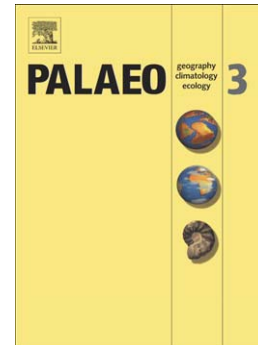# Accepted Manuscript

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Multiproxy Record of Holocene Paleoenvironmental Change, Tierra del Fuego, Argentina

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Abstract

We interpret Holocene environmental conditions in a subantarctic high Andean valley from palynological and diatom analysis, peat stratigraphy, and local geomorphology. The multiproxy data from Las Cotorras mire (54º 41' 13'' S; 68º 02' 51'' W; 420 m a.s.l.) indicate the development of a soligenous mire, as a result of a fine grained tephra layer deposition over the mineral soils sometime prior to 8000 cal yr BP. The paleoecological conditions in the mire after 8000 cal yr BP show a rapid succession from a limnic to a telmatic stage as the mire is colonized by sedges (Cyperaceae) and herbaceous communities. The upland vegetation changed from cushion and shrub heaths to an expansion of *Nothofagus* forest at high altitudes after 6500 cal yr BP. The peat is interbedded with clastic sediment that originates from mass wasting events or floods. These depositional changes affected the mire ecosystem water-table level and nutrient status (oligotrophic and/or eutrophic conditions). Maxima in total pollen influx at about 2800, 1100 and 700 cal yr BP coincide with heightened mineral flux, and these changes are related to precipitation and slope processes. The major vegetational change registered in the pollen record is the decline of *Nothofagus* pollen after 1000 cal yr BP, which reaches a minimum between *ca.* 680 and 300 cal yr BP. This minimum was likely caused by cool, wet conditions that coincided with the Little Ice Age (LIA) in the Southern Hemisphere. Our results indicate the sensitivity of subantarctic *Nothofagus* forest and mire ecosystems to changes during the Holocene.

1. Introduction

Late Cenozoic paleoecological conditions from de Tierra del Fuego, southernmost Patagonia, are largely based on palynological records along the Beagle Channel (Heusser, 1989a, 1989b, 1990, 1995, 1998, 2003; Markgraf, 1993; Borromei and Quattrocchio, 2001, 2007, 2008; Pendall et al., 2001). Few studies exist for sites in the inner valleys of the Fuegian Andes (Borromei, 1995; Borromei et al., 2007) or at high elevation (Markgraf, 1993).

We summarize the palaeoenvironmental and paleoclimatic conditions that prevailed during the Holocene for a high elevation mire north of the Beagle Channel. The 1 ha mire, informally named 'Las Cotorras' (54º 41' 13.53'' S; 68º 02' 51.42'' W, 420 m a.s.l.) lies at the foot of a west-facing slope in the Las Cotorras valley, about 20 km northeast of the city of Ushuaia (Figure 1). The mire is near the present-day tree line and in close proximity to a cirque glacier. Dendroecological studies on *Nothofagus pumilio* populations found at the upper treeline in Tierra del Fuego and Isla de los Estados (Boninsegna et al., 1989; D'Arrigo and Villalba, 2000; Massacceci et al., 2008) as well as in southern Chile at 55°S (Aravena et al., 2002), indicate that the tree-growth may be negatively affected by lower temperatures and higher precipitations related to more extended snowfall seasons and snow accumulation through the spring.

Due to the mire´s elevation and proximity to a present glacier, this study brings up the opportunity to infer temperature and precipitation changes that are pertinent to fluctuations of nearby glaciers. Although Neoglacial fluctuations have been recognized by geomorphological studies in the surrounding valleys (Coronato, 1995; Rabassa et al., 2000; Planas et al., 2001), absolute chronologies have not been established yet in this region due to the lack of datable material. Evidence of climate conditions favoring Neoglacial expansion of alpine glaciers are not clearly identified by pollen records from

the Beagle Channel coast (Heusser, 1989a, 1989c, 1998), but the Mediaeval Warm Period (MWP) and the Little Ice Age (LIA) have been identified by Mauquoy et al. (2004) and Chambers et al. (2007) from palaeoenvironmental evidence from peat-cores taken in a low, inner Andorra valley (175 m a.s.l., Figure 1).

2. Physical setting

Las Cotorras is a NW-SE hanging glacial valley in the Sierras de Alvear range 4.3 km long. The mire reported in this study is located on the valley floor at the foot-slope of the west facing slope (Figure 2).

Cryoplanation surfaces and patterned ground are present at the summits of the valley heads (1010 m above sea level; Valcarcel-Díaz et al., 2006) and on the terraces close to the col (Valcarcel-Díaz et al., 2005). Debris cones are present and many of the slopes in proximity to the mire are mantled with till and colluvium.

West of the valley heads there is a W-E oriented cirque hosting the Alvear Este Glacier, a proglacial lake and roche-mountonné features. The outlet of the small lake forms Las Cotorras Creek at 750 m a.s.l.

Above 600 m a.s.l., convex slopes are dominant whereas straight and concave segments are common on the middle and low slopes. The slope value range between 14º - 33º. The studied mire is located at the foot of a slope with a gradient of 35º and concave shape, two characteristics which sustain mass wasting processes. Past and present evidence of landslides, rockslides, snow avalanches scars and debris deposits can be observed in both slopes of the valley. Gravity and mass-wasting deposits accumulated along the foot-slopes are colonized by lichens, mosses, grasses, herbs and trees.

The hanging valley where the mire is located was glaciated by an alpine-type glacier which joined the Carbajal-Lasifashaj glacier almost at 200 m a.s.l. This mountain ice network joined the main regional Beagle Channel palaeoglacier (Figure 2) 50 km down ice-stream. Unfortunately, no absolute dates are yet available in sedimentary deposits of these hanging valleys that would help in the understanding of Quaternary glacial dynamics. Nevertheless, regional studies suggest that the Last Glacial Maximum took place at *ca.* 25 cal ka BP (McCulloch et al., 2005; Coronato and Rabassa, 2007) and the ice receded from the inner valley slopes at around 10.3 – 9.3 ^{14}C ka BP (Coronato, 1995; Borromei et al., 2007).

3**. Modern climate and vegetation**

The climate in the southern Fuegian ranges is cold-temperate and it is influenced predominantly by the seasonal shifts of the Polar Front and the cyclonic activity related to the southern westerlies. Frequent heavy rain storms strike the Pacific coastal sector and Patagonian Andes and become diverted southeastward by the axial trend of the Andes (Pisano, 1977). Meteorological information is based on instrumental records from 2003-2004 from neighboring Mt. Krund slope (460 m a.s.l., Figure 1). Daily mean air temperature between October and April was 4.6 ºC, with a daily maximum and minimum of 14.4 ºC and -1.8 ºC respectively. Mean relative air humidity is 73 % (A. Moretto, pers. comm.).

Prevailing winds originate from the W-SW and are most frequent during spring and summer. Although NW-N-NE winds are less frequent, they develop higher intensity and blow strongly down–slope to the bottom of the valleys. Precipitation is regularly distributed through the year, as a consequence of year-round passage of humid and cold air-masses crossing the mountain barriers. Precipitation as snow occurs between April

and November, and frozen ground may occur between April and September (Tuhkanen, 1992).

