

## POSTGLACIAL VEGETATION AND CLIMATE CHANGES INFERRED FROM A PEAT POLLEN RECORD IN THE RÍO PIPO VALLEY, SOUTHERN TIERRA DEL FUEGO

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**Abstract.** The pollen analysis from Cañadón del Toro peat bog (54° 49' 36" S; 68° 27' 36" W), located in an interior valley of the Fuegian Andes, provides information about vegetation and climate changes during the last 13,500 years. The results indicate the postglacial development of steppe-like vegetation under drier and colder conditions than today, followed by the expansion of *Nothofagus* into the valley after 10,350 cal. yr BP. At this time, the predominance of a forest-steppe ecotone suggests warm conditions and an increase in moisture availability. By about 6,700 cal. yr BP, the closed-canopy *Nothofagus* forest spread under cold and wet conditions. The mire environment also reflects the increasing trend of effective moisture changing from an initial minerotrophic Cyperaceae fen to an ombrotrophic *Sphagnum* bog development.

**Key words.** Vegetation and climate history. Lateglacial-Holocene. Interior valleys. Tierra del Fuego.

**Resumen.** CAMBIOS DE LA VEGETACIÓN Y CLIMA POSTGLACIAL INFERIDOS A PARTIR DE UN REGISTRO POLÍNICO DE UNA TURBERA EN EL VALLE DEL RÍO PIPO, SUR DE TIERRA DEL FUEGO. El análisis polínico de la turbera Cañadón del Toro (54° 49' 36" S; 68° 27' 36" W), ubicada en un valle interior de los Andes Fueguinos, brindó información sobre los cambios de la vegetación y del clima durante los últimos 13.500 años. Los resultados indicaron el desarrollo postglacial de una vegetación de estepa bajo condiciones más secas y frías que las actuales, seguidas por la expansión de *Nothofagus* en el valle con posterioridad a los 10.350 años cal. AP. Durante este período, la predominancia del ecotono bosque-estepa sugiere condiciones más cálidas y un incremento en la disponibilidad de humedad. Alrededor de los 6.700 años cal. AP, el bosque cerrado de *Nothofagus* se expande bajo condiciones frías y húmedas. El ambiente de la turbera también refleja el paulatino incremento de humedad efectiva cambiando desde una turbera minerotrófica de Cyperaceae a una ombrotrófica de *Sphagnum*.

**Palabras clave.** Historia de la vegetación y el clima. Tardiglacial-Holoceno. Valles interiores. Tierra del Fuego.

THE VEGETATION and climate reconstructions after deglaciation from Isla Grande de Tierra del Fuego have been carried out from several pollen records mainly located at low-elevation sites along the Canal Beagle, southernmost part of the island (Markgraf, 1983, 1991, 1993; Heusser, 1989a,b, 1990, 1995, 1998, 2003; Borromei and Quattrocchio, 2001, 2007; Pendall *et al.*, 2001; Grill *et al.*, 2002; Markgraf and Huber, 2010; Borromei *et al.*, 2014). In contrast, few palynological studies consider the inner valleys of the Fuegian Andes (Borromei, 1995; Mauquoy *et al.*, 2004; Borromei *et*

*al.*, 2007; Borromei and Quattrocchio, 2008), or at high-elevation sites (Markgraf, 1993; Borromei *et al.*, 2010; Markgraf and Huber, 2010). Taken together, the pollen data show a deglacial open ground vegetation dominated by grasses, dwarf shrub heaths and scrubs, with scattered *Nothofagus* Blume 1850 trees. After 11,500 cal. yr BP, the *Nothofagus* woodland containing grasses, composites, and ferns dominated the landscape under warmer and drier climatic conditions than today, and high fire activity. The closed-canopy forest developed after *ca.* 7000 cal. yr BP, under colder and

wetter climate conditions. These changes in vegetal paleo-communities have been interpreted in terms of variations in the amount of precipitation of westerly origin related to shifts in the latitudinal location and/or strength of the Southern Westerly Winds (SWW), Antarctic sea-ice extent, and position of the Antarctic Polar Front (Markgraf and Huber, 2010; Kilian and Lamy, 2012).

The mountain valleys of the Fuegian Andes, tributaries to the Canal Beagle valley, show the effect of extensive Pleistocene glacier erosion (Coronato, 1995; Rabassa *et al.*, 2000). These valleys were occupied by multiple alpine-type glaciers, ranging from 20 to 30 km in length, though smaller, single-valley glaciers were also present (Rabassa, 2008). They were fed by local cirques, independent of the Cordillera Darwin mountain ice sheet, from where the main glacier (the Beagle Glacier) was nourished. As in all interdependent ice system, the glacial activity in these tributary valleys was controlled by the glaciological behavior of the main ice stream and regional climatic variations. Most likely, these local glaciers were more severely affected by the abrupt climate change, and thus receded fast (Coronato, 1990; Rabassa, 2008).

The present contribution gives insight into the regional and local vegetation dynamics for the interior Andean valleys on the Andean Pacific slope during the last 13,500 yr. The studied peat core was collected from a peat bog (Cañadón del Toro, Fig. 1.1–2) located into the Río Pipo valley, which constitutes the oldest pollen record from low interior valleys. The pollen/spores analysis provides valuable information about the development of plant communities and environmental changes since deglaciation. The results are compared with other pollen records retrieved from sites located at different altitudes in the southernmost part of Tierra del Fuego (Tab. 1) to obtain a better understanding of the regional vegetation and climate patterns during the Lateglacial and Holocene times.

## ENVIRONMENTAL SETTING

The studied site, herein named as Cañadón del Toro (TCT), is a raised bog (54° 49' 36" S; 68° 27' 36" W; 90 m a.s.l., Fig. 1.3–4) located in the Río Pipo valley, Tierra del Fuego National Park, 3 km north of Canal Beagle coast, in the southern part of Isla Grande de Tierra del Fuego. Canal Beagle is a marine channel 200 km long on a W–E trend and constitutes a connection between the Atlantic and Pacific oceans. It is a former tectonic valley that was completely covered by ice during the Last Glacial Maximum (LGM) (Rabassa *et al.*, 2000), with ice limits reaching a maximum extent by *ca.* 25,000 cal. yr BP (Rabassa, 2008).

The peat bog reported in this study is 70 ha in extent. It was developed in a glacial basin, and then transformed into a lake, located between the Cañadón del Toro terminal moraines and the sub-glacially eroded rocky hills which enclose part of the valley 2 km to the east. The sides of the lake received colluvium deposits from the valley (Coronato, 1993). The peat bog forms an ombrotrophic type with hummocky surface formed mainly by *Sphagnum magellanicum* Brid. 1798 and *S. fimbriatum* Wilson in J. D. Hooker 1847 and covered by *Empetrum rubrum* Vahl ex Willd. 1806 with minor amounts of Cyperaceae, Juncaginaceae and Juncaceae, and scattered low shrubby *Nothofagus antarctica* (Forster f.) Oersted 1871. It is surrounded by forest communities of *N. pumilio* (Poeppig and Endl.) Krasser 1896.

## MODERN CLIMATE AND VEGETATION

The climate of Isla Grande de Tierra del Fuego is determined by its upper middle-latitude location in the belt of prevailing SWW, in the path of eastward moving cyclones, not far from the Antarctic ice. The latitudinal position and strength of the SWW are controlled by the intensity and latitudinal location of the subtropical high-pressure cells in the Pacific and the circum-Antarctic low-pressure trough (Tuhkanen, 1992). Regional climate is highly oceanic in the

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**Figure 1.** 1, Modern-day vegetation map of the Isla Grande de Tierra del Fuego with the mean annual precipitation (mm) isohyets and the peat core location (pink star). The highlighted area in the rectangle is shown enlarged in b (modified from Tuhkanen, 1992). 2, Location of the study sites as well as of the other sites referred to in the text. 3, Overall view of Cañadón del Toro peat bog to the northwest; low hills covered by forest are the terminal moraines of the Cañadón del Toro valley. 4, Detail photograph of the coring site; at the back La Portada rocky-hill which limits the valley to the south.

