays interbedded with sandy lenses or layers. In Unit c, the TOC values vary between 0.7% and 2.3%, while the carbonate content ranges between 0.7% and 2.8%. Unit b shows values similar to those of the previous unit, with TOC (0.7–2.0%) and carbonate (0.9–2.0%). While in Unit a, TOC values decrease (0.5–1.7%) and carbonate content surpasses the 1.4% reaching a maximum value of 5.7% at 5 cm-depth.

Age/depth relationship (Fig. 2) showed an average deposition rate of 0.24 mm yr^{-1} from the estimated basal age of 4200 cal yr BP to 2100 cal yr BP, followed by a comparatively higher value of 0.71 mm yr^{-1} between 2100 and 1400 cal yr BP, and to lower values (0.11 mm yr^{-1}) from 1400 cal yr BP to present. Radiocarbon ages from the sedimentary core LCTF1 (Fig. 1C; Table 2) dated 3300 ± 30 ^{14}C yr BP at 113.75 cm depth and 1220 ± 30 ^{14}C yr BP at 13.75 cm depth (Coronato et al., 2017), confirm the late Holocene age for the studied sequence.

4.2. Palynomorph analysis

The palynological record from core LCTF2 has been divided into five local palynological zones (C-1 to C-5) (Fig. 3). Because of the independence of the measurements, the calculation of the palynomorph concentrations (Fig. 4) is a useful tool to interpret past plant communities where high local pollen production leads an over-representation of some taxa giving a false impression of the past vegetation.

Zone C-1 (115–86 cm; ca. 4200–3000 cal yr BP) is dominated by Poaceae (up to 52%) accompanied by Chenopodiaceae (5–18%), and Asteraceae subf. Asteroideae (8–13%). *Empetrum rubrum*, herbaceous taxa (Caryophyllaceae, *Acaena*, Asteroideae subf. Cichorioideae), and Cyperaceae are present in low values < 5%. The arboreal component, *Nothofagus dombeyi*-type, decreases from 34% to 16% towards the upper boundary of the zone. Palynological richness values vary between 12 and 16. Total pollen concentrations range between 4300 and 15,500 grains/g, contributed mainly by shrubs and herbs (11,500 grains/g) with Poaceae concentration values of 5800 grains/g. *N. dombeyi*-type records up to 3800 grains/g. Among NPPs, *Pediastrum* shows low proportions (4%) at the beginning of this zone, and rises to 39% after 3500 cal yr BP. *Botryococcus braunii* varies between 10 and 30%. Total algae concentrations reach up to 10,600 algae/g.

In zone C-2 (86–68 cm; 3000–2100 cal yr BP) Poaceae decrease (26–32%), while Chenopodiaceae (20–33%) and Asteraceae subf. Asteroideae (10–24%) increase. Caryophyllaceae reach up to 6%. Other herbs (*Acaena*, Rubiaceae) and *E. rubrum* are present with low values (2%). Cyperaceae (3%) show similar percentages to those in the previous zone (C-1). *Nothofagus dombeyi*-type declines to 17%. Palynological richness remains with similar values to those recorded in the previous zone (C-1). Total pollen concentration values decrease to < 12,800 grains/g with shrub and herb concentrations to < 10,300 grains/g. Tree concentrations are low < 2200 grains/g. Among algae, *Pediastrum* ranges between 3 and 27% with a maximum peak of 65%, and *B. braunii* are present with 9–24%. Total algae concentrations decline to < 9000 algae/g with a maximum peak of 19,400 algae/g belonging to *Pediastrum*.

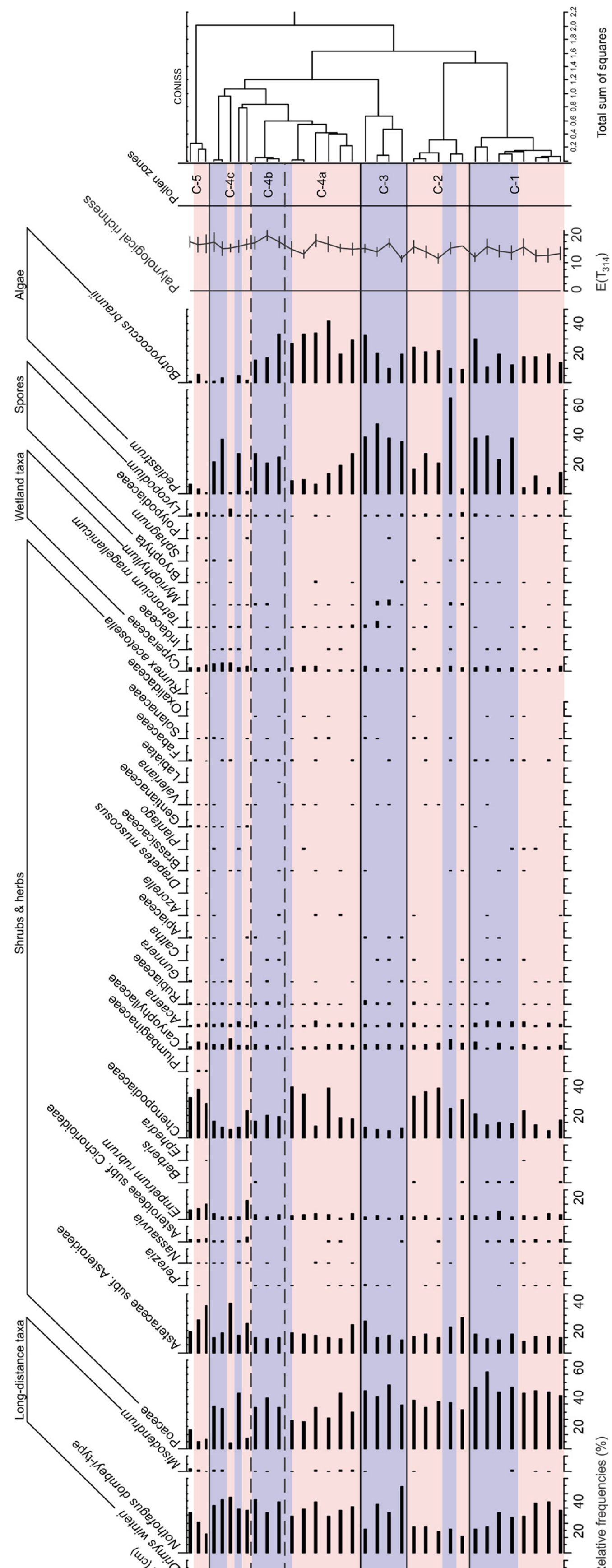

Fig. 3. Fossil palynomorph percentage diagram from LCTF2 sedimentary core at Laguna Carmen site, including palynological richness (base sum of 314). The pink horizontal rectangles indicate the inferred dry intervals (LCd), whereas the blue rectangles indicate wet intervals (LCw). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