Vegetation at lower altitudes is dominated by the Subantarctic Deciduous Forest (Pisano, 1977; Moore, 1983). It is characterized by two species, *Nothofagus pumilio* ("lenga") and *N. antarctica* ("ñire"), which grow from sea level to tree-line (550-600 m a.s.l.) and become dominant where precipitation reaches between 400 and 800 mm/year. Between the treeline and snowline, Andean Tundra develops (Pisano, 1977; Roig, 1998; Heusser, 2003). It is made up of cushion heath featuring *Bolax gummifera* associated with *Azorella lycopodioides*, *Colobanthus subulatus* and *Drapetes muscosus*. Dwarf shrub heath is variably dominated by *Empetrum rubrum*, *Pernettya pumila* and *Myrteola nummularia*. Inhabiting open ground in the feldmark are *Nassauvia latissima*, *N. pygmaea*, *Saxifraga magellanica* and *Senecio humifusus*. Alpine meadows can be found along drainage courses fed by melting snow or the receding glacier. These are sites for herbaceous communities rich in species like *Abrotanella linearifolia*, *Caltha appendiculata* and *Plantago barbata*, with less frequent associates such as *Acaena antarctica*, *Ourisia fuegiana*, *Primula magellanica*, *Cardamine glacialis*, *Tapeinia obscura* and *Hamadryas magellanica*. Where mires occur, plant cover is a mixture of grasses, sedges and rushes (Heusser, 2003).

4. Materials and methods

We collected peat samples with a Russian peat corer (chamber length 0.5 m and 5 cm diameter). Sampling at the site was extremely difficult since the thick layers of mineral soils hindered penetration of the corer. We transported the core to the Göteborg University laboratories (Sweden) where we described the stratigraphy and sub-sampled the core at 5 cm resolution for analysis discussed below.

The volcanic grains were mounted in epoxy resin and polished to a flat surface using 1 micron diamond slurry (Table 1). The element analyses were performed with a LINK Oxford energy dispersive spectrometer with a Ge detector, mounted in a Zeiss DSM 940 scanning electron microscope. A cobalt standard linked to simple oxide and metal standards was used to monitor drift of the instrument. Accelerating voltage of 25kV, sample current about 1 nA and counting live-time of 100 sec were used. Precision reproducibility of analyses was typically better than 1-4% (Schmitz and Haggstrom, 2006). We used 21 grains for element analysis of major oxides.

Eight peat samples provided chronologic control for the core. The NSF-Arizona AMS Laboratory, U.S.A undertook the radiocarbon analysis on the samples, and we converted the radiocarbon ages to calendar years BP using the program CALIB 5.0.2 (Stuiver et al., 2005) and the South Hemisphere curve (SHCal04) (McCormac et al., 2004) (Table 2). We used a second-term polynomial curve to construct an age-depth model for the core (Figure 3).

We prepared 82 samples from the core for palynological analysis according to standard Faegri and Iversen (1979) techniques. *Lycopodium* spore tablets added to each sample prior to treatment (Stockmarr, 1971) allowed us to calculate the pollen concentration per gram of sediment and the accumulation rates (influx). Frequencies (%) of tree, shrub and herb pollen of terrestrial origin were calculated from sums mostly of ≥ 300 grains. Pollen of aquatic plants and cryptogams were calculated separately and related to the sum of terrestrial pollen. Fossil pollen data are plotted in Figures 4 and 5 showing the main pollen taxa percentages and accumulation rates (influx), respectively; other herbs include taxa with low values, such as Caryophyllaceae, Rubiaceae, *Valeriana*, *Gentiana*, *Myrteola nummularia*, Brassicaceae, Scrophulariaceae, Cichorioideae, Chenopodiaceae, *Misodendrum* and *Plantago*. Using the Cavalli-Sforza

Distance (TGView 2.0.2, Grimm, 2004), we applied a stratigraphically constrained cluster analysis to distinguish pollen zones based on taxa that reached percentages of >1% of the sum of terrestrial pollen.

We combined pollen from the evergreen species *N. betuloides* and the deciduous species *N. pumilio* and *N. antarctica* given the difficulty in species separation and report these pollen as "*Nothofagus dombeyi* type". Another special case is *Empetrum rubrum* and *Gaultheria/Pernettya* (Ericaceae), which are morphologically similar. The latter sometimes is included together with *Empetrum* when its surface sculpture is not well-defined. We also compared our fossil pollen spectra with regional pollen spectra from surface soil samples (Heusser, 1989a) and with present-day vegetation from Tierra del Fuego (Pisano, 1977; Roig, 1998; Heusser, 2003).

Non-pollen palynomorphs (NPPs) are numbered according to an informal "Type" denomination used in van Geel (1978), van Geel et al. (1981) and van Geel et al. (1983). Several NPPs types still have no taxonomic identification, but a large amount of information about their indicator value and stratigraphic distribution has been published, and they can also be used for palaeoecological reconstruction (van Geel, 2001). We calculated the frequency (%) of non-pollen palynomorphs (NPPs) on the total sums of pollen and spores (Figure 6). The most common NPPs are shown in Figures 7 and 8.

We also analyzed the diatom content of inorganic sediments present in the peat core. Warm hydrogen peroxide oxidized organic material within the samples selected for analysis, and these were then mounted onto microscope slides following standard procedures (Battarbee, 1986). We prepared duplicate permanent slides for light microscopy with Naphrax resin, and we counted a minimum of 400 valves per slide to calculate relative frequencies (Figure 9). Identification of the diatom taxa at species level or variety was based on various studies (Simonsen, 1987; Rumrich et al., 2000,

among others). Nomenclature followed criteria established by Round et al. (1990). The most abundant diatom taxa are shown in Figure 10.

5. Results

5.1. Mire stratigraphy

The mire at Las Cotorras site consists of approximately 5 m of massive peat in various stages of decomposition that is interbedded with silt, sand, and gravel units (Figure 4). The peat consists primarily of bryophytes (*Sphagnum fimbriatum*, *Drepanocladus* spp.) and vascular plants (*Carex* and grasses).

Thick clastic units in the peat occur at 185-270, 105-120 and 55-85 cm while thinner beds are centered at 470, 450, 410 and 310 cm depth (Figure 4). The clastic bed at 185-270 cm depth is interpreted to be a debris flow deposit based on its poor sorting and coarse grain size. The origin for the other clastic units is unknown, but these sediments may be distal deposits from mass wasting events or floods.

The basal tephra at Las Cotorras mire consists of silt-sized glass shards and mineral matter. Seventy-seven percent of the particles are finer than 61 µm, and the median grain size is 15 µm. Peat directly above this tephra yielded a calibrated radiocarbon age of 7821 cal yr BP (Table 2). The geochemical properties of the tephra (Table 1) coincide well with the thick high-K-andesite tephra deposits recorded in Harberton Bog located southeast on the Beagle Channel coast (L.Franzen, unpublished data). At the time of the basal tephra deposition in the mire, regionally widespread Holocene tephra layers have been recorded in the southernmost Patagonia coming from the southern portion of the Andean Southern Volcanic Zone (SVZ) located at 33-46º S (Stern, 2008). The analyzed tephra have similar geochemical signal to the Hudson volcano one, at

2,600 m altitude, 46º20´S and 73º00´W, as it was reported by Naranjo and Stern (1998) and Stern (2008).