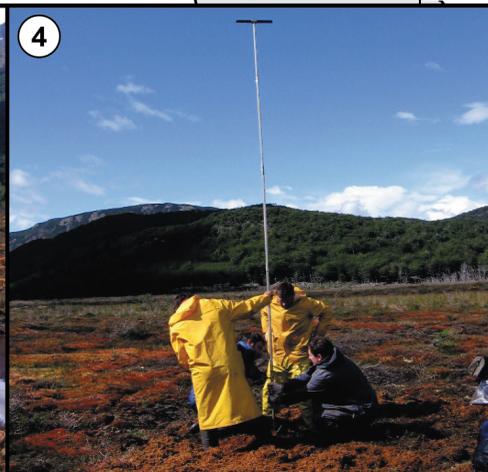
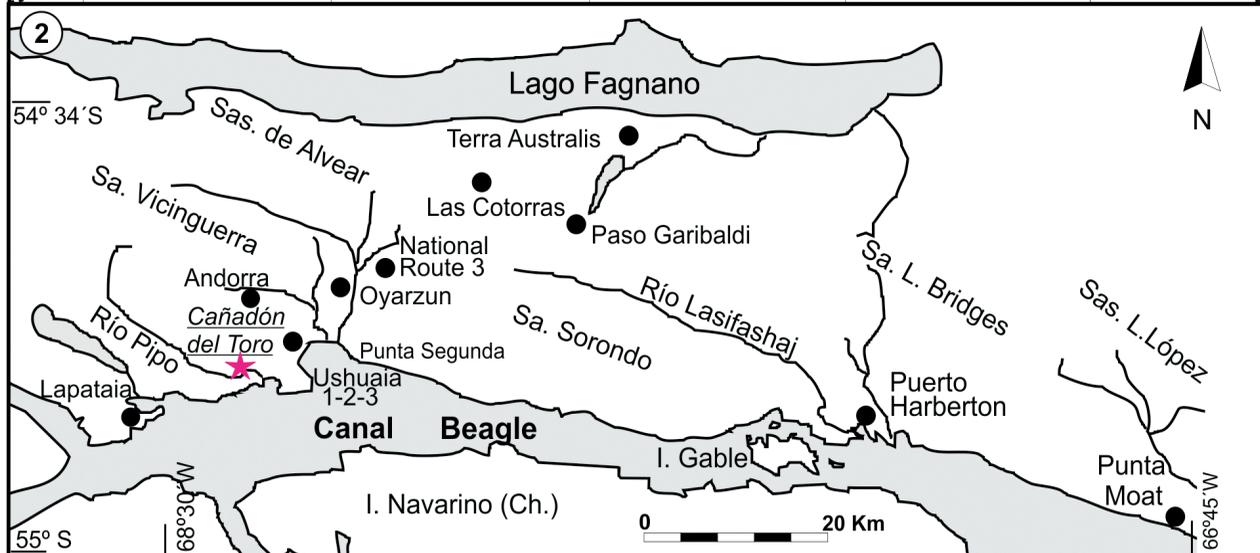
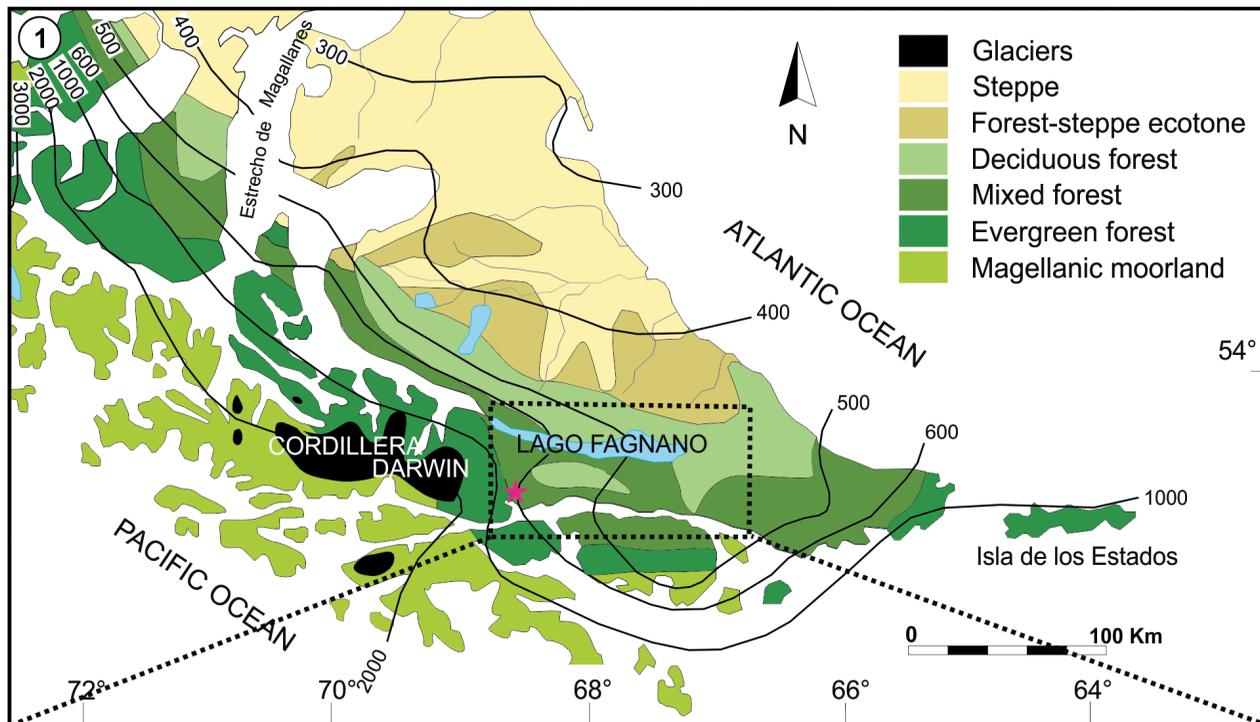


TABLE 1 – Late Quaternary pollen records from different peat bogs and exposures of Isla Grande de Tierra del Fuego discussed in this study. The sites are listed according to their altitude above sea level (m a.s.l.).

<i>Pacific Andean slope</i>	<i>Sites</i>	<i>Altitude (m.a.s.l.)</i>	<i>Lat. South</i>	<i>Long. West</i>	<i>Core depth (cm)</i>	<i>Age range (ka cal BP)</i>	<i>References</i>
	<i>Cañadón del Toro</i>	90	54° 49'	68° 27'	678	0–13.5	<i>This paper</i>
<i>Low Andean valleys</i>	<i>Valle de Carbajal</i>	140	54° 44'	68° 12'	580	0–? Late Glacial	<i>Borromei et al. (2007)</i>
	<i>Valle de Andorra</i>	180	54° 45'	68° 18'	690	0–10.5	<i>Borromei (1995)</i>
	<i>National Route 3</i>	270	54° 43'	68° 90'	exposure	12.0	<i>Borromei et al. (2007)</i>
<i>High Andean valleys</i>	<i>Las Cotorras</i>	420	54° 41'	68° 02'	480	0–8.0	<i>Borromei et al. (2010)</i>
	<i>Paso Garibaldi</i>	420	54° 43'	67° 50'	306	0–14.0	<i>Markgraf and Huber (2010)</i>
<i>Lowlands (Canal Beagle coast)</i>	<i>Ushuaia 3</i>	7	54° 48'	68° 23'	550	0–13.9	<i>Heusser (1998)</i>
	<i>Puerto Harberton</i>	10	54° 52'	67° 53'	104	0–17.7	<i>Heusser (1990); Markgraf and Huber (2010)</i>
	<i>Lapataia</i>	18	54° 51'	68° 32'	510	0–11.6	<i>Heusser (1998)</i>
	<i>Punta Moat</i>	40	54° 58'	66° 44'	450–100	5.0–11.2	<i>Borromei et al. (2014)</i>
	<i>Ushuaia 2</i>	80	54° 47'	68° 18'	820	0–14.4	<i>Heusser (1998)</i>
	<i>Ushuaia 1</i>	280	54° 47'	68° 23'	700	0–13.8	<i>Heusser (1998)</i>

west and south parts of the archipelago and increasing continental towards the east and north. The daily temperature in summer (January) at Ushuaia averages 9.2° C and in winter (July) 1.6° C; the mean annual precipitation is 574 mm (Prohaska, 1976).