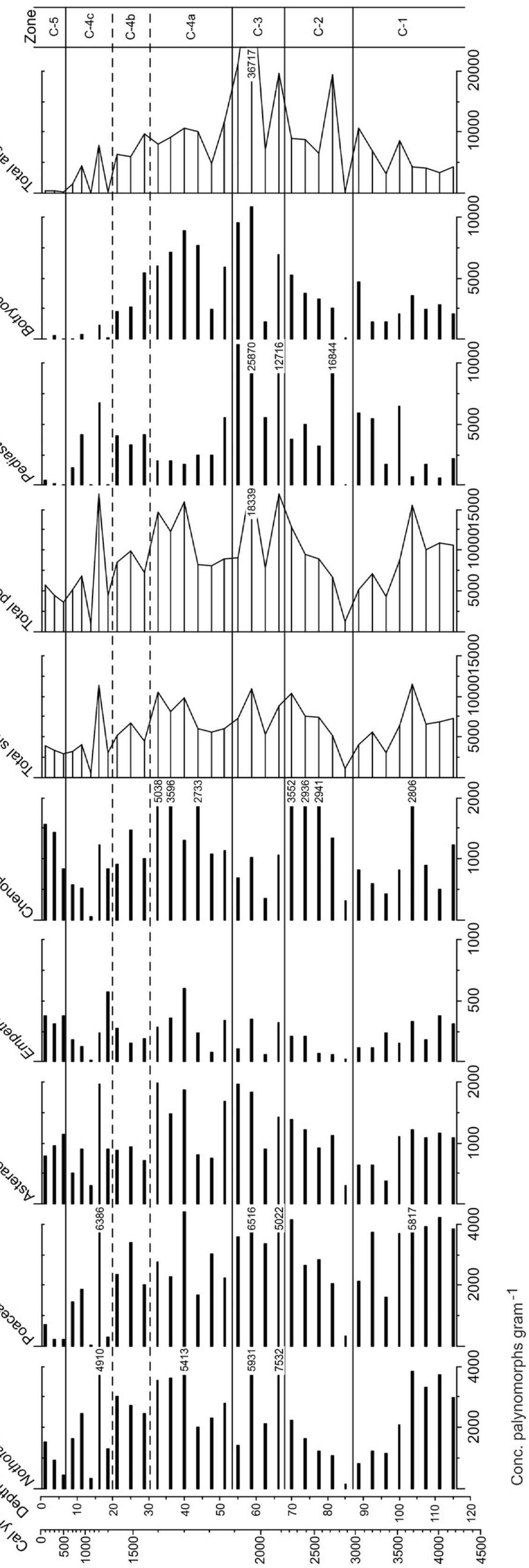

Fig. 4. Fossil palynomorph concentration (palynomorphs gram^{-1}) diagram from LCTF2 sedimentary core at Laguna Carmen site.

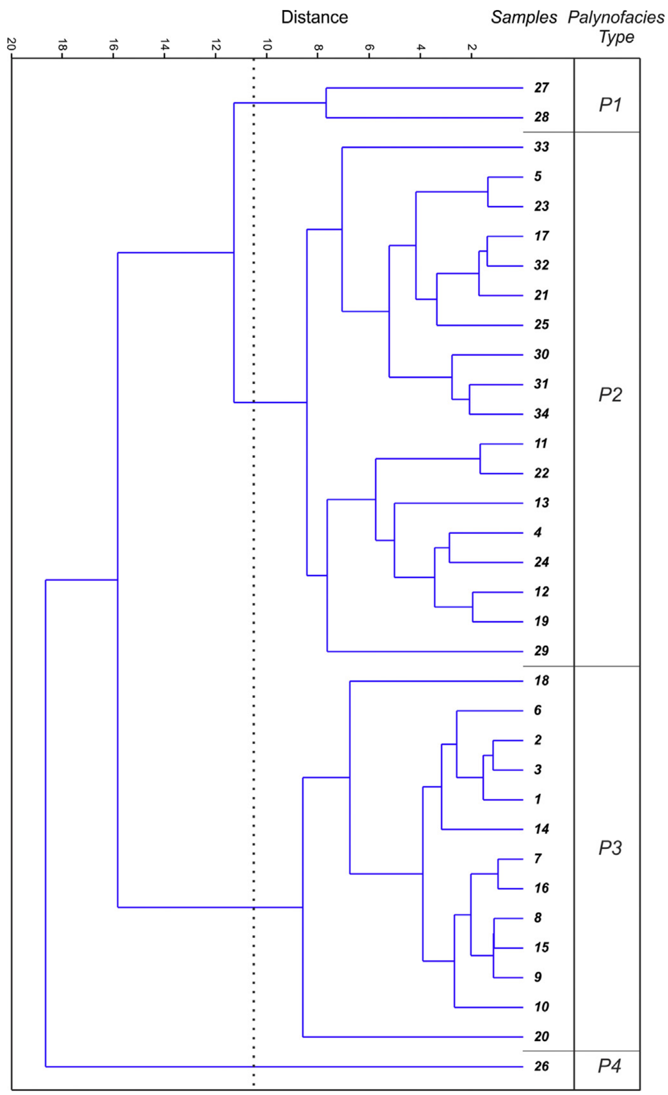

Fig. 5. Cluster analysis and types of palynofacies from LCTF2 sedimentary core. Four principal palynofacies are recognized in this core, P1–P4 (see text for more details).

Zone C-3 (68–52 cm; 2100–1900 cal yr BP) displays an increase in Poaceae (30–43%). Asteraceae subf. Asteroideae decrease varying between 8 and 22%, also Chenopodiaceae abruptly decline to < 8%. Other taxa include Rubiaceae (< 3%), Caryophyllaceae (< 3%), *E. rubrum* (< 2%), and *Acaena* (2%). Cyperaceae (3%) maintain similar values compared to the previous zone (C-2). *Tetroncium magellanicum* and *Myriophyllum* increase to 4% and 3%, respectively. *N. dombeyi*-type decreases from 45% to 16% towards the upper boundary of the zone. The palynological richness values increase to 17. Total pollen concentration values vary between 7800 and 18,300 grains/g with shrub and herb concentrations of 10,900 grains/g and *N. dombeyi*-type concentrations of 7500 grains g^{-1}. The alga *Pediastrum* increases to 35–47% and *B. braunii* varies between 10% and 32%. Total algae concentration values reach up to 36,700 algae/g contributed mainly by *Pediastrum* (25,800 algae/g).