5.2. Palynological analysis

Cluster analysis recognized four main zones: LC-1 to LC-4 based on conspicuous changes in the pollen stratigraphy (Figure 4). Zones LC-1 and LC-2 are divided into two subzones, respectively. In order, from the lower to the upper part of the section, they are:

Zone LC-1 (480-270 cm, *ca.* 8000-2800 cal yr BP)

Pollen

Nothofagus dombeyi type is the dominant pollen taxon throughout the zone and often reaches 90%. Cyperaceae fluctuates between 20% and 1% with several marked peaks. Among the herbaceous taxa, Poaceae (9%), *Acaena* (7%) and *Empetrum/*Ericaceae (4%) are recorded. Meanwhile, *Azorella* grains prevail in the Subzone LC-1b and reach a peak of 11%. Other taxa (Caryophyllaceae, *Caltha*, Ranunculaceae, Rubiaceae, *Gunnera*, Apiaceae, *Valeriana*, *Nassauvia*, Asteroideae, *Drapetes muscosus*, Brassicaceae, Chenopodiaceae) are present with low frequencies (<3%). In the lowermost part of Subzone LC-1a (Figure 5), total pollen influx is low (<1600 grains/gr/yr), and increases at the end of this subzone (<50,000 grains/gr/yr) contributed mainly by *Nothofagus dombeyi* type. Total influx decreases at 410 cm depth (5000 grains/gr/yr) coincident with a mineral layer. During the following Subzone LC-1b (Figure 5), total influx increases and shows high and variable values peaking at 320 and 295 cm depth (~53,500 grains/gr/yr) and towards the end of the subzone, at 275 cm depth (236,000 grains/gr/yr).

Non-pollen palynomorphs (NPPs)

In the lowermost part of the section (Subzone LC1-a, Figure 6), the relative abundance of *Rivularia*-type (Type 170) (Cyanophyceae) associated with Zygnemataceae like *Mougeotia* sp. (Type 313) and *Zygnema* sp. (Type 314) suggests oligo-mesotrophic (poor to moderate nutrient) conditions in the mire (van Geel et al., 1981; López Sáez et al., 1998, 2000) related to high water-table level.

The gradual decrease of *Rivularia*-type (Cyanophyceae) and Zygnemateaceae - *Mougeotia* sp. (Type 313) and *Zygnema* sp. (Type 314)-, along with increases in *Spirogyra* sp. (Type 315) (Zygnemataceae), Type 16 and Type 66 frequencies (van Geel, 1978; López Sáez et al., 1998; van Geel and Aptroot, 2006) points to changes in the trophic conditions towards mesotrophic or meso-oligotrophic conditions. The record of ascospores of coprophilous species as *Chaetomium* sp. (Type 7A), *Sordaria* sp. (Type 55A) and *Sporormiella* sp. (Type 113) (van Geel, 1978, 2001; Graf and Chmura, 2006; van Geel and Aptroot, 2006) throughout the section are indicative of dung produced by herbivorous animals (López Sáez and López Merino, 2007). Drier conditions are indicated by the presence of fungal Types 810, 811, 812 and 813, along with Type 5 and *Clasterosporium caricinum* (Type 126). The existence of transient shallow ponds on the mire surface is suggested by the record of spermatophores of Copepoda (Type 28) (van Geel, 1978; van Geel and Middeldorp, 1988).

During Subzone LC-1b (Figure 6) gradual changes to meso-eutrophic (moderate to rich in nutrients) or eutrophic conditions are suggested by the decline of *Rivularia*-type (Type 170) and the presence of *Spirogyra* sp. (Type 315) associated with microremains of invertebrate animals as oocytes produced by aquatic flatworms of Turbellaria (*Neorhabdocoela*) (Type 353) (Haas, 1996). According to this author, the presence of

Type 353 indicates nutrient-rich environments. Decrease in spermatophores of Copepoda (Type 28) suggests a reduction of seasonal shallow ponds on the mire surface (van Geel, 1978; van Geel and Middeldorp, 1988). The record of Type 411, a bog species fungal parasite, indicates the presence of sedge-like vegetation.

Diatoms

Inorganic levels at 470-450 cm, 410 cm and 310 cm respectively, were diatom sterile.

Zone LC-2 (200-90 cm, *ca.* 2400-680 cal yr BP)

Pollen

Nothofagus dombeyi type maintains its dominance (98%) in Subzone LC-2a, but decreases within Subzone LC-2b (90%). The herbaceous taxa are primarily Poaceae (6%) and *Acaena* (9%) accompanied by peaks of *Gunnera* (10%) and *Empetrum*/Ericaceae (8%). There are low values of Cyperaceae (< 4%) in Subzone LC-2a which subsequently increase abruptly in the next Subzone LC-2b, reaching their highest frequency values (21%). Total pollen influx (Figure 5) records high values (up to 56,000 grains/gr/yr) and reaches maximum (100,124 grains/gr/yr) towards the end of Subzone LC-2a. Total influx declines (20,500 grains/gr/yr) during Subzone LC-2b and increases at the end of this subzone (77,000 grains/gr/yr). Deposition times decrease to 18 yr/gr during Subzone LC-2a, and reach low values (11-6 yr/gr) during the following subzone when the mineral layer was deposited.

Non-pollen palynomorphs (NPPs)

The trophic conditions changed throughout Subzone LC-2a likely due to changes in the local groundwater table. The presence of *Mycrothyrium* sp. (Type 8B), Type 411 and

oocytes of Turbellaria (*Neorhabdocoela*) (Type 353) along with the absence of spores of *Spirogyra* sp. (Type 315), *Rivularia*-type (Type 170) and Type 28 suggest eu-mesotrophic conditions, lower water levels and drier conditions. The record of *Spirogyra* sp. (Type 315), algae Type 128A, Type 28 and *Arcella* sp. (Type 352) (Testaceae), which proliferate in freshwater shallow pools, reflect meso-eutrophic or mesotrophic conditions associated with a gradual rise of water-table level. The increase in *Rivularia*-type (Type 170) and Type 225 (van Geel et al., 1989) algal microfossil abundance and the decline in *Spirogyra* sp. (Type 315) percentages are indicative of meso-oligotrophic conditions driven by a rise in water-table level.

During Subzone LC-2b (Figure 6) the record of *Spirogyra* sp. (Type 315) and oocytes of Turbellaria (*Neorhabdocoela*) (Type 353) along with spermatophores of Copepoda (Type 28) suggests meso-eutrophic conditions associated with seasonal shallow ponds probably related to sealed substrata due to deposition of debris-flow sediments over the mire.

Diatoms

At a depth of 240 cm and between 200-190 cm (Figure 9), the diatoms are abundant and the dominant forms are *Fragilaria capucina* var. *vaucheria* (Kütz.) L.-Bert. (benthic) and *Planothidium lanceolatum* (Bréb.) Round & Bukht. (epiphytic, frequently attached to sand grains).

Between 120-100 cm, the samples are most heterogeneous level (Figure 9). At 120 cm, with scarce, highly eroded and fragmented material, the dominant form is *Staurosirella pinnata* (Ehr.) Williams & Round. This species has a wide tolerance and it can be found in different environments, under variable ecological conditions (Paull et al., 2008). Some paleoenvironmental studies suggest it is a pioneer species after a cold

period (Stoermer, 1993). At 115 cm depth, the number of taxa increases. *S. pinnata* is replaced by *Psammothidium abundans* (Manguin) Bukht. et Round and *Achnanthidium minutissimum* (Kütz.) Czarn. At 110 and 100 cm depth, *Fragilaria capucina* var. *vaucheria* and *Distrionella germainii* var. a*costa* (L.-Bert.). Morales *et al.* are dominant along with *Planothidium lanceolatum*. All these species are common in slightly acid to circumneutral aquatic environments with low to moderate conductivity (Van de Vijver and Beyens, 1997; Van de Vijver *et al*., 2008). The identified diatom assemblages could indicate a colonizer succession in aquatic environments subject to disturbances such as cold period.