Vegetation composition follows the climatic and topographic gradients across Tierra del Fuego (Moore, 1983; Tuhkanen, 1992) (Fig. 1.1). The modern vegetation in the north corresponds to the Fuego-Patagonian Steppe with a mean annual precipitation less than 400 mm. The tussock grassland of *Festuca gracillima* Hooker f. 1847 covers the area, grading into scrub of shrubby composites or into dwarf shrub heaths of *Empetrum rubrum* (Moore, 1983; Collantes *et al.*, 1989). Contact of steppe with deciduous forest occurs through an ecotone under precipitation of 350 to 500 mm

annually (Tuhkanen, 1992). Subantarctic Deciduous Forest is represented by two species of southern beech, *Nothofagus pumilio* (lenga) and *N. antarctica* (ñire), which grow to an average altitudinal limit of 550–600 m a.s.l. and become dominant where precipitation exceeds 450 mm yr<sup>-1</sup>. Towards the south and west of Tierra del Fuego, the annual precipitation rises to over 700 mm and the Subantarctic Evergreen Forest develops, which is dominated by *N. betuloides* (Mirbel) Oersted 1871 (guindo), accompanied by *Drimys winteri* Forster and Forster f. 1775 (canelo), *Maytenus magellanica* (Lam.) Hooker f. 1847 (maitén) and abundant ferns and mosses. Initially, *N. betuloides* is intermingled with *N. pumilio* in an association distinguished as Mixed Evergreen-Deciduous Forest which can be better considered as ecotonal between the two communities (Moore, 1983).

Magellanic moorland occurs beyond the forest along the exposed outermost coast under conditions of increased precipitation ( $>1500 \text{ mm yr}^{-1}$ ), high winds and poor drainage. It consists of a mosaic of barren rock, marginal grassland, cushion bogs, scrub, and fragments of evergreen forest (Moore, 1983). Above treeline in the Fuegian cordillera, Andean tundra is comprised of cushion plants, dwarf shrub heaths, and meadow communities (Pisano, 1977; Heusser, 2003).

## MATERIAL AND METHODS

### Stratigraphy and chronology, age-depth model

A 678 cm sediment-peat core (221 samples) from the mire was obtained using a Russian-type peat corer (chamber length 0.5 m and 5 cm diameter) (Fig. 1.4). During sectioning of the samples, the morpho-stratigraphic consistency was preserved. Thus, the first 50 cm were taken in varying thicknesses by high morphological variability of peat. The remainder of the core was taken every 2 or 3 cm thick. The volcanic ash layer was also individualized. Eleven AMS radiocarbon age determinations established the chronology for the section (Tab. 2). They were obtained at Ångström Laboratory-Tandem Laboratory, Uppsala Univer-

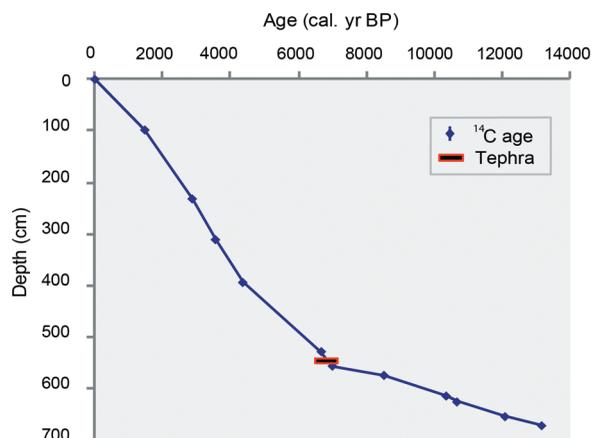


Figure 2. Age-depth model for the Cañadón del Toro peat core.

sity (Sweden), and at National Accelerator Centre (CNA, CSIC, Sevilla, Spain). Calibrated dates were calculated using the program CALIB 7.1 software (Stuiver *et al.*, 2015) and the Southern Hemisphere curve SHCal13 (Hogg *et al.*, 2013). The average dates, taking into account the maximum probability interval at 2 sigma ranges, which is considered a robust statistical value (Telford *et al.*, 2004), were used to build an age-depth model by linear interpolation (Fig. 2).

TABLE 2 – Radiocarbon and calibrated ages from Cañadón del Toro peat core.

Samples	Depth (cm)	$^{14}\text{C}$ age (BP)	Cal age (BP)	Maximum $2\sigma$ BP	Minimum $2\sigma$ BP	$\delta^{13}\text{C}$ ‰	Sample material	Analysis No.
TCT-26	100	1655 ± 25	1504	1564	1425	-27.1	peat	Ua-35766
TCT-69	233	2830 ± 30	2887	2968	2784	-26.6	peat	Ua-35767
TCT-94	312	3380 ± 35	3573	3644	3464	-27.0	peat	Ua-35768
TCT-121	395	3980 ± 35	4376	4516	4470	-27.2	peat	Ua-35769
TCT-164	529	5910 ± 40	6689	6790	6558	-27.3	peat	Ua-35771
TCT-173	556	6170 ± 70	7019	7178	6796	-28.66	tephra	CNA442
TCT-179	575	7800 ± 50	8531	8627	8422	-27.6	peat	Ua-35773
TCT-192	615	9235 ± 55	10,359	10,507	10,237	-27.4	peat	Ua-35774
TCT-196	626	9490 ± 55	10,689	10,516	10,811	-27.4	peat	Ua-35775
TCT-210	654.5	10,290 ± 65	11,959	12,175	11,705	-27.6	peat	Ua-35776
TCT-218	671.5	11,280 ± 120	13,098	13,320	12,800	-32.79	organic matter	CNA443

All dates mentioned in this paper are given as calibrated years (BP).

### Geochemical analysis

Inorganic ash content was obtained by dry ashing at 600 °C for 12 hours (Pontevedra-Pombal *et al.*, 2013), expressing the results as the percentage of dry peat mass (105 °C) according to the equation:

$$\text{Ash (\%)} = (a/b) \times 100$$

where a is the weight of the burned sample, and b is the weight of the dried sample at 105 °C.

The content of aluminum extractable with pyrophosphate (Alp) was determined from an extraction with 0.1 M Na-pyrophosphate (pH 10) in a sample/solution ratio of 1:100, which was stirred for 16 hs. The obtained suspension was centrifuged (15 min at 2500 rpm, with three drops of 'superfloc') (Buurman *et al.*, 1996) and the supernatant filtered. Aluminium in the extracts was measured using flame atomic absorption spectrometry. The results, which are the mean of duplicate analysis that are less than 10% apart, are expressed to oven dry weight (105° C).

The X-ray diffraction (XRD) allows identifying the mineral components and the crystalline state of a sample. The amorphous phases generate a broad diffuse pattern, which helps increase the background noise in the form of broad bands. For analysis of the mineral composition of the tephra, 0.05 g of finely ground and homogenized sample was used. The equipment used was a PW1710 Philips Diffractometer with a PW1820/00 vertical goniometer and Bragg-Brentano  $\theta/2\theta$  geometry, generator with glass tube of 2.2 kW, PW 2773/00 Cu anode, PW1711/10 proportional detector, and PW1752/00 graphite monochromator. The measurement time was 1 second per step (step: 0.02°, 2-65° 2Theta). EVA DIFFRAC plus software (Bruker AXS 2001) was used for semi-quantification.