Zone C-4 (52–7 cm; 1900–700 cal yr BP) can be subdivided into subzone 4a, 4b and 4c. In subzone C-4a (52–30 cm; 1900–1600 cal yr BP) Poaceae (18–38%) decrease and Chenopodiaceae reach maxima values (up to 34%). Asteraceae subf. Asteroideae (< 20%), *E. rubrum* (4%), *Acaena* (4%), and Caryophyllaceae (3%) show similar values as in the previous zone (C-3). *Misodendrum*, *Perezia*, Rubiaceae, Brassicaceae, and *Valeriana* record low proportions < 1%. *N. dombeyi*-type increases and maintains percentages ranging between 24 and 35% throughout the subzone. Long-distance taxa including *Podocarpus*, *N. obliqua*-type and *Drimys winteri* are present with low values of < 1%. Palynological richness values increase to 18. Total pollen (< 15,800 grains/g), shrub and herb (< 10,500 grains/g) and tree (< 5500 grains/g) concentration values decrease. Among algae, *Pediastrum* decreases from 27% to 6% at mid of the zone, and *B. braunii* increases up to 42%. Total algae concentrations decline to < 11,500 algae/g.

In subzone C-4b (30–20 cm; 1600–1400 cal yr BP) Poaceae vary between 28 and 34%, Asteraceae subf. Asteroideae are present with < 10%, and *E. rubrum* with < 3%. Chenopodiaceae do not surpass 15%. *N. dombeyi*-type ranges between 34 and 36%. Long-distance taxa including *Podocarpus* and *N. obliqua*-type are also present (< 1%). Palynological richness records the highest values (20). Total pollen (< 9900 grains g^{-1}), shrub and herb (< 6700 grains/g) and tree (< 3000 grains/g) concentrations decline. *Pediastrum* frequencies rise up to 25% and *B. braunii* declines to 15%. Total algae concentrations also drop to < 9600 algae/g.

Subzone C-4c (20–7 cm; 1400–700 cal yr BP) is characterized by lower and highly fluctuating values of Poaceae (from 4% to 38%) and Asteraceae subf. Asteroideae (from 10 to 34%). Chenopodiaceae decrease to 5%. *E. rubrum* (2–13%), Caryophyllaceae (2–7%), *Acaena* (4%), and Asteroideae subf. Cichorioideae (2%) increase. Other taxa including *Nassauvia*, Rubiaceae, *Gunnera*, Euphorbiaceae are present with low values (< 1%). Cyperaceae (6%) and *Lycopodium* (5%) increase, while *T. magellanicum* and *Myriophyllum* record proportions of < 1%. *N. dombeyi*-type rises to 29–38% and *Drimys winteri* is recorded with < 1%. Palynological richness values decline to 17. Total pollen concentrations increase up to 16,900 grains/g with shrub and herb concentration values up to 11,300 grains/g and tree concentrations up to 4900 grains/g. The algae *Pediastrum* reports fluctuation percentages from 1% to 36%, and *B. braunii* decreases to < 5%. Total algae concentrations decline to < 7900 algae/g.

Zone C-5 (7–0 cm; 700–0 cal yr BP) shows a decrease in the proportions of Poaceae (< 13%). While Chenopodiaceae (up to 32%), Asteraceae subf. Asteroideae (up to 31%), and *E. rubrum* (up to 10%) increase their frequencies. Other taxa include Cyperaceae (5%), Caryophyllaceae (4%), Asteraceae subf. Cichorioideae (2%), and *Acaena* (2%). *Nassauvia*, Plumbaginaceae, Rubiaceae, Gentianaceae, and *Valeriana* are present with low values < 1%. *N. dombeyi*-type declines to 12–27%. Palynological richness remains with values similar to those recorded in the previous subzone (C-4b). Total pollen concentrations record low values (< 5700 grains/g) with shrub and herb concentrations < 4000 grains/g and *N. dombeyi*-type concentrations < 1500 grains/g. *Pediastrum* declines to < 5% and *B. braunii* maintains similar values than the previous subzone (C-4a). Total algae concentrations also decrease to < 450 algae/g.

4.3. Palynofacies analysis

Cluster analysis of all sediment samples resulted in four palynofacies types (Fig. 5), based on the relative frequencies of four identified categories of palynological organic matter. Many variables are involved in the deposition of palynological matter, as described by several authors (e.g., Batten, 1983; Tyson, 1995; Candel et al., 2013). Principal components of organic matter and their palaeoenvironmental interpretation are showed in Fig. 6 and Table 3.

Palynofacies type 1 (P1) is represented by samples 27 and 28. It is characterized by a high proportion of mainly non-biostructured translucent phytoclasts (74.7–75.8%). Although biostructured phytoclasts are less abundant, they show the highest values throughout the section of 7.5%. The opaque phytoclasts (up to 5.5%) are mainly of blade-shaped form. AOM, (mainly spongy), is present with values up to 6.5%. The palynomorph group varies from 14 to 18.3%, and the zooclast group represents only 0.2% of the total.