Zone LC-3 (90-25 cm, *ca*. 680-300 cal yr BP)

Pollen

Nothofagus dombeyi type has the lowest values (50%) in the entire peat core, and Cyperaceae decreases sharply down to 3%. Among the herbaceous taxa, *Acaena* reaches maximum values of 34% accompanied by Poaceae (7%), Ranunculaceae (6%), Apiaceae (6%) and cushion-forming plants of *Drapetes muscosus* (7%). Fern spores (Polypodiaceae) are also present. *Gunnera* increases its proportions in the upper part of this zone (16%). Total pollen influx values are similar to that of previous zone, although *Nothofagus* decreases (<9000 grains/gr/yr) with peaks of <18,000 grains/gr/yr and shrubs and herbs show higher values than during the previous zone (Figure 5). Deposition times decrease reaching their lowest values (3-7 yr/gr) when inorganic strata are deposited.

Non-pollen palynomorphs (NPPs)

The increase in *Rivularia*-type (Type 170) percentages during this zone (Figure 6) indicates meso-oligotrophic conditions with a high water level. At the same time, the significant rise of spermatophores of Copepoda (Type 28) and *Spirogyra* sp. (Type 315) are probably related to a period of mesotrophic conditions with moderate nutrients availability associated with shallow and slow-moving freshwater environments (López Sáez et al., 1998). At this point eggs of the tardigrade *Macrobiotus ambiguus* type are also registered. This tardigrade is recorded from high latitudes of the Northern Hemisphere (Jankovská, 1991) and Antarctica (Cromer et al., 2008). Towards the uppermost part of this zone *Rivularia*-type (Type 170) percentages decrease as a consequence of changing trophic conditions towards drier and meso-eutrophic conditions in the mire. Also, *Ustulina deusta* (Type 44), a tree parasite fungus (van Geel, 1978; van Geel et al., 1981), is listed. According to van Geel and Aptroot (2006) there is a strong relation between this parasite fungus record and the establishment of arboreal elements.

Diatoms

Between 85-60 cm, the dominant species are *Fragilaria capucina* var. *vaucheria* and *Planothidium lanceolatum* (Figure 9). The co-dominants are *Psammothidium incognitum* (Krasske) Van de Vijver and *P. abundans*. The former species is commonly associated with submerged mosses in lakes and mountain streams from Chile (Krasske, 1939) and subantarctic lakes (Van de Vijver and Beyens, 1997). The identified diatom assemblages might be related to bog environments with variable water levels.

Zone LC-4 (25-0 cm, *ca.* 300-0 cal yr BP)

Pollen

Nothofagus dombeyi type shows an increase in its percentages (90%) along with *Azorella* (10%), Cyperaceae (9%), Poaceae (7%) and peaks of *Nassauvia* (13%). A considerable increase in total pollen influx values (<68,000 grains/gr/yr) and depositional times (10 yr/gr) are observed during this zone compared with the previous zone (Figure 5).

Non-pollen palynomorphs (NPPs)

The decline in the percentages of *Rivularia*-type (Type 170) and the presence of *Spirogyra* sp. (Type 315) and *Mougeotia* sp. (Type 313) suggest mesotrophic conditions. Peaks of spermatophores of Copepoda (Type 28) might be associated with transient shallow pools related to deposition of debris-flow sediments over the mire.

Diatoms

At 30 cm depth (sample 6) the diatom valves are scarce and highly fragmented (Figure 9). There is a very low number of species (8), and *Staurosirella pinnata* is the dominant form (47.4%).

6. Discussion

6.1. *Paleoenvironmental evolution at Las Cotorras mire*

Las Cotorras mire records rapid changes in Holocene environmental conditions that can be used to infer broader scale changes for the Fuegian Andes. The stratigraphy of the mire is indicative of a soligenous mire with a fluctuating groundwater table and an environment that episodically receives input of clastic sediments. The clastic sediments are primarily silt-sized materials that probably reached the site through mass wasting events (e.g. distal debris flow deposits) or during floods such as those that can

occur during autumn precipitation events or during snowmelt and then deposited over a very short time scale.

The mire formed at *ca.* 8000 cal yr BP. The initial pollen assemblage (Zone LC-1, Figure 4) suggests a *Nothofagus* forest in association with communities of alpine meadow vegetation (Poaceae, *Acaena*, *Caltha*, *Gunnera*), cushion heaths (*Azorella*), dwarf shrub heaths (*Empetrum*/Ericaceae) and mires of sedge (Cyperaceae). In spite of the high frequencies of *Nothofagus* pollen, the initial low influx values imply limited numbers of *Nothofagus* trees between 8000 and *ca.* 6500 cal yr BP (Subzone LC-1a, Figure 5). The development of an open *Nothofagus* forest at this high elevation site suggests warm and dry conditions. This plant assemblage resembles the present forest-steppe ecotone of the central part of Tierra del Fuego, with annual precipitation estimated at 400-500 mm and summer temperatures possibly averaged 10-11°C (Heusser, 1989a).

The initial environmental conditions at the mire (*ca.* 8000-7500 cal yr BP, Figure 6) corresponded to a limnic stage, relatively poor in nutrients (oligo-mesotrophic) and with a high water-table level that favored the proliferation of cyanobacteria of the *Rivularia*-type. After 7500 cal yr BP, as the telmatic stage begins, the mire gradually became drier and was colonised by sedges and grasses. Meso-oligotrophic to mesotrophic conditions prevailed with a lower groundwater table. The absence of diatoms in the inorganic strata at 470-450 cm and 410 cm depth suggests that sediments were rapidly deposited. Inorganic detritus deposition over the mire by superficial runoff would have favored the development of transient shallow ponds as are indicated by the record of Copepoda (Type 28) (Figure 6). The open forest and warm and dry conditions during the early Holocene probably favored the spread of herbivorous grazers (most likely, "guanaco", *Lama guanicoe*) in the valley as can be inferred by the record of

coprophilous fungi such as *Chaetomium* sp. (Type 7A), *Sordaria* sp. (Type 55A) and *Sporormiella* sp. (Type 113) (Figure 6).

The development of a closed *Nothofagus* forest after *ca* 6500 cal yr BP as revealed by the increase in arboreal pollen influx (Subzone LC-1b, Figures 4 and 5), suggests an increase in effective moisture. Today, dense *Nothofagus* forest occurs where precipitation range between 500 and 800 mm/year and mean annual temperature average 6.5°C in the south of Tierra del Fuego (Pisano, 1977; Heusser, 1998). The Cyperaceae mire vegetation reflects enhanced minerotrophic conditions, probably due to an increase of water at the foot of the slope.

According to the non-pollen palynomorphs record, the mire paleoecological conditions changed to meso-eutrophic to eutrophic conditions with a variable but lower water level (Subzone LC-1b, Figure 6) as indicated by the decrease in cyanobacteria (*Rivularia*- type) and the presence of Type 411 driven by the development of sedges. The low record of spermatophores of Copepoda (Type 28) also suggests a reduction in the seasonal shallow ponds on the mire surface.

At 2800 cal yr BP a major mass wasting event is recorded at 270-185 cm depth, likely due to an extreme runoff event. The diatom content from the inorganic strata at 240 and 200-190 cm depth (Figure 9) suggests the existence of local streams or water transported from nearby diatom rich freshwaters during frequent small debris flows or floods. That water transported diatoms should be deposited over the mire during frequent small debris flows or floods. This indicates an increase of mass wasting processes along the slopes or even, a runoff increase. In any case, changes in effective moisture, particularly in the high slopes and summits, should be considered as the cause of the slope processes activity.