### Pollen/spores analysis

The samples were prepared in the Laboratorio de Palinología (INGEOSUR-CONICET, Universidad Nacional del Sur, Argentina) according to standard techniques (Faegri and Iversen, 1989). Prior to treatment, *Lycopodium clavatum* spore tablets (Stockmarr, 1971) were added to each sample

in order to calculate pollen concentration per gram of sediment (grains  $\text{gr}^{-1}$ ). Frequencies (%) of tree, shrub and herb pollen were calculated from sums mostly of  $\geq 300$  grains. Frequencies (%) of pollen of aquatic plants and spores of cryptogams were calculated separately and related to the sum of the total land pollen (TLP). "Other shrubs and herbs" include taxa with low frequency values, such as *Berberis* L. 1753, Brassicaceae, Chenopodiaceae, Asteraceae subf. Cichorioideae, *Astelia pumila* (Forster f.) Gaudich. 1825, *Latua* Phil. 1858, Labiateae, Plumbaginaceae, and *Plantago* L. 1753 We combined pollen from the evergreen species *N. betuloides* and the deciduous *N. pumilio* and *N. antarctica*, given the difficulty in species separation and report these as "Nothofagus dombeyi-type".

Plotting of palynological diagrams and statistical analysis were carried out using Tilia 2.0.1 program (Grimm, 2004). The pollen/spores spectrum was subdivided into zones based on visual inspection of the pollen record and a stratigraphically constrained cluster analysis using Edwards and Cavalli-Sforza's chord distance (TGView 2.0.2, Grimm, 2004). For the analysis, all taxa with percentages of  $\geq 1\%$  of the sum of terrestrial pollen were included. The fossil pollen spectra were compared with modern pollen datasets from surface soil samples (Heusser, 1989a; Trivi de Mandri *et al.*, 2006; Musotto *et al.*, 2012) and with present-day plant formations from Tierra del Fuego (Pisano, 1977; Heusser, 2003).

## RESULTS

### Stratigraphy and chronology

The studied core consisted of organic rich layers interspersed with bluish gray clays [678–624 cm]. The overlying sediments consisted of strongly decomposed black peat [624–584 cm], changing into moderately decomposed dark brown peat [584–557 cm]. A 13-cm-thick tephra layer [557–544 cm] was recognized. From 544 to 520 cm the core consisted of highly humified brownish black peat, which was overlain by dark brown peat between 520 and 403 cm. From 403 to 74 cm the core consisted of dark brown *Sphagnum* peat interspersed with reddish *Sphagnum* peat containing woody detritus. The upper 74 cm of the core were composed by reddish unhumified *Sphagnum* peat.

In the range of ca. 570–534 cm a turnaround in the in-

organic material concentration (ash) is detected. At an average depth of 550 cm, this drastic increase represents a rise of almost 6 and 12 times the ash content detected in the first (from ca. 10,100 to 8500 cal. yr BP; average: 7.02%) and second (last 6800 cal. yr BP; average: 2.55%) ombrotrophization cycles, respectively (Fig. 3). This inorganic material has a high content of Alp indicating their high reactivity, characteristic of amorphous organomineral complex (García-Rodeja *et al.*, 2004). In correlation with this chemical feature, the X-ray diagram is clearly dominated by a large amorphous band (noise) where amorphous quartz and albite are detected, typical of an andesitic volcanic ash (Fig. 4).

The tephra layer was dated at 6170  $\pm$  70  $^{14}\text{C}$  yr BP (556–553 cm; 7178–6796 cal. yr BP). The source of this tephra is unknown, but its age is similar within statistics to the age of the greenish andesitic tephra derived from a large explosive eruption ( $H_1$ ) of the Volcán Hudson (45° 54' S; 72° 58' W, 1905 m a.s.l.), regionally dated 7960–7423 cal. yr BP (Stern, 2008), and widely distributed in Tierra del Fuego. This volcano is located in the southern portion of the Zona Volcánica Sur (ZVS, 33°–46° S), more than 900 km farther northwest.  $H_1$  has also been identified in the Harberton raised bog (Kilian *et al.*, 2003), 75 km east of TCT. X-ray spectra obtained for the tephra located in TCT and Harberton raised bog show a close resemblance (Fig. 4).

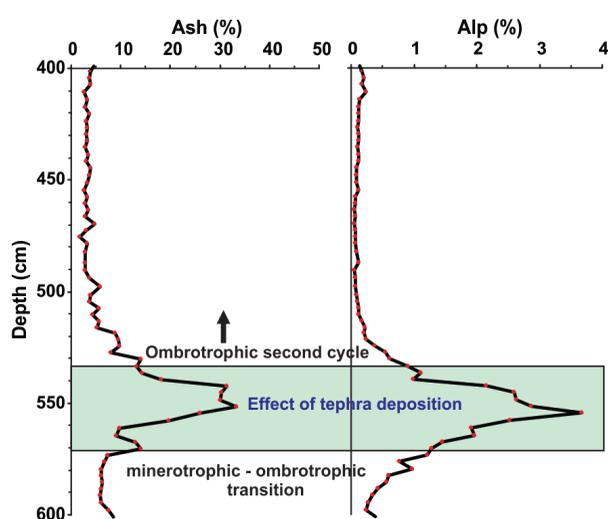


Figure 3. Effect of deposition of tephra on the inorganic ash and sodium pyrophosphate extractable Al content in Cañadón del Toro peat bog.

### Pollen/spores analysis

The pollen record from Cañadón del Toro has been divided into three local pollen assemblage zones, CDT-1 to CDT-3 (Fig. 5). Zone CDT-3 was divided into three subzones. The main pollen concentration values (Fig. 6) were calculated in order to assess the independent behavior of pollen types and to add a new dimension to the study of vegetation history. From the lower to the upper part of the section, they are:

Zone CDT-1 (678–613.5 cm; 13,500–10,350 cal. yr BP). This zone is characterized by the dominance of Poaceae (28–77%), accompanied by Asteraceae subf. Asteroideae (48%), *Acaena* Mutis ex L. 1771 (32%), *Empetrum rubrum* (28%), *Gunnera* L. 1767 (12%), and *Caltha* L. 1753 (<10%). Other herbaceous taxa such as Rubiaceae, Apiaceae, *Gentiana* L. 1753, Caryophyllaceae and *Azorella* Lam. 1783 are present with low frequencies (<5%). *Nothofagus dombeyi*-type records low values (0.3–13%) increasing towards the end of the zone (23%). Cyperaceae shows percentages of 43% at the base and increases rapidly to reach its maximum abundance (68%) followed by an abrupt decline toward the end of the zone (3%). Total pollen concentration is low (3000 grains  $\text{gr}^{-1}$ ) at the onset of the sequence increasing up to 191000 grains  $\text{gr}^{-1}$  towards the end of the zone. It is contributed mainly by Poaceae (1300–105200 grains  $\text{gr}^{-1}$ ), Asteraceae subf. Asteroideae (165–62500 grains  $\text{gr}^{-1}$ ), and *E. rubrum* (335–4500 grains  $\text{gr}^{-1}$ ). Among the aquatic taxa, Cyperaceae records its highest values up to 171200

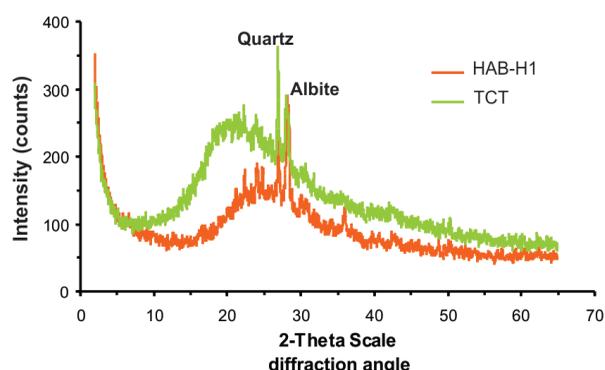


Figure 4. X-ray spectra of Harberton (HAB- $H_1$ ) and Cañadón del Toro (TCT) peat bogs.