Palynofacies type 2 (P2) is present in most of the samples and is

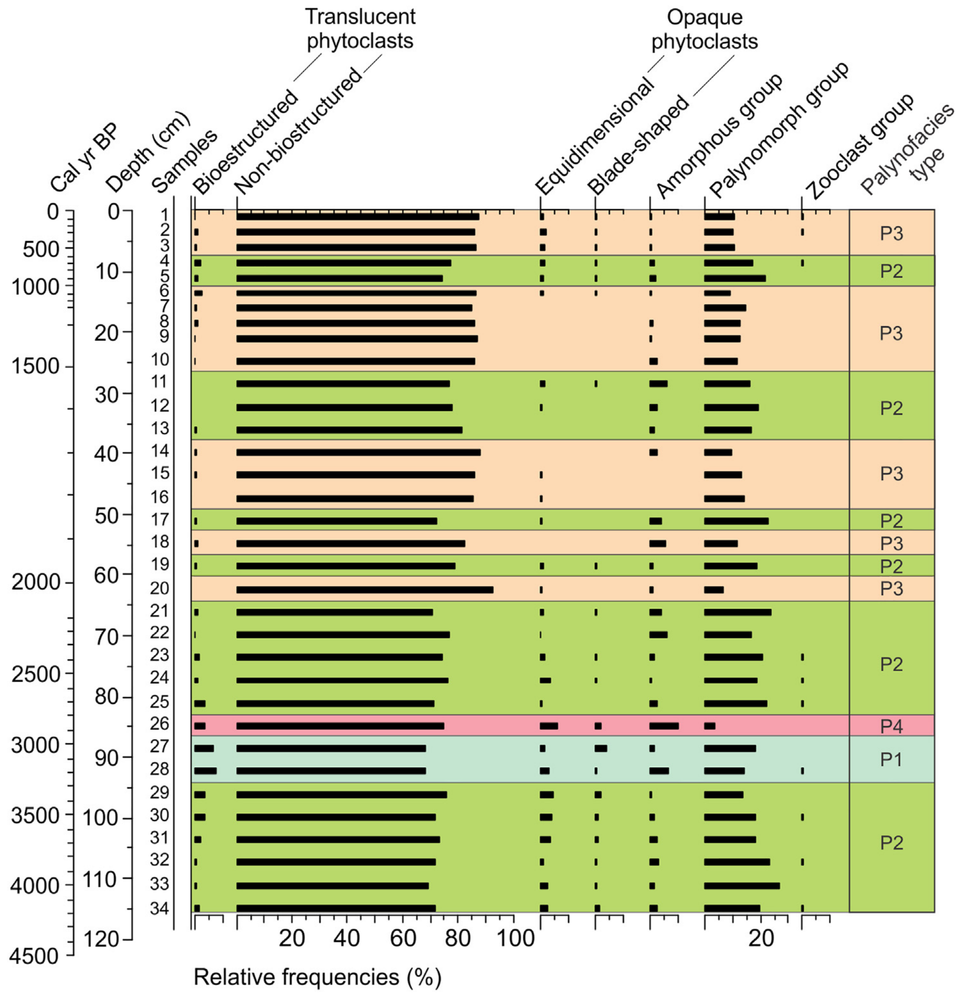

Fig. 6. Frequencies (%) of the palynologic matter (PM) types extracted from LCTF2 sedimentary core. There are four main PM groups (see text for more details).

characterized by high proportion of non-biostructured translucent phytoclasts (69.7–82.1%). Opaque phytoclasts represent 0.2–6.5% of the total palynological matter with predominance of equidimensional types. The palynomorphs show the highest frequencies with 26.5%. AOM, mainly represented by the spongy and fibrous types, shows low values of 0.6–6%. The zooclast group is scarce (up to 0.4%).

Palynofacies type 3 (P3) is characterized by the highest percentages (83–92.5%) of translucent phytoclasts in all samples. Among the opaque phytoclasts, the equidimensional type is present with low values (0.4–2.2%). The palynomorphs show values ranging from 6.3 to 14.4%. AOM reaches values up to 5.5%, and zooclasts up to 0.4%.

Palynofacies type 4 (P4), only represented in sample 26, shows the

Table 3
Summary of palynofacies parameters used for palaeoenvironmental interpretation of the LCTF2 core sediments, Laguna Carmen.

Palynofacies (P)	Principal components of organic matter	Palaeoenvironmental interpretation
P1	Greater supply of larger and “fresh”, biostructured translucent phytoclasts.	Increase in the fluvial runoff related to humid climatic conditions.
	Presence of blade-shaped opaque phytoclasts and equidimensional forms.	Oxidation by air or subaerial exposure of organic matter affected by seasonal fluctuating water table conditions; relatively long distances and/or times of transport; or local reworking from sediments of high maturation level.
P2	High participation of palynomorphs and non-biostructured translucent phytoclasts.	Environments close to the terrestrial source area.
	Increased AOM values, mainly spongy and fibrous amorphous masses and fibrous debris.	AOM is probably produced by bacterial action on palynomorphs under restricted circulation conditions (suboxic to anoxic conditions). Degradation of freshwater algae such as *Botryococcus braunii* and *Pediastrum*.
P3	Highest participation of non-biostructured translucent phytoclasts. Low amounts of palynomorph group.	High terrestrial organic matter contributions as a result of dilution of other components implying proximity to a fluvial source, or development of oxidizing environments in which other organic constituents have been selectively destroyed.
P4	Highest values of opaque phytoclasts.	Relatively high energy fluvial runoff and/or post-depositional oxidation within sandy subaerial sediments.
	Spongy, membranous and fibrous AOM.	Bacterial action on *B. braunii* and *Pediastrum*.
	Lowest values of palynomorphs.	Dilution by high inputs of terrigenous matter from sites located near to the lake shore and/or by poor preservation of palynomorphs in coarse lithologies.

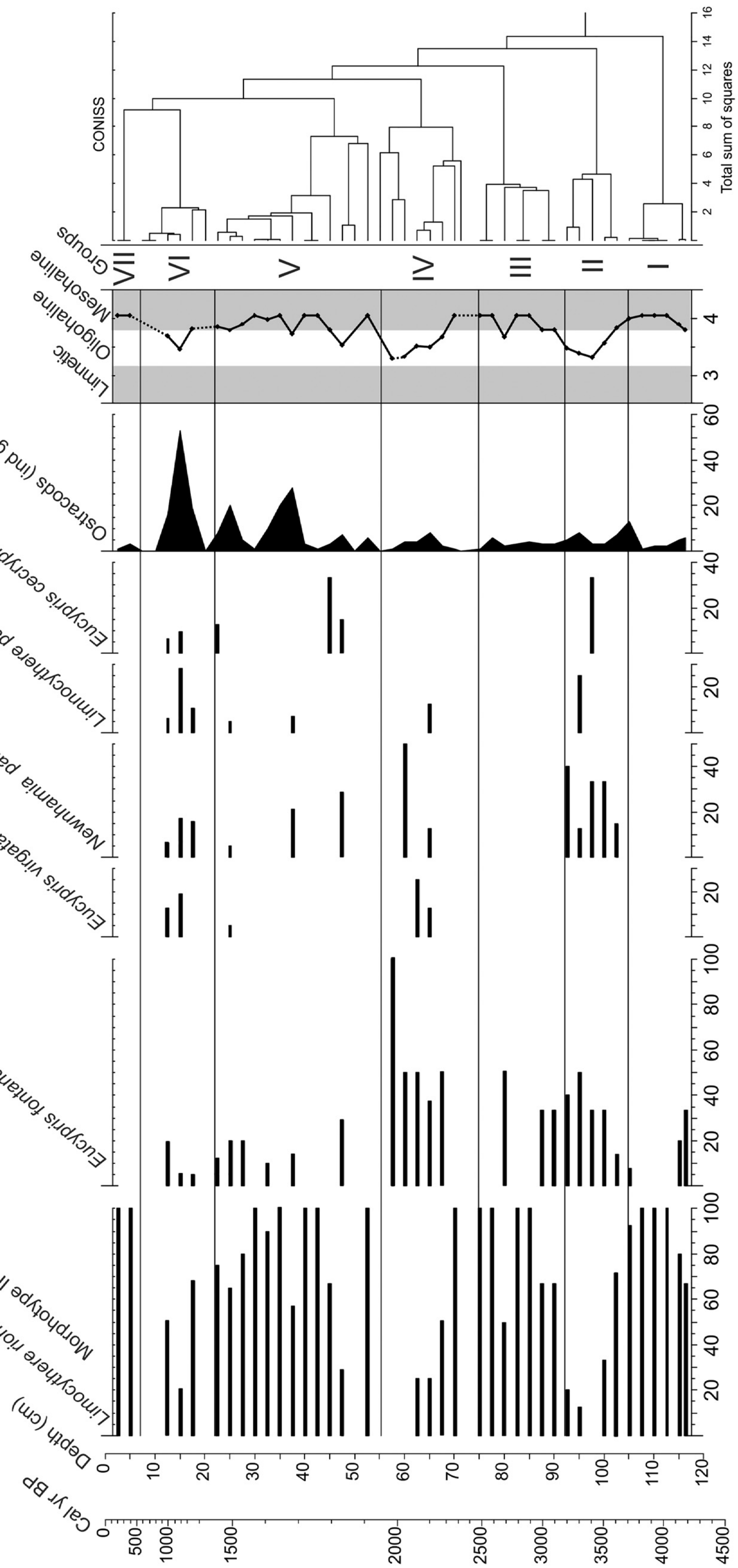

Fig. 7. Fossil ostracod percentage diagram from LCTF2 sedimentary core at Laguna Carmen site, including ostracod density (individuals g^{-1}) and electrical conductivity (EC) reconstruction.