After 2400 cal yr BP, high *Nothofagus* concentrations occur with a maximum between *ca.* 1300 and 1000 cal yr BP (Subzone LC-2a). These data suggest a closed-canopy forest under environmental conditions comparable to those of the previous subzone (LC-1b). The increase in percentages of *Acaena* and the decline in the abundance of Cyperaceae along with peaks of *Gunnera* and *Empetrum*/Ericaceae indicate disturbed open ground with wetland and scattered shrub heath communities on the landscape.

During this subzone (LC-2a), the non-pollen palynomorphs (Figure 6) indicate high variability in the water-table level at the mire. The fluctuations from low to high water-table level led to changes in the nutrient status, which in turn drove transitions among eu/meso/oligotrophic conditions.

After *ca.* 1000 cal yr BP, *Nothofagus* pollen declines (Subzone LC-2b, Figure 5) and later, rises to a maximum value at *ca.* 700 cal yr BP, at the end of this subzone. Between *ca.* 680 and 300 cal yr BP (Zone LC-3, Figure 5), low values of arboreal taxa and high values of herbaceous and cushion heath taxa indicate a more open *Nothofagus* forest at the site, suggesting a lowering of the treeline under cooler conditions than today. The identified diatom assemblages at 120 and 100 cm depth (Figure 9) suggest disturbed aquatic environments under cold conditions. Thus, the abrupt decline of *Nothofagus* forest led to a greater exposure of the slopes, which may have enhanced debris flows or mass wasting processes.

Decreased percentages of Cyperaceae following a short interval of abundance in Subzone LC-2b, occurred in conjunction with increased percentages of *Acaena*, Ranunculaceae, *Caltha*, Apiaceae, fern spores and peak values of *Gunnera* indicating damp environments for the mire surface with shallow pools or slow-moving streams

(Zone LC-3). *Drapetes muscosus*, a typical cushion-forming species, is recorded among the upland taxa.

A high groundwater table at the mire is also reflected by the cyanobacteria proliferation (*Rivularia*-type) under meso-oligotrophic conditions (Figure 6). The increase in water depth would have impeded Cyperaceae growth. Towards the uppermost part of the Zone LC-3, debris-flow deposition over the mire favored the development of shallow ponds with the algae *Spirogyra* sp. and the tardigrade *Macrobiotus ambiguus*, a species of cold freshwater environments, under mesotrophic conditions with moderately nutrients supply (Figure 6). The diatom content of the inorganic strata at 85-60 cm (Figure 9) could be related to wetlands with variable water levels.

After 300 cal yr BP (Zone LC-4), vegetation comprised grasses with cushion heaths of *Azorella* and communities of *Nassauvia* occupying rock debris or fell-fields. The development of a mire dominated by Cyperaceae suggests increased nutrient supply by surface runoff derived from slow-melting snow patches (Moore, 1983; Coronato et al., 2006). Meanwhile, the increase of *Nothofagus* pollen implies forest expansion and warm conditions for tree growth. Today, this vegetation unit resembles the Andean Tundra governed by exposure to wind, water availability and physical nature of the substrata (Pisano, 1977; Heusser, 2003) and seasonal snow cover.

The paleoecological conditions in the mire are not so humid as those in Zone LC-2 (Figure 6). Lower water-table levels and mesotrophic conditions are reflected by the decline of cyanobacteria (*Rivularia*-type) frequencies and the expansion of mire vegetation (Cyperaceae) along with the small quantities and poor preservation of diatom valves found at 30 cm in the core (Figure 9).

6.2. Regional implications

We summarize the Holocene climate from Southern Patagonia and Fuegian Archipelago as recorded in selected peat and lake cores (Figure 11). Las Cotorras mire developed an open *Nothofagus* forest under warm and dry conditions between *ca.* 8000-6500 cal yr BP. Similar conditions are mirrored in the pollen record from Paso Garibaldi valley site (54º 43' S; 67º 50' W, 500 m a.s.l., Markgraf, 1993), 14 km east of the mire (Figure 1), and from low elevation sites along the Beagle Channel at Ushuaia, Lapataia, Puerto Harberton, Bahía Moat and Caleta Róbalo sites (Figure 1) (Heusser, 1989a, 1995, 1998). These conditions are also recorded in the interior, forested valleys of the Fuegian Andes such as the Valle de Andorra and Valle Carbajal (Figure 1; Borromei, 1995; Borromei et al., 2007). The highest fire activity has been recorded in the present areas dominated by deciduous and mixed forests of Tierra del Fuego when the forest-steppe ecotone prevailed under more variable moisture conditions (Huber et al., 2004; Pendall et al., 2001).

Presently, precipitation over the Fuegian Archipelago comes from the Pacific Ocean carried by the Southern Hemisphere Westerly winds, although the Polar Front also promotes precipitation in the southern part of the archipelago. Thus, the drier climatic conditions recorded between *ca.* 8000 and 6500 cal yr BP would be related to reduced southwesterlies during the early Holocene warmth.

Warm and dry conditions lasted until *ca.* 6500 cal yr B.P and were followed by the onset of cold and wet environmental conditions in Las Cotorras mire leading to the establishment of closed-canopy forest of *Nothofagus*. At this time, fire frequency in southern Tierra del Fuego decreased dramatically, providing additional evidence for increased and less variable precipitation (Markgraf and Anderson, 1994; Pendall et al., 2001). The increase in arboreal pollen influx, with maxima between *ca.* 4000 and 2800

cal yr BP, indicates increased levels of effective moisture. Pollen records from the Beagle Channel area (Heusser, 1998; Pendall et al., 2001), interior valleys (Borromei et al., 2007), Paso Garibaldi high elevation site (Markgraf, 1993), Lago Fagnano record (Waldmann et al., 2008) and also from western Staaten Island (54.4º S; 64º W) (Ponce, 2009) all record wetter conditions during this time. Further north, in the forest-steppe ecotone zone of SW Argentinean Patagonia (50º S), the increase in *Nothofagus* pollen between *ca.* 5800 and 3200 cal yr BP indicates moist conditions (Mancini, 2009). In Chilean Patagonia (51º S), the development of a closed *Nothofagus* forest at 6800 cal yr BP, punctuated by step-wise increases at 5100 and 2400 cal yr BP, are indicative of prominent increases in precipitation, probably of westerly origin (Villa-Martínez and Moreno, 2007).

All these paleoclimate data indicate intensification or latitudinal shifts in the regional westerlies between 50-54º S during the mid-Holocene, affecting the Southern Patagonian and Fuegian Andean climate and favoring the *Nothofagus* forest expansion.

The onset of the Neoglacial advances in Southern Patagonia and Tierra del Fuego is well correlated with the increase in westerly precipitation as well as decreased temperature (Waldmann et al., 2008; Moy et al., 2008; Moreno et al., 2009). Data from South Patagonian glaciers showed Neoglacial maxima between ~5180-4700, ~4500-3900, ~3080-2200, ~1400-1050 cal yr B.P., and during the Little Ice Age (LIA, ~600-100 cal yr B.P.) (Moreno et al., 2009). When comparing the timing of these events with our pollen data, we note concordance for cool, wet climate conditions at *ca.* 3080-2200 cal yr B.P. Total pollen influx peaks at about 2800, 1100 and 700 cal yr BP (Figure 5) are followed by mass wasting events. This might indicate more pollen input via surface runoff related to precipitation and slope processes. Major changes in our pollen stratigraphy, concurrent with the LIA event, occur between 680-300 cal yr BP including

a drop of *Nothofagus* pollen coupled with mass-wasting processes (Figures 4 and 5).