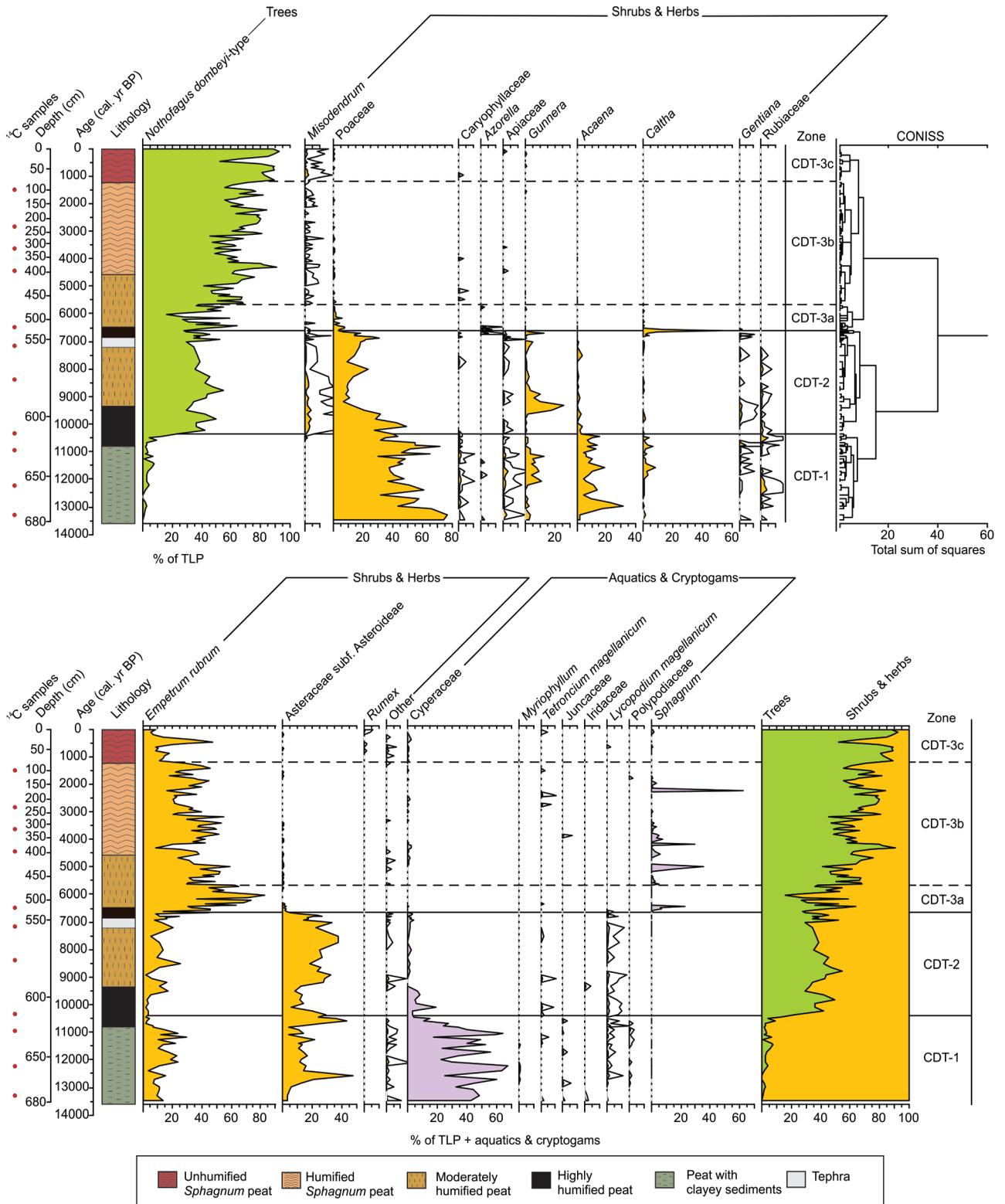


Figure 5. Fossil pollen/spore frequency (%) diagram and lithology at Cañadón del Toro mire. Outline curve represents an exaggeration percentage curve (10x) for minor taxa.

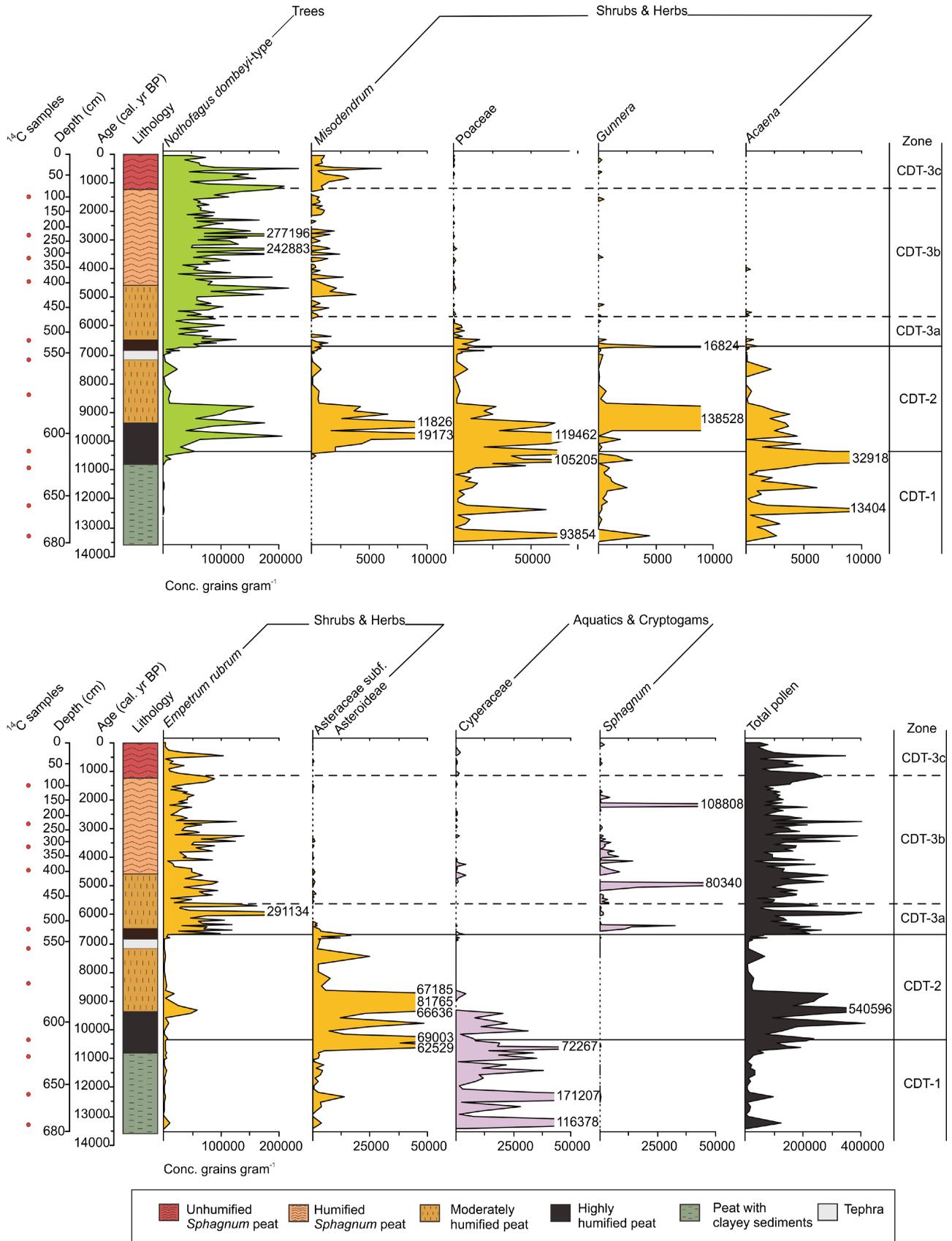


Figure 6. Fossil pollen concentration diagram (grains  $\text{gram}^{-1}$ ) and lithology at Cañadón del Toro peat bog.

grains  $\text{gr}^{-1}$ . *N. dombeyi*-type concentration is less than 5500 grains  $\text{gr}^{-1}$  throughout the zone.