Table 4
Ostracod associations and their palaeoenvironmental interpretation from LCTF2 sedimentary core at Laguna Carmen.

Groups	Age (cal BP)	Ostracod association characteristics	Palaeoenvironmental interpretation
VII	Present-600	*Limnocythere rionegroensis* Morph. II is the only species recorded.	Mesohaline shallow lake; drier conditions.
VI	1400–600	Dominance of *L. rionegroensis* Morph. II. *Eucypris fontana, Eucypris virgata, Eucypris cecryphalium, Newnhamia patagonica*, and *Limnocythere patagonica* are present. Several sterile levels.	Alternance between oligohaline to mesohaline conditions. The sterile levels suggest an unfavorable period for ostracods development related to strong droughts.
V	1900–1400	Abundance of *L. rionegroensis* Morph. II. Declined *E. fontana* density. *L. patagonica, N. patagonica, E. virgata* and *E. cecryphalium* are present.	Increase in salinity conditions. Highly fluctuating hydrological behavior indicated by the occurrence of oligohaline-limnetic ostracods.
IV	2300–1900	Dominance of *E. fontana. E. virgata, L. patagonica*, and *N. patagonica* are present in some levels. High diversity.	Limnetic to oligohaline conditions. Significant presence of *E. fontana* indicates lower salinity concentrations.
III	3100–2300	Dominance of *L. rionegroensis* Morph. II. *E. fontana* is present in a few levels.	Mesohaline shallow lake. Some oligohaline pulses are also recorded.
II	3600–3100	High frequencies of *E. fontana* and *N. patagonica*. Decline of *L. rionegroensis* Morph. II. *E. cecryphalium* and L. *patagonica* are present.	Low water salinity, possibly consequence of an increase in lake level, and therefore a reduction in evaporation/precipitation balance.
I	4200–3600	Dominance of *L. rionegroensis* Morph. II. *E. fontana* is only present at lower and upper levels.	High salinity (mesohaline) conditions; low water level, associated with a negative P:E balance.

highest frequencies of opaque phytoclast (8.2%) and AOM (10%), while the palynomorphs record the lowest frequency values (3.3%) throughout the sequence. The translucent phytoclasts mainly non-biostructured, maintain their high values (78.5%).

4.4. Ostracod analysis

According to the cluster analysis seven main groups have been recognized based on the faunal associations (Fig. 7). The identified ostracod associations and their related abundances and diversity to palaeoenvironmental conditions are shown in Table 4. These species have been described for Pleistocene to Holocene sequences in Patagonia (Whatley and Cusminsky, 1999; Schwalb et al., 2002; Cusminsky et al., 2005, 2011; Ohlendorf et al., 2014; Ramón Mercau et al., 2012; Ramón Mercau and Laprida, 2016; Coviaga et al., 2017a, 2017b). The ostracod associations are represented mainly by *Limnocythere rionegroensis* Morphotype II, accompanied by L. *patagonica*, *Eucypris fontana*, *E. virgata, E. cecryphalium* and *Newnhamia patagonica*. Ostracod density varied throughout the record (Fig. 7), with a mean of < 10 individuals/g of sediment (6.4 ± 9.3 ind/g). Nevertheless, high abundance values have been registered at 37.5 (28 ind/g), 35 (20 ind/g), 25 (20 ind/g), 17.5 (19 ind/g) and 15 (53 ind/g) cm-depth levels. Levels at 71.25, 55, 50, 20, 10, and 7.5 cm depth were sterile.

Group I (116.25–105 cm; 4200–3600 cal yr BP) is dominated by *Limnocythere rionegroensis* Morph. II (> 60%). *Eucypris fontana* is only present at the lower (< 33%), and at the upper levels (8%) of the zone.

In Group II (105–92 cm; 3600–3100 cal yr BP) *Eucypris fontana* (34 ± 13%) and *Newnhamia patagonica* (26 ± 12%) record high frequencies, while *L. rionegroensis* Morph. II values notably decreased to 27 ± 27%, being even absent in some samples. *Eucypris cecryphalium* (33%) and L. *patagonica* (25%) are only recorded at 97.5 and 95 cm-depth levels, respectively.

Group III (92–74 cm; 3100–2300 cal yr BP), similar to Group I, shows dominance of *L. rionegroensis* Morph. II (83 ± 22%) and few occurrences of *E. fontana* at 90 (33%), 87.5 (33%) and 80 (50%) cm-depth levels.

Group IV (74–54 cm; 2300–1900 cal yr BP), is characterized by a high diversity (5 determined species). *Eucypris fontana* (43 ± 32%) dominates this association, especially in the upper levels of the zone, while *L. rionegroensis* Morph. II is the only species recorded at level 70 cm-depth. *Eucypris virgata*, *L. patagonica*, and *N. patagonica* are present (< 20%) in some levels, although the last one reaches a high value (50%) at 60 cm-depth.

In Group V (54–22 cm; 1900–1400 cal yr BP) *L. rionegroensis* Morph. II (75 ± 28%) is the most abundant species, while *E. fontana* decreases to < 30%, and is accompanied by *N. patagonica*, *E. virgata*, *L. patagonica*, and *E. cecryphalium.*

Group VI (22–7 cm; 1400–600 cal yr BP) is composed by several sterile levels (20, 10 and 7.5 cm-depth). In the remaining levels, the diversity reaches six species. *Limnocythere rionegroensis* Morph. II (46 ± 24%) dominates the assemblage, while *E. fontana, E. virgata, E cecryphalium, N. patagonica*, and *L. patagonica* are recorded with an abundance of about 20%.

In Group VII (7–0 cm; 600–0 cal yr BP) *Limnocythere rionegroensis* Morph. II is the only species that conforms this assemblage.