Because the distribution of *Nothofagus* forest at higher elevations is highly dependent

upon the temperature and precipitation regime (Massaccesi et al., 2008), these

fluctuations probably represent lower temperatures and increase in effective moisture.

At the eastern end of the Beagle Channel, the pollen record from Bahía Moat site

indicates that precipitation increased at *ca.* 2800 cal yr BP and followed by an

accentuation at *ca.*700 cal yr BP that led to peak abundance of Magellanic Moorland

taxa between *ca.* 700-140 cal yr BP (Heusser, 1995: in Moreno et al., 2009). In the Lago

Fagnano sediment core (~54° S) (Waldmann et al., 2008), the LIA is represented by

high iron content intervals at 50 cm depth and linked to the intensification of the

Southern Westerlies and humidity increase. This climate pattern has been further

recognised at inland areas at Valle de Andorra site (Figure 1) by multy-proxy analyses

in peat-bogs (Mauquoy et al., 2004). Although these climatic signals are present in the

lowlands, the LIA chronology has not yet been established in the cirques of the

surrounding mountains due to the lack of datable material. Pollen data from western

Staaten Island indicate a drop of *Nothofagus* pollen after *ca.* 700 cal yr BP related to

colder and windy conditions (Ponce, 2009). Paleoclimate data from Chilean Patagonia

(51° S) showed a correspondence of the LIA event with increased precipitation of

westerly origin interval at 570-60 cal yr BP (Moreno et al., 2009). Regional evidence

for climatic deterioration is suggested by Bahía Pía glacier system advances in the

Cordillera Darwin, western Tierra del Fuego, reaching one of its maximum positions

prior to *ca.* 800 cal yr BP and between *ca.* 800 and 600 cal yr BP (Kuylenstierna et al.,

1996). Compared with our data, these cooling periods could be related to the Last

Neoglacial advance occurring before the LIA, as they were documented in Southern

Patagonia (Rabassa, 2008; Mancini, 2009). Westward in Tierra del Fuego, in the Ema

Glacier Valley, a glacial advance has been reported at 330 ^{14}C yr BP (or 1670 AD, after Strelin et al., 2001). These data correlate well with Las Cotorras mire and suggests a cooling at *ca.* AD 1600 along the Fuegian Andes at *ca.* 55º S and between 68º - 71º W.

7. Conclusions

The following conclusions can be drawn from our analysis of Las Cotorras mire:

1) The location of Las Cotorras mire, close to the present tree-line zone, is especially sensitive to rapid environmental change during the Holocene.

2) The tephra layer indicates that a regional eruption in the Southern Patagonian Volcanos occurred before 7821 cal yr BP. Based on the geochemical signal and radiocarbon dates on supra and infra peat layers, it could be assumed that the tephra was produced by an eruption of the Hudson volcano, located in the Southern Volcanic Zone.

3) Episodic mass wasting is an important type of disturbance in mire ecosystems of the region. Reasons for an increase in episodic mass wasting events are unclear but could arise from heavy rainfall events either involving very high intensities or depths accumulations of rainfall over a very short time scale.

4) The major mass wasting event was preceded by maxima in the total pollen influx possibly related to enhanced precipitation or delivery of pollen to the mire by flood water.

5) Paleoecological conditions in the mire after 8000 cal yr BP indicate rapid succession from limnic to telmatic stage while the mire became to be colonized by sedges (Cyperaceae) and herbaceous vegetal communities, meanwhile the *Nothofagus* forest expansion in association with alpine vegetation evolved according to the regional pattern of increased moisture environments after 6500 cal yr BP.

6) Major vegetation change associated with cool, wet conditions occurred after 1000 cal yr BP and was most pronounced between 680 and 300 cal yr BP. The timing of these late Holocene events broadly coincides with the onset and maxima of the Little Ice Age.

7) The concordance between Las Cotorras data and the regional paleoenvironmental records indicates the following broad-scale changes in Holocene climate for southernmost Patagonia: a dry and warm early Holocene followed by wet and cool condition that commenced during the mid Holocene and culminated during the Little Ice Age.

8) The paleoclimate data from the Las Cotorras mire provide additional information related to the influence of the Southern Westerlies between 50-54º S along the Holocene and recent centuries.

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References of Figures

Figure 1. Location map.

Figure 2. Geomorphological map.

Figure 3. Age-depth curve from Las Cotorras mire showing radiocarbon (circles) and calendar (squares) dates and second-order polynomial regression against sediment depth.

Figure 4. Fossil pollen/spore frequency diagram (%) and stratigraphy at Las Cotorras mire.

Figure 5. Fossil pollen accumulation rate (grains/gr/yr) diagram and stratigraphy at Las Cotorras mire.

Figure 6. Fossil non-pollen palynomorphs (NPPs) frequency (%) diagram and stratigraphy at Las Cotorras mire.

Figure 7. Major non-pollen palynomorphs (NPPs) identified at Las Cotorras mire. A: *Chaetomium* sp (Type 7A); B: spermatophores of Copepoda (Type 28); C: Acari-Oribatei (Type 36); D: *Ustulina deusta* (Type 4); E: *Sordaria* sp. (Type 55A); F: *Alona rustica* (Type 72A); G: mandibles of chironomids (Type 88); H: *Sporormiella* sp. (Type 113); I: *Rivularia*-type (Type 170). Scale bar is 10 µm except in photos A and I where the scale bar is 2 µm.

Figure 8. Major non-pollen palynomorphs (NPPs) identified at Las Cotorras mire. A: *Zygnema* sp. (Type 314); B: *Spirogyra* sp. (Type 315); C: *Arcella* sp. (Type 352); D: Neorhabdocoela (Type 353); E: Neorhabdocoela (Type 353a); F: *Macrobiotus ambiguus* type. Scale bar is 20 µm except in photo A where the scale bar is 5 µm.

Figure 9. Relative abundance (%) of diatom species from Las Cotorras mire.

Figure 10. The most abundant diatoms. 1-4: *Psammothidium incognitum*. 1. raphe valve (LM); 2. rapheless valve (LM); 3. raphe valve, external view (SEM); 4. rapheless valve, internal view (SEM); 5. *Psammothidium abundans*; rapheless valve,

internal view (SEM); 6-7. *Planothidium lanceolatum* (LM). 6. raphe valve; 7. rapheless valve; 8. *Fragilaria capucina* var. *vaucheria* (LM); 9. *Staurosirella pinnata*; 10-11. *Distrionella germainii* fa. *Acostata*; 10. LM; 11. SEM; 12. *Brachysira minor* (SEM).

LM: light microscope; SEM: scanning electron microscope. Scale bars: 10 µm (photos 1, 2, 6-10); 5 µm (photos 3-5, 11, 12).

Figure 11. Comparative Holocene climate changes from selected peat and lake records from Southern Patagonia and Fuegian Archipelago. Black lines show the onset of Southern Westerlies and the localities where the LIA event has been reported. References : 1, Mancini (2009) ; 2, Villa-Martínez and Moreno (2007); Moreno et al. (2009); 3, Markgraf (1993) ; 4, Borromei (1995) ; Mauquoy et al. (2004) ; 5, Borromei et al. (2007) ; 6, Waldmann et al. (2008) ; 7, 8, 9, Heusser (2003) ; 10, Pendall et al. (2001) ; 11, Heusser (1995) ; 12, Ponce (2009).