Zone CDT-2 (613.5–530.5 cm; 10,350–6700 cal. yr BP). In this zone *Nothofagus dombeyi*-type (29–55%) expands abruptly along with decreases in Poaceae (8–49%), *Acaena* (<4%) and *Caltha* (<4%). Asteraceae subf. Asteroideae (38%) and *Empetrum rubrum* (25%) maintain similar percentages compared with those of the previous zone CDT-1. *Misodendrum Banks ex DC. 1830*, a hemiparasite on *Nothofagus* species, appears in low values (5%). *Gunnera* (26%) reaches its highest abundance in the record followed by its decline toward the end of the zone. Among the aquatic taxa, Cyperaceae decreases to <19%. Total pollen concentration exhibits an increasing trend (up to 540–600 grains  $\text{gr}^{-1}$ ) in the lowermost part of the zone. *N. dombeyi*-type (206500 grains  $\text{gr}^{-1}$ ), Poaceae (119500 grains  $\text{gr}^{-1}$ ), Asteraceae subf. Asteroideae (81800 grains  $\text{gr}^{-1}$ ) and *E. rubrum* (57500 grains  $\text{gr}^{-1}$ ) show high values, while Cyperaceae declines (22000 grains  $\text{gr}^{-1}$ ). Total pollen concentration values record an abrupt decline (<66500 grains  $\text{gr}^{-1}$ ) between 8800 and 7000 cal. yr BP, increasing toward the end of the zone up to 73400 grains  $\text{gr}^{-1}$ .

Zone CDT-3 (530.5–0 cm; 6700–0 cal. yr BP). Three subzones can be differentiated on the basis of proportional changes between *Nothofagus dombeyi*-type and *Empetrum rubrum*.

Subzone CDT-3a (530.5–469.5 cm; 6700–5650 cal. yr BP). This subzone displays an increase in *E. rubrum* (14–82%). *N. dombeyi*-type (16–59%) maintains similar frequencies compared with those of the previous zone CDT-2. *Caltha* peaks at 53% at the beginning of the subzone followed by its virtual disappearance. Poaceae (7%) displays low values. *Sphagnum* records 23%.

Subzone CDT-3b (469.5–81.5 cm; 5650–1200 cal. yr BP). During this subzone *N. dombeyi*-type shows an increase in its percentages (41–81%) along with decreases in *E. rubrum* (8–58%). *Sphagnum* reaches three peaks, up to 30, 36 and 62%.

Subzone CDT-3c (81.5–0 cm; 1200–0 cal. yr BP). This subzone is characterized by an increase in *N. dombeyi*-type (up to 93%), while *E. rubrum* (18%) decreases in relation to the previous Subzone CDT-3b. Between 510 and 380 cal. yr BP, *N. dombeyi*-type registers low frequency values

(52–67%), while *E. rubrum* increases up to 47%.

In this zone total pollen concentration records its highest values (405800 grains  $\text{gr}^{-1}$ ). The main contributor is *N. dombeyi*-type that reaches up to 277200 grains  $\text{gr}^{-1}$ . *E. rubrum* records 140200 grains  $\text{gr}^{-1}$  with a peak of 291100 grains  $\text{gr}^{-1}$ .

## DISCUSSION

### Local glacial history

In the Canal Beagle area, the LGM (ca. 25,000 cal. yr BP; Rabassa, 2008) is represented by a complex system of basal, lateral and terminal moraines. The latter moraine is located at Punta Moat, 120 km to the east of the Río Pipo valley, where Cañadón del Toro peat bog was formed. This event has been locally named Moat Glaciation (Rabassa *et al.*, 1990). Recessional moraines have been identified 100 km west of the frontal position, at Punta Segunda, situated in the north coast of the channel. Although no absolute ages could be obtained from these moraines, a Lateglacial age was inferred (Rabassa *et al.*, 2000).

Hall *et al.* (2013), based on the basal peat bog date from several sites of Cordillera Darwin (54–55° S; 69–70° W), postulated that a collapse of a massive ice in the cordillera began at 18,400 cal. yr BP, which had progressed such that ice was confined into the interior fjords by 16,800 cal. yr BP. The authors showed evidences that central Canal Beagle must have been free of ice at least at 14,800 cal. yr BP. A basal radiocarbon date from Ushuaia 2 peat bog located in the low terrains (25 m a.s.l.) along the Canal Beagle coast at Ushuaia city, confirms that this area was free of ice by 14,470 cal. yr BP; and by about 13,900 cal. yr BP (Ushuaia 1 peat bog) at elevations of 300 m above Ushuaia city. Eight km to the southwest, the landscape was free of ice by 11,640 cal. yr BP when Lapataia peat bog started to develop (Heusser, 1998).

No Lateglacial re-advances have been located and dated in the lowlands of the Canal Beagle (Rabassa *et al.*, 2006). However, geomorphological evidences from the tributary valleys of Fuegian Andes allowed to identify moraines that demarcated advances of glaciers during the Antarctic Cold Reversal (ACR, 14,500–12,900 cal. yr BP), the Younger Dryas Chronozone (YD, 12,900–11,700 cal. yr BP), and the presence of one, and locally two, closely spaced moraines located up to 2 km downvalley of Little Ice Age (LIA, <1000

cal. yr BP) (Menounos *et al.*, 2013). In these tributary valleys, several moraine deposits related to a Holocene glacier expansion have been identified (Rabassa *et al.*, 1990; Strelin *et al.*, 2001; Planas *et al.*, 2002; Menounos *et al.*, 2013, Ponce *et al.*, 2015). Menounos *et al.* (2013) have reported geological evidences for one or more advances of glaciers sometime between 7960–7340 and 5290–5050 cal. yr BP to limits only tens of meters beyond LIA maximum positions. No absolute ages are yet available for the inner moraines. However, these moraines have been assigned to advances of the LIA (<1000 cal. yr BP) based on their fresh, uneroded forms, proximity to existing ice, and similarity of their positions to moraines in the vicinity that had already been assigned to the LIA (Menounos *et al.*, 2013). These terminal moraines descend to 680±131 m a.s.l. (Ponce *et al.*, 2015). Menounos *et al.* (2013) suggested that the LIA event was the more extended neoglacial advance in the region.

#### **Palaeoenvironmental reconstruction at Cañadón del Toro peat bog**

After 13,500 cal. yr BP, the initial Lateglacial vegetal communities that colonized the deglaciated terrain were characterized by the dominance of pioneer grasses (Poaceae) and dwarf shrub heaths (*Empetrum rubrum*). By about 13,000 cal. yr BP, the spread of shrubs (Asteraceae subf. Asteroideae) along with *Acaena*, an indicator of open/disturbed grounds, suggests the prevalence of grassland-shrub environments. With soil development and increased humidity, the landscape was invaded by wetland herbs such as *Caltha*, *Gunnera*, and *Gentiana*. Among the more frequent steppe-associated plants, Apiaceae, Rubiaceae, Caryophyllaceae and *Azorella* were recorded. During this interval, the *Nothofagus* populations were poorly represented with low frequency and concentration values. Meanwhile, mire plants were characterized mainly by the dominance of sedges (Cyperaceae) showing at this initial stage the development of a minerotrophic mire (fen). These vegetal palaeocommunities resemble the present Fuegian steppe of the northern part of Tierra del Fuego, where mean annual precipitation is less than 400 mm and mean annual temperatures average 5.5 °C (Tuhkanen, 1992).