5. Palaeoenvironmental and palaeoclimatic reconstruction

5.1. Local vegetation reconstruction and lacustrine conditions at Laguna Carmen

Taken together, the proxy data (Fig. 8) from Laguna Carmen suggested the presence of climate changes characterized by the alternation of dry (LCd) and wet intervals **(**LCw**)** during the late Holocene. From the base of the sequence at ca. 4200 to ca.1400 cal yr BP (zones C-1 to C-4b), the pollen assemblages showed the development of a local grassland (Poaceae) steppe vegetation with an open shrub layers of Asteraceae subf. Asteroideae, and scarce dwarf shrubs of *Empetrum rubrum*. The pollen spectra resembled the present south-central steppe of Tierra del Fuego with rainfall values of < 400 mm yr^{-1} when compared with modern analogues from surface sediments (Trivi de Mandri et al., 2006; Musotto et al., 2012). During this time, the dry intervals (LCd), among 4200–3600, 3000–2800, 2600–2100, 1900–1600 and 1400 cal yr BP, were characterized by spread of halophytic (Chenopodiaceae) vegetation around the lake, increased amounts of *Botryococcus braunii*, and predominance of *Limnocythere rionegroensis* Morph. II (groups I, III, and V), suggesting mesohaline or slightly alkaline conditions, higher conductivity, enhanced evaporation, and probably low lake levels (Fig. 9). During these events, shrub (Asteraceae subf. Asteroideae) vegetation expanded into the area. Predominance of *B. braunii* over *Pediastrum* indicates a brackish, shallow, and ephemeral water body related to relatively low rainfall (Guy-Ohlson, 1992; Tyson, 1995). The highest proportions of *B. braunii* were recorded during the zone C4-a (Fig. 8). According to Tyson (1995, p. 316), blooms of *B. braunii* have been recorded from shallow, often temporary, partly saline lakes in regions, which are generally arid but subject to climatic extremes. The salinity index was high, in line with shrinking of the water body and less humid conditions. A lithology composed mostly by massive clayey-silt sediments characterized these drier intervals. The analysis of palynofacies showed predominance of translucent phytoclasts suggesting environments relatively close to the terrestrial organic matter source area with bacterial action on palynomorphs under restricted circulation in suboxic to anoxic conditions, and oxidizing environments. Levels with high TOC and carbonate content values, as

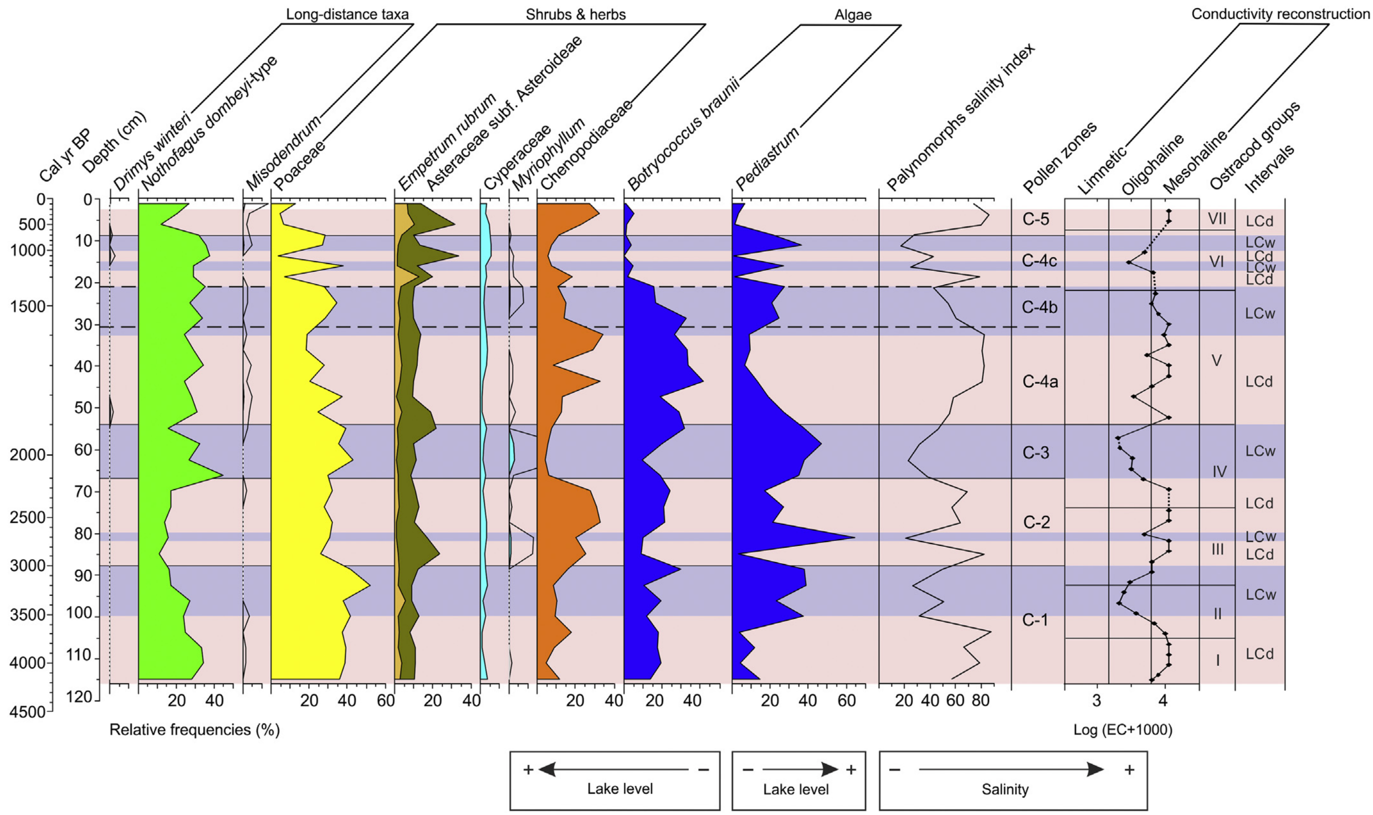

Fig. 8. Percentage diagram of main palynomorphs used to reconstruct the past landscape, palynomorphs salinity index (PSI) and ostracod-based conductivity from LCTF2 sedimentary core at Laguna Carmen site. Outline curve represents an exaggeration of 10× for *Misodendrum* and *Myriophyllum* pollen. Environmental and/or climatic significance of each proxy is indicated at the bottom of each profile. The pink horizontal rectangles indicate the inferred dry intervals (LCd), whereas the blue rectangles indicate wet intervals (LCw). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

those recorded in Unit c at 105 cm-depth (Fig. 2), have previously been reported from Holocene *Botryococcus*-rich anoxic lake floor carbonated sediments in Australia (Tyson, 1995).