Table 1. Chemical composition of the basal tephra from Las Cotorras mire.

Table 2. AMS ^{14}C dates and calibrated ages of selected samples from Las Cotorras mire.

Shard	Na2O	MgO	Al2O3	SiO2	K2O	CaO	TiO2	MnO	FeO	Total
1	3.46	1.62	15.55	65.44	2.85	3.38	1.64	0.31	5.6	99.85
2	3.73	1.54	17.51	65.50	2.43	3.06	1.17	0.17	4.65	99.76
3	4.27	1.31	17.32	66.00	2.75	2.99	1.13	0.12	4.06	99.95
4	4.92	1.50	17.62	65.47	2.17	2.91	1.20	0.14	3.53	99.46
5	3.44	1.27	16.59	66.27	2.79	2.68	1.51	0.29	4.73	99.57
6	3.99	1.42	17.96	65.95	1.88	2.66	1.01	0.05	4.04	98.96
7	3.05	1.19	16.11	67.01	2.94	2.59	1.30	0.14	4.61	98.94
8	3.74	1.41	16.64	66.74	2.74	2.60	1.32	0.16	4.40	99.75
9	3.39	1.45	16.14	66.10	2.76	3.07	1.40	0.26	5.38	99.95
10	3.49	1.29	15.84	66.12	2.99	2.82	1.31	0.19	4.92	98.97
11	3.81	1.59	16.39	65.83	2.73	3.10	1.37	0.17	4.93	99.92
12	3.86	1.45	16.82	66.28	2.68	2.60	1.03	0.08	4.16	98.96
13	3.86	2.53	17.09	62.28	2.39	4.20	1.22	0.22	5.37	99.16
14	3.71	1.49	16.55	65.24	2.82	3.48	1.24	0.16	5.27	99.96
15	3.88	1.49	16.7	65.38	2.77	2.96	1.38	0.14	4.47	99.17
16	3.49	1.45	16.39	66.47	2.92	2.95	1.26	0.08	4.94	99.95
17	4.04	1.32	16.28	65.59	2.86	3.07	1.29	0.13	4.97	99.55
18	3.91	1.31	16.41	65.52	2.85	3.28	1.28	0.13	5.26	99.95
19	3.52	1.39	16.34	65.37	2.86	3.13	1.35	0.06	5.01	99.03
20	3.77	1.88	16.08	64.57	2.69	4.04	1.27	0.13	5.52	99.95
21	4.10	1.52	16.57	65.11	2.76	2.82	1.23	0.20	4.44	98.75
Mean	**3.78**	**1.49**	**16.61**	**65.63**	**2.69**	**3.06**	**1.28**	**0.15**	**4.77**	**99.50**

Table 1.