A significant vegetation change occurred by 10,350 cal.

yr BP. The steppe environments were replaced by a forest-steppe ecotone that prevailed until 6500 cal. yr BP. During this interval, stands of *Nothofagus* forest were interspersed with shrubs (Asteraceae subf. Asteroideae), grasses (Poaceae), and herbs (*Gunnera*, *Acaena*, Apiaceae, Rubiaceae, and *Gentiana*). The increase in the arboreal frequencies and concentrations together with the persistence in the record of the mistletoe *Misodendrum* seems to be a good evidence for the local presence of *Nothofagus*. Analogous communities exist today in central Isla Grande de Tierra del Fuego, with annual precipitation estimated at 350–500 mm and summer temperatures averaging 11 °C (Tuhkanen, 1992). During this period, the mire environment suggests a transitional stage between Cyperaceae fen and *Sphagnum* bog, due to an increase in atmospheric humidity. Between ca. 8600 and 7000 cal. yr BP, the total pollen concentration values drop abruptly, displaying synchronous fluctuations of taxa in the same direction (Fig. 5). Many complex factors such as mechanical, chemical, and biological agents, determine the differential preservation of the pollen in a specific type of deposit (Bryant, 1978). The increase in the ash during this interval (570–534 cm depth, Fig. 3) could reflect the tephra deposition process itself combined with increased mineralization of organic matter derived from the enhancement of microbial activity, resulting in a temporary alteration of trophic and water environment. The low concentration rates may also give some indication of oxidizing conditions at the mire surface probably caused by a seasonally fluctuating water table, which would account for a lack of pollen preservation (Heusser, 1998; Cook, 2009). This is in line with a reduced precipitation pattern and warmer conditions that prevailed during this period. Almost immediately after the tephra deposition, the development of new suitable habitats for pioneer plants is manifested by the increase in *Caltha* and *Gunnera* pollen.

After 6500 cal. yr BP, the pollen assemblage reflects the development of a closed-canopy *Nothofagus* forest spreading into the valley as a response of cooler and wetter conditions. This climate change is also evidenced in the mire setting. The increasing percentages of *Sphagnum* and *E. rubrum* suggest that the mire switched to ombrotrophic conditions. *Sphagnum* species colonize bog surface, whereas

*E. rubrum* grows on dry, elevated areas such as unhumified hummocks (Birks and Birks, 1980; Markgraf and Huber, 2010). Presently, these vegetal communities develop in the south of Tierra del Fuego with annual precipitation of more than 500 mm (Tuhkanen, 1992). By about 500 cal. yr BP, *Nothofagus* frequencies decline along with an increase in *E. rubrum* pollen, followed by the return of a closed-canopy forest at the site. *Rumex acetosella* L. 1753, an introduced taxon, indicates vegetation disturbance, including logging, fire and grazing (Mancini, 2009).

### Comparison with other sites

Lateglacial pollen evidences show a vegetation pattern dominated by a mosaic of highly diverse steppe-like communities with scarce *Nothofagus* trees, at Puerto Harberton, and Ushuaia 2 and 3 sites, situated in the lowlands along the Canal Beagle coast (Heusser, 1990, 1998; Markgraf and Huber, 2010). In the low interior valleys, the pollen records from Cañadón del Toro (this paper), Valle de Carbajal (Oyarzun peat bog), and National Route 3 exposure (Borromei *et al.*, 2007), as well as Paso Garibaldi, a high-elevation site (Markgraf and Huber, 2010), display a broadly similar vegetational pattern. The vegetation probably changed following its own internal dynamics, including the spread of plants and colonization of new ground, competition for suitable habitats and succession (Fontana and Bennett, 2012). During this time, at Puerto Harberton (Fig. 7), the *Nothofagus* pollen data suggest the survival of small tree populations in glacial refugia, distributed within the modern forested areas outside the glacier limits (Premoli *et al.*, 2010; Fontana and Bennett, 2012). It is likely that the early presence of the prostrate shrub *Empetrum rubrum* in the deglaciated valleys may have favoured the regional establishment of *Nothofagus* species (Fontana and Bennett, 2012). Today, the canopy of *E. rubrum* has an important nurse effect on growth of *N. antarctica* seedlings in the early stages of post-glacial succession by influencing microclimate and/or soil resource availability (Henríquez and Lusk, 2005). In Terra Australis mire, at central Tierra del Fuego (Fig. 1), the record of fungal remains of *cf. Microthyrium fagi* Ellis 1977 concurrent with increases in *Nothofagus* frequencies may indicate that some trees were locally present during the Lateglacial period (Musotto *et al.*, 2016). *Mi-*

*crothyrium fagi* is found on dead autumn leaves of *N. pumilio* (Arambarri and Gamundi, 1984); while other microthyriaceous fungi, including *cf. M. fagi*, have been reported in the surface samples from deciduous beech forest (Musotto *et al.*, 2012).

Particularly, in the Cañadón del Toro sequence, there is no indication in the arboreal composition (both frequencies and concentrations) of a major cold reversal related to the ACR and the YD Chronozone. However, Heusser (1998) identified two episodes of cooling characterized by low *Nothofagus* influx and separated by intervals of high arboreal influx associated to warmth conditions, from dated peat bog sections (Puerto Harberton, Ushuaia 1, 2 and 3) located along the Canal Beagle coast.

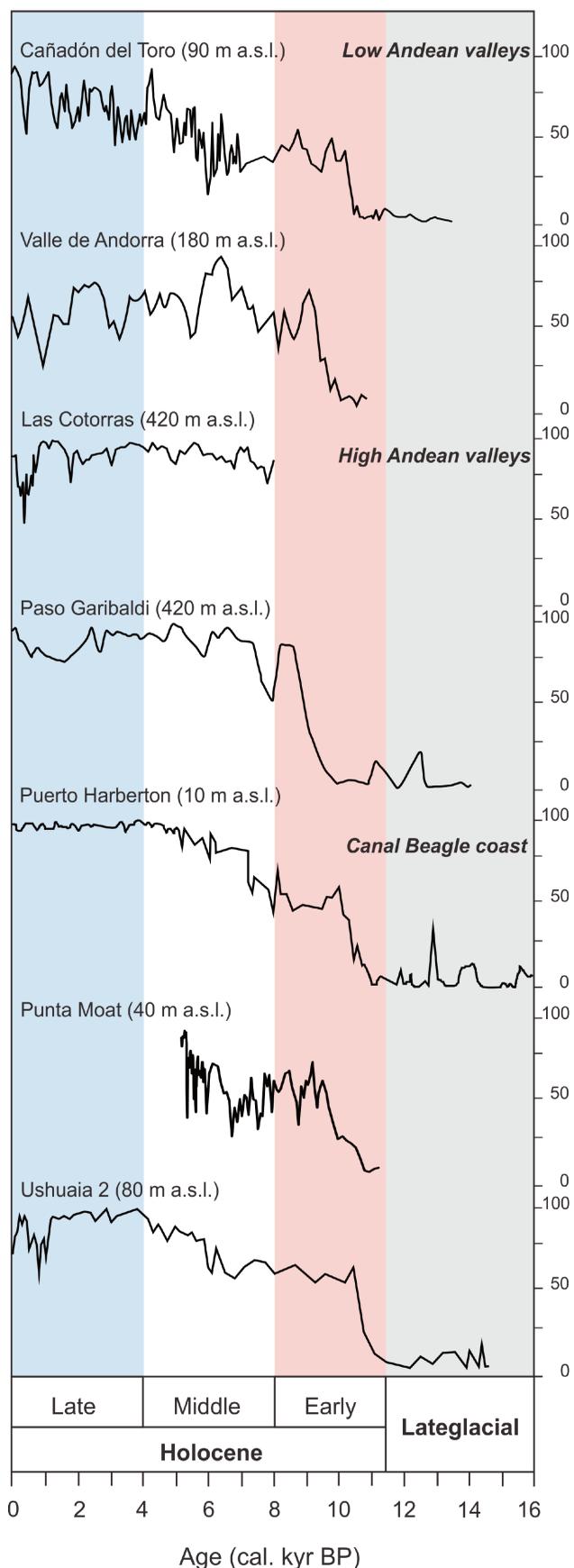
The expansion of *Nothofagus* woodland (Fig. 7) started during the Early Holocene, by about 11,500 cal. yr BP in the low terrains at Puerto Harberton, eastward Canal Beagle, and earlier, by about 12,400 cal. yr BP, at elevations of 300 m above Ushuaia city (Ushuaia 1 site). In Cañadón del Toro, the development of woodland-dominated vegetation occurred after *ca.* 10,500 cal. yr BP, like in the lowlands at Ushuaia 2 and 3. In the inner valleys of Andorra and Carbajal (Oyarzun site), *Nothofagus* woodland spread later. It seems probable that the expansion of *Nothofagus* has been distinctly affected by the prevailing westerly circulation and the local conditions at different sites (*e.g.*, soil-types, drainage, slope, facing).