Conversely, the wet intervals (LCw), among 3600–3000, 2700, 2100–1900 and 1600–1400 cal yr BP, were characterized mainly by expansion of grasses, retraction of halophytes, presence of *Myriophyllum*, proliferation of *Pediastrum*, and the remarkable diminishing of *L. rionegroensis* Morph. II joined with the predominance of *Eucypris fontana* and *Newnhamia patagonica* species (groups II and IV), suggesting a freshwater supply, high nutrient loading, oligohaline and deep lake conditions (Fig. 9). The record of high proportions of *Pediastrum* indicates clear, deeper and mainly eutrophicated water body (Tyson, 1995; Medeanic et al., 2003; Jankovská and Pokorný, 2013). Also, increases in the Poaceae proportions along with sedges (Cyperaceae) and hygrophyllous taxa (*Tetroncium magellanicum* and *Myriophyllum*) point to the development of moist environments surrounding the lake (Collantes et al., 2009). Low salinity index allowed also to infer the presence of freshwater environments. These wetter intervals were represented by a lithology composed mostly by silty-sand levels and sandy lenses indicative of increased sediment input into the lake by tributary streams during times of increased frequency and/or intensity of rainfall (Coronato et al., 2017). The analysis of palynofacies indicated supply of translucent phytoclasts implying proximity to a fluvial source. The presence of opaque phytoclasts could be reflecting the complexity of the taphonomic history of the sedimentary organic matter prior to final deposition.

During the ca. last 1400 years (zones C-4c and C-5), high environmental variability has been observed. The lithology shows the sedimentation of laminated clayey-silts (Fig. 2). By this time, the palynofacies analysis presents a slight increase in opaque phytoclasts indicative of oxidation by air or subaerial exposure of organic matter possibly affected by seasonal fluctuating of lake water level. Dryness conditions at 1200–1000 and 700–200 cal yr BP, are inferred by the high proportions of shrubs (Asteraceae subf. Asteroideae), heath (*Empetrum rubrum*), halophytes (Chenopodiaceae), and notably lower proportions of grasses (Poaceae) in concert with low proportions of both *Botryococcus braunii* and *Pediastrum*. According to Oliva et al. (2001), the shrubs unlike grasses and forbs, develop a deep root system that allow them to take advantage of deep soil moisture under conditions of extreme drought, low temperatures and high evaporation. The ostracod association (group VI) showed fluctuations between oligohaline to mesohaline conditions indicating also high environmental variability. During these intervals, the algal content reached its lowest frequency and concentration values (Figs. 3 and 4) suggesting changes in the nutrient content that might have hampered the development of these algae in the lake. These dry intervals alternated with more humid intervals at 1300, 1000–700 and 200–0 cal yr BP, in which grass steppe predominated along with proliferation of *Pediastrum*. The rise of TOC upward in the sequence recorded at 8 cm-depth (Fig. 2), concomitant with the record of *Pediastrum* (ca. 900 cal yr BP, zone C4-c), seems to be associated with AOM and organic-rich laminated sediments deposited under anoxic conditions during more humid intervals (Tyson, 1995). Taken together, the abrupt increase in carbonates in the uppermost part of the profile (Fig. 2), the palynological data, and the ostracod association (group VII), all indicate that severe aridity conditions occurred at ca. 500 cal yr BP (zone C-5). After that, the palynological record displayed a slight increase in grasses replacing the shrubby steppe communities suggesting relatively more humid conditions than before. Also, freshwater input into the shallow lake can be inferred by the decline in halophytes and proliferation of *Pediastrum* along with the decrease in the salinity index. The presence of *Rumex acetosella* suggests anthropic impact related to livestock farming expanding in the region

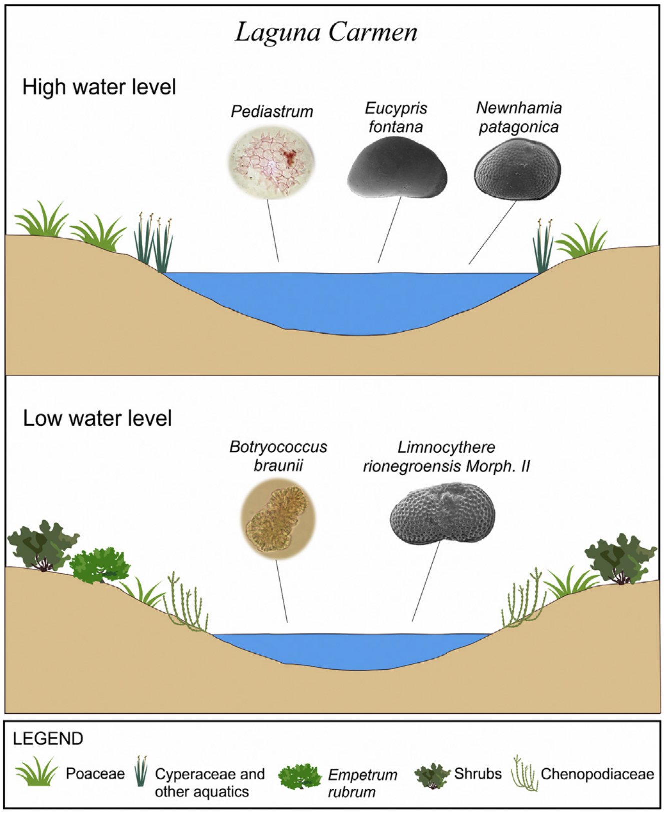

Fig. 9. Schematic palaeoenvironmental reconstruction of the wet intervals (high water level) and the dry intervals (low water level) identified in the Laguna Carmen record (Fuegian steppe, Argentina) during the late Holocene.

following establishment of European settlements. Palynological richness remains mostly unchanged throughout the record and its values are like those from the lateglacial steppe environments located in the south-central of Tierra del Fuego (Musotto et al., 2017a).

Concerning long-distance taxa, the dominant *Nothofagus dombeyi*-type is accompanied by *Misodendrum* (a hemiparasite on *Nothofagus* species) and *Drimys winteri* (a small tree associated with *Nothofagus betuloides* in Subantarctic Evergreen Forest communities in the coastal areas to the west) (Fig. 3). The frequency values of *Nothofagus* pollen throughout the record are similar to those from surface samples located near the forest-steppe boundary (Trivi de Mandri et al., 2006; Musotto et al., 2012), and do not necessarily indicate local presence of southern beech in the Laguna Carmen area. Significant amounts of wind-carried *Nothofagus* pollen, even as high as 30%, are deposited in sites of the Fuegian steppe located ca. 50 km beyond the forest-steppe limit (Heusser, 2003). According to surface sample values, the record of *Nothofagus* frequencies should increase to 50% or more, to infer that the edge of the forest was at or close to the studied site (Trivi de Mandri et al., 2006; Musotto et al., 2012).

5.2. Palaeoclimatic inferences

The comparison among our proxy data and other records from sites located in the southern Patagonia (50°–52°S) and Fuegian Archipelago (Fig. 1A) allow us to infer some regional palaeoclimate changes during the late Holocene, in spite of possible uncertainties due to the radiocarbon dating. Northern Tierra del Fuego is under the present predominance of westerly winds throughout the year. Hence, any change in the strength or frequency of the atmospheric circulation pattern will affect the west coast of the island, the Andean mountains, and the extra-Andean landscape in different ways (Schneider et al., 2003).