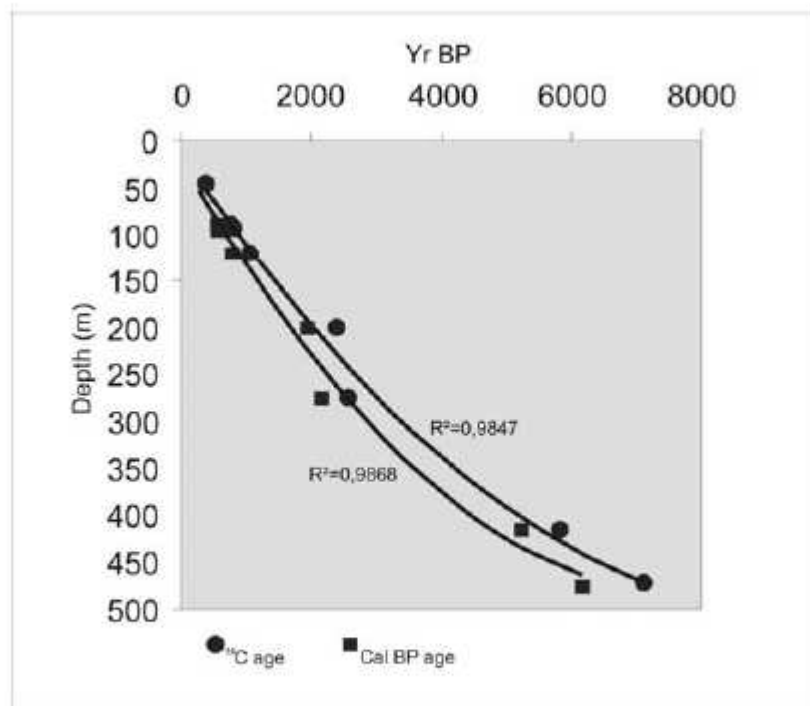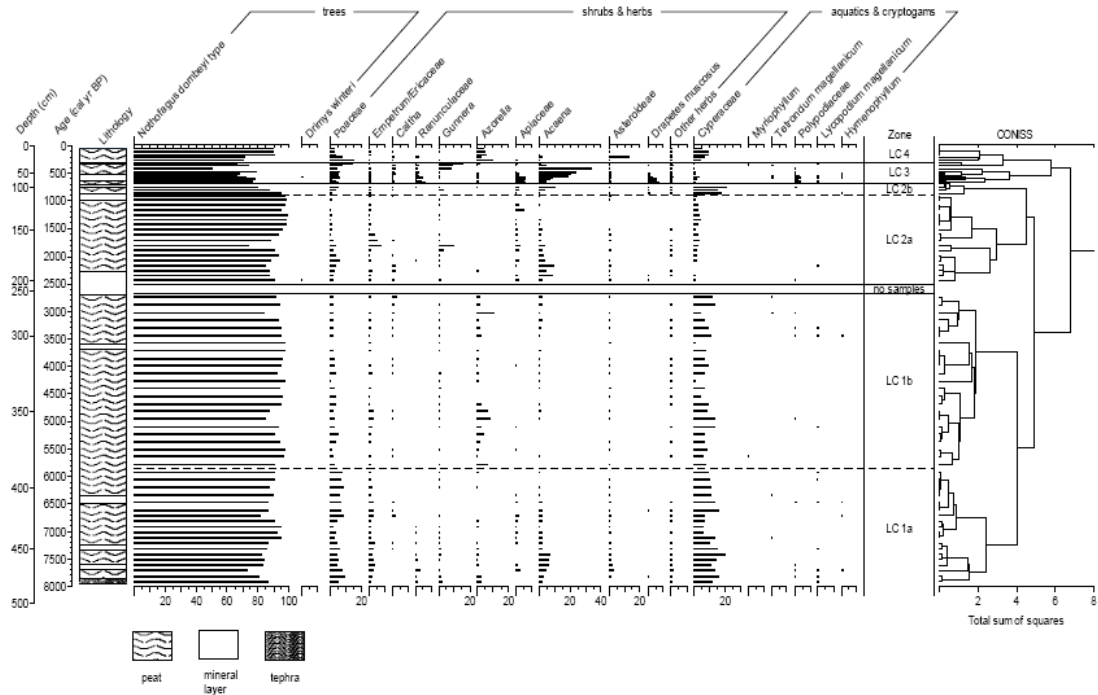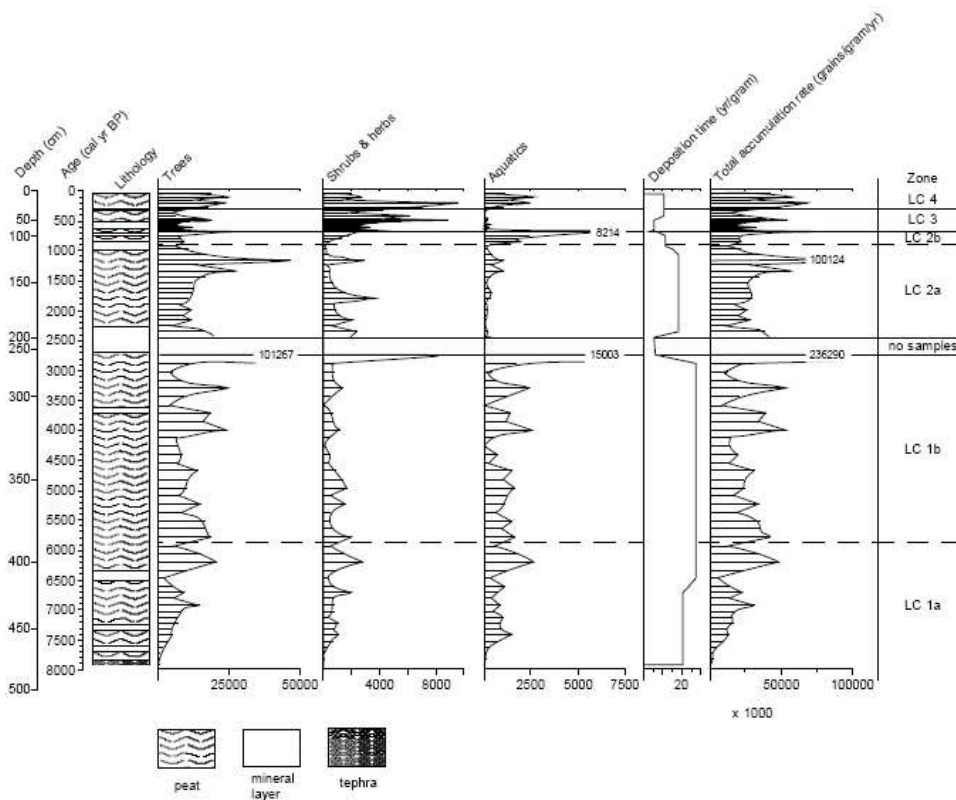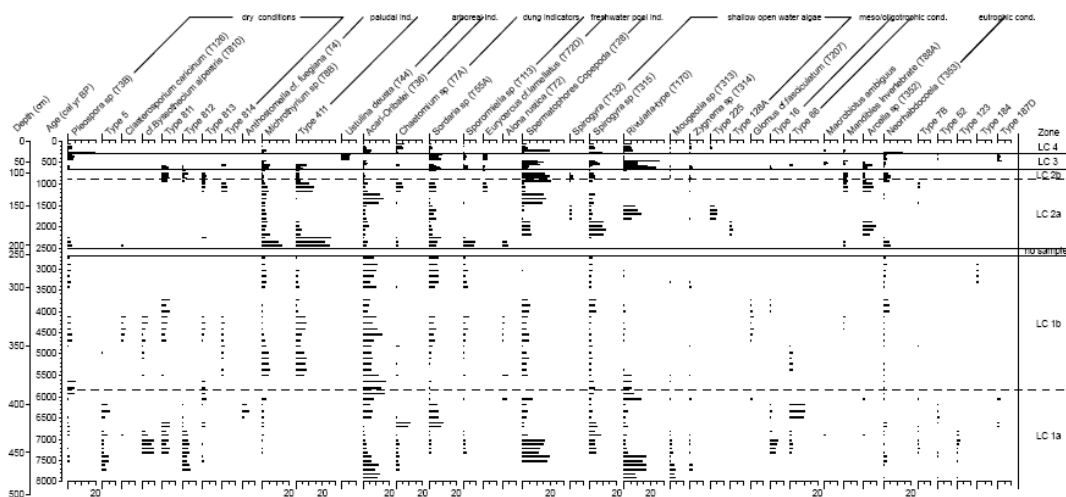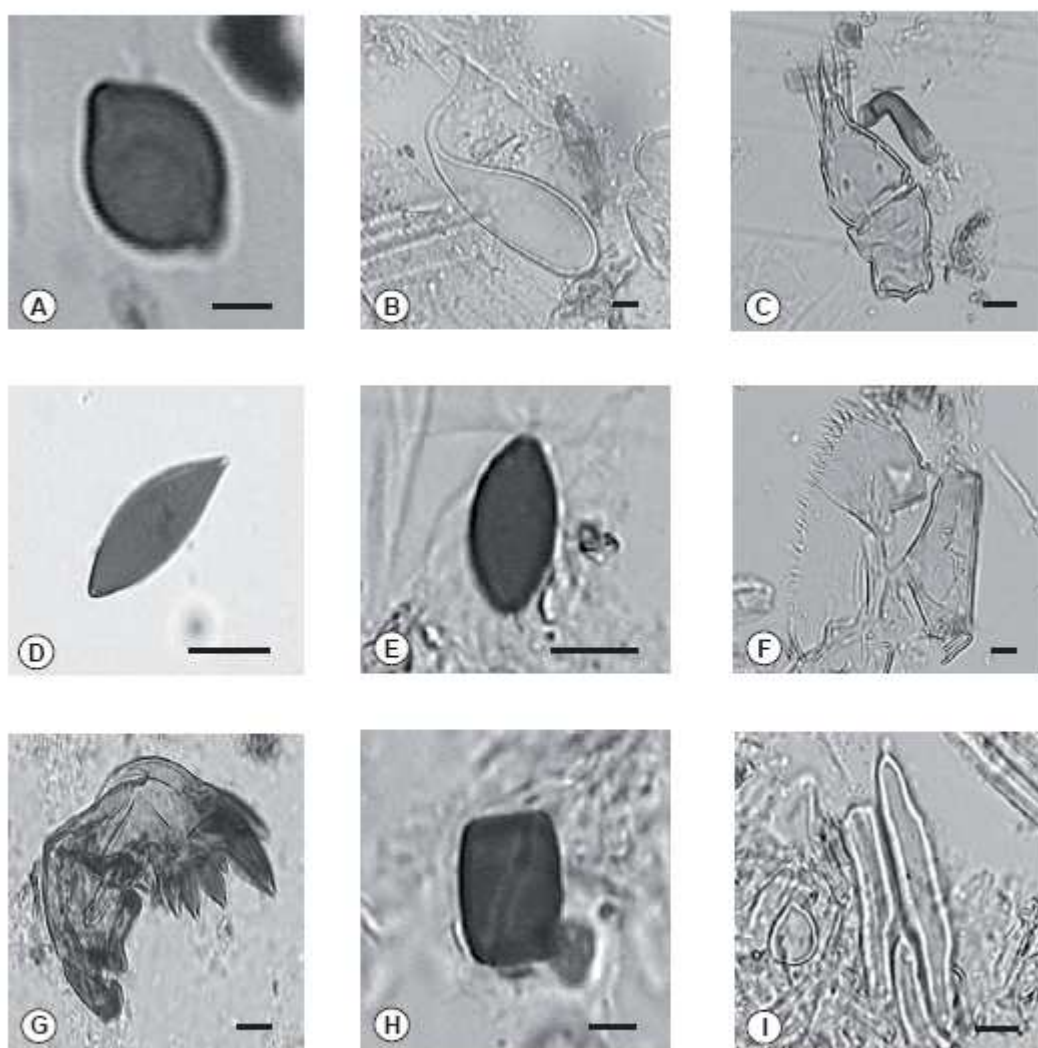