During this period, the *Nothofagus* populations along with the steppe communities constituted an ecotone indicating warmer and drier conditions than today. Noticeable is the increase in *Misodendrum* frequencies in all the pollen sequences. This mistletoe is a hemiparasite that thrives exclusively on *Nothofagus* species; the intensity of infestation is dependent upon light and host availability, being maximal under high luminosity conditions and intermediate *Nothofagus* densities (Moreno *et al.*, 2014). High fire frequencies in Tierra del Fuego during the early Holocene must have favoured the development of open ground tracts and, at the same time, retarded the spread of the *Nothofagus* woodland (Whitlock *et al.*, 2007; Markgraf and Huber, 2010). In the Terra Australis record, the mycorrhizal *Glomus* Tul. and C. Tul. 1845 was probably associated with the presence of grasses and shrubs indicating relatively dry environmental

conditions, while the fungal spores of *Gelasinospora* Daw. 1933 have been related to fire events in the area during this time (Musotto *et al.*, 2016).

Towards the eastern sector of the Canal Beagle, at Punta Moat site, distant <1 km from the coast-line, the influence of the relative rise of the sea-level and the marine spray-humidity favoured the early development of a closed-canopy *Nothofagus* forest by 9500 cal. yr BP (Borromei *et al.*, 2014) (Fig. 7). Also, in the high-elevation sites, such as Paso Garibaldi and Las Cotorras, the closed-canopy *Nothofagus* forest reached those altitudes by about 8800 and 8000 cal. yr BP, respectively (Fig. 7). Although no charcoal analysis was performed on Las Cotorras peat core, Markgraf and Huber (2010) indicated that fires were absent at the upper treeline at Paso Garibaldi and did not influence the *Nothofagus* communities there. At these elevation sites, the development of a closed-canopy forest suggests modern moisture levels with a treeline at or even above present (Markgraf and Huber, 2010). Meanwhile, dense forest populations developed after about 7000 cal. yr BP in the lowlands along Canal Beagle coast and after 6500 cal. yr BP in the interior valleys (Fig. 7).

There are no clear evidences for the Holocene glacier fluctuations in the vegetation composition of these fossil localities. However, the intervals of low *Nothofagus* influx, at 6380–5000 cal. yr BP, 2334–360 cal. yr BP and recently at Puerto Harberton, are indicative of cooler episodes (Heusser, 1989b). The first interval of decline in arboreal influx at Puerto Harberton may be related to the one of the glacier advances reported by Menounos *et al.* (2013) between 7960–7340 and 5290–5050 cal. yr BP. During the last 1000 years (Fig. 7), decreases in the frequency of *Nothofagus* pollen have been recorded in the Cañadón del Toro valley at ca. 500 cal. yr BP. In Las Cotorras, a major vegetational change towards colder conditions has been re-



**Figure 7.** *Nothofagus* pollen frequency records from Cañadón del Toro (this paper); Valle de Andorra (Borromei, 1995); Las Cotorras (Borromei *et al.*, 2010); Paso Garibaldi (Markgraf and Huber, 2010); Puerto Harberton (Markgraf and Huber, 2010); Punta Moat (Borromei *et al.*, 2014); and Ushuaia 2 (Heusser, 1998) sites. The peat bogs are listed according to their altitude above sea level (m a.s.l.).

ported after 1000 cal. yr BP, when the decline of *Nothofagus* pollen reached a minimum between ca. 680 and 300 cal. yr BP. During this interval, the stratigraphy of the mire showed peat interspersed with clastic sediments. They were indicative of a clastic input coming from mass wasting events or floods occurring during snowmelt and deposited over a very short time scale (Borromei *et al.*, 2010). Presumably, the reduced vegetal cover, due to a less dense forest, favoured the landslides downslope in the valley. The multiproxy analyses of a ca. 1400-yr peat record from Valle de Andorra also registered climatic fluctuations including a period of cooler and/or wetter conditions (Mauquoy *et al.*, 2004). In Paso Garibaldi high-elevation site, the spread of Andean grasslands along with a less dense forest indicated the treeline lowering below the site between 2500 and 400 cal. yr BP, probably related to minor temperature depressions (Markgraf and Huber, 2010). Taken together, these pollen data could be related to the LIA (<1000 cal. yr BP) chronozone. Climatic factors, such as strength and latitudinal position of the SWW, changes in solar irradiance and in atmospheric-ocean circulation have been mentioned among the more important external drivers for Holocene glacier fluctuations in Tierra del Fuego (Menounos *et al.*, 2013).

## CONCLUSIONS

The palaeovegetation reconstruction from Cañadón del Toro peat bog show changes in the plant communities that follow similar patterns to those recorded in the lowlands and in the high-elevation sites of the forested region in southern Tierra del Fuego, although these changes were not simultaneous. For most of the Lateglacial period, after ca. 13,500 cal. yr BP, the Río Pipo valley remained with scattered *Nothofagus* trees and grasses, shrubs and heaths dominated the vegetation. Initially, the mire was a Cyperaceae fen. *Nothofagus* spread into the valley during the Early Holocene, around 10,350 cal. yr BP, like an ecotone when the climate conditions were warmer and drier than today. The regional fires may have restrained the *Nothofagus* forest expansion favouring the development of open ground vegetation dominated by shrubs and grasses. Meanwhile, the mire showed a transitional physiognomy between Cyperaceae fen and *Sphagnum* bog.

The dated tephra at 6170 +/- 70 <sup>14</sup>C yr BP (7178–6796

cal. yr BP) seems to correspond, in chronology and composition, to the H<sub>1</sub> tephra from the Volcán Hudson. The pollen and geochemical spectra of this event record a temporary impact during the development of the peat bog between ca. 8600 and 7000 cal. yr BP.

During the mid- to Late Holocene, by about 6700 cal. yr BP, a climatic change towards colder and wetter conditions may have facilitated the expansion of dense forest on the Pacific Andean slope in southernmost Tierra del Fuego. By this time, the mire also changed to ombrotrophic conditions, contributed essentially by *Sphagnum*, reflecting greater water depth and less mineral input. During the last 1000 cal. yr BP, the record showed a decline in the *Nothofagus* frequencies at ca. 500 cal. yr BP most probably related to colder conditions. The palaeoenvironmental conditions recorded throughout the studied sequence are closely related to oscillations in precipitation and temperature as a response to the variations in the position and/or strength of the southern margin of the SWW at these high latitudes.

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