The long-distance *Nothofagus* pollen input at Laguna Carmen correlates well with records from the Andean forests reflecting changes in the intensity and latitudinal position of the westerlies. In the studied site, high *Nothofagus* frequencies were recorded at ca. 4000 cal yr BP. Sites directly west of Laguna Carmen (Punta Yartou[2], Onamonte[3]) (Mansilla et al., 2016; Heusser, 1993), in south-central (La Correntina[4]) (Musotto et al., 2016) Tierra del Fuego, and also along the Beagle Channel (Heusser, 1998) (Fig. 1A), evidenced expansion of *Nothofagus* forest under cool and wet conditions associated with a strengthening of the westerlies. Similar conditions were also observed in the south-western Patagonia (Villa-Martínez and Moreno, 2007; Moreno et al., 2009; Echeverría et al., 2014). At Laguna Carmen, *Nothofagus* declined from ca. 4000 to 2100 cal yr BP. Mansilla et al. (2016) identified at Punta Yartou[2], a transitional phase to relatively dry conditions between 4150 and 3320 cal yr BP followed by a drier phase between 3320 and 2100 cal yr BP. Similar less humid conditions related to a weakening of westerly winds, were reported from southwest Patagonia between 4000 and 2000 cal yr BP (Echeverría et al., 2017 and authors therein cited). At Laguna Carmen, the record revealed an increase in the arboreal frequencies along with the cuasi-continuous presence of *Misodendrum* pollen between ca. 2100 and 700 cal yr BP suggesting that the forest/steppe boundary was probably not so far from the studied site. An increase in effective moisture in the western region was also reported from Punta Yartou[2] (Mansilla et al., 2016) after 2100 cal yr BP, and at Onamonte[3] (Heusser, 1993) around 1500 years ago associated to an intensification in the westerly winds.

Meanwhile, vegetation at Laguna Carmen did not evidenced major changes in the distribution of their palaeocommunities between ca. 4000 and 1400 cal yr BP, being analogous to the present ones. Some increases in the dominant grass communities appear to be related to the humid intervals. On the other hand, the lacustrine proxies showed synchronous short-term variations of alternating wet and dry intervals. Humid-arid cycles have been also reported from a sequence of aeolian deposits and paleosols at Laguna Arturo (Fig. 1B) (Coronato et al., 2011). At present, a moderate increase in the easterly winds along with the greater input of Atlantic moisture when the zonal westerlies are weak, results in more humid conditions over eastern Patagonia (Schneider et al., 2003; Berman et al., 2012) and northern Tierra del Fuego (Quiroga, 2018). Whereas, arid and evaporative conditions at the leeward side of the Andes; or at this case, in the Fuegian steppe, are the result of the strengthening of westerly winds and the SW-NE decreasing precipitation gradient (Garreaud et al., 2013).

Likewise, some shallow lakes located in Patagonia recorded fluctuations from saline to freshwater conditions related to environmental variability during the late Holocene. In particular, the interval of high lake level observed in Laguna Carmen between 3600 and 3000 cal yr BP, has been also recognized in sediments of Laguna Huergo (51°S 72°W) located in the forest-steppe ecotone (SW Patagonia), by a similar ostracod assemblage between 3400 and 3000 cal yr BP (Laprida et al., 2014; Ramón Mercau, 2015). Another humid interval identified in Laguna Carmen between 2100 and 1900 cal yr BP, correlate well with one of the moist periods inferred by the geochemical analyses carried out on sedimentary record from Laguna Potrok Aike (51°S 69°W), southeastern Patagonia, at 1980 cal yr BP (Haberzettl et al., 2007).

The Medieval Climate Anomaly (MCA, 1100–800 cal yr BP) and the Little Ice Age (LIA, 600–100 cal yr BP) (Moreno et al., 2014) are noticeable climate episodes of the last millennium. The extent, timing, and nature of these events in Tierra del Fuego are still uncertain (Mauquoy et al., 2004) and are not globally consistent in southern South America (Moy et al., 2009; Echeverría et al., 2017). In the studied site, the humid interval recorded between ca. 1000 and 700 cal yr BP was followed by dryness conditions at 500 cal yr BP. These intervals could be linked to the MCA and LIA events, respectively. In Tierra del Fuego (Mauquoy et al., 2004; Favier-Dubois, 2007; Waldmann et al., 2010) as well as in Isla de los Estados (Ponce et al., 2011) the MCA event evidenced an opposite climate signal. The high resolution data from Laguna Potrok Aike showed that the MCA was a persistent period, but not necessarily one of drought or warm constant conditions. At least two distinct moist interruptions during the MCA were determined (Haberzettl et al., 2005).

On the other hand, the LIA event was mentioned in most of the pollen records from peat bogs in south-central Tierra del Fuego (Las Cotorras[6], Cañadón del Toro[5], Terra Australis[7], La Correntina[4]) (Borromei et al., 2010, 2016; Musotto et al., 2016, 2017b) as well as from Isla de los Estados (Bahía Franklin[8]) (Ponce et al., 2017). During this period, the lowest frequency and concentration values in the arboreal component recorded in these sequences as well as in Laguna Carmen, were interpreted as cold and windy conditions. While, palaeoclimate data from Lago Fagnano and multiproxy analyses from an inner Fuegian valley postulated moist conditions (Mauquoy et al., 2004; Waldmann et al., 2010). In southern Patagonia, the palaeohydric balance from eastern steppe environments showed an increase in precipitation by about 1000 cal yr BP, and a decrease between 700 and 500 cal yr BP (Echeverría et al., 2017). In this sense, the climate conditions linked to the LIA event have been related to a northward displacement of the westerlies from their present day focus, producing lower precipitations at these high latitudes (Echeverría et al., 2017).

6. Conclusions

The location of Laguna Carmen, lying leeward of the Fuegian Andes, in the westerlies path – with SW-W as the main directions – and close to the Atlantic coast, makes it especially sensitive to changing episodes of humidity and aridity that occurred during the late Holocene. The proxy data suggested palaeoclimate changes related to variations in the strength and/or latitudinal position of the westerly winds over the last ca. 4200 cal yr BP. The record of *Nothofagus* pollen, linked to extra-regional pollen input from the Andean forests, showed variations that correlated well with broad regional climate changes. Among lacustrine proxies, Chenopodiaceae pollen in conjunction with the algae *Botryococcus braunii* and *Pediastrum*, and ostracods served to estimate even minor lake level fluctuations since they are highly sensitive to changes of salinity and depth. Also, the palynofacies analysis along with lithology evidenced variations in the environment deposition. Taking together, they showed short-term palaeoenvironmental variations most probably linked to both regional and local climate changes. In particular, the short-time wet intervals at 80 cm-depth (ca. 2700 cal yr BP) and at 15 cm-depth (ca. 1300 cal yr BP) could be indicating instantaneous sediment deposition due to seasonal rainfall events. Furthermore, high variability in hydric conditions has been observed in other lake records from southern Patagonia.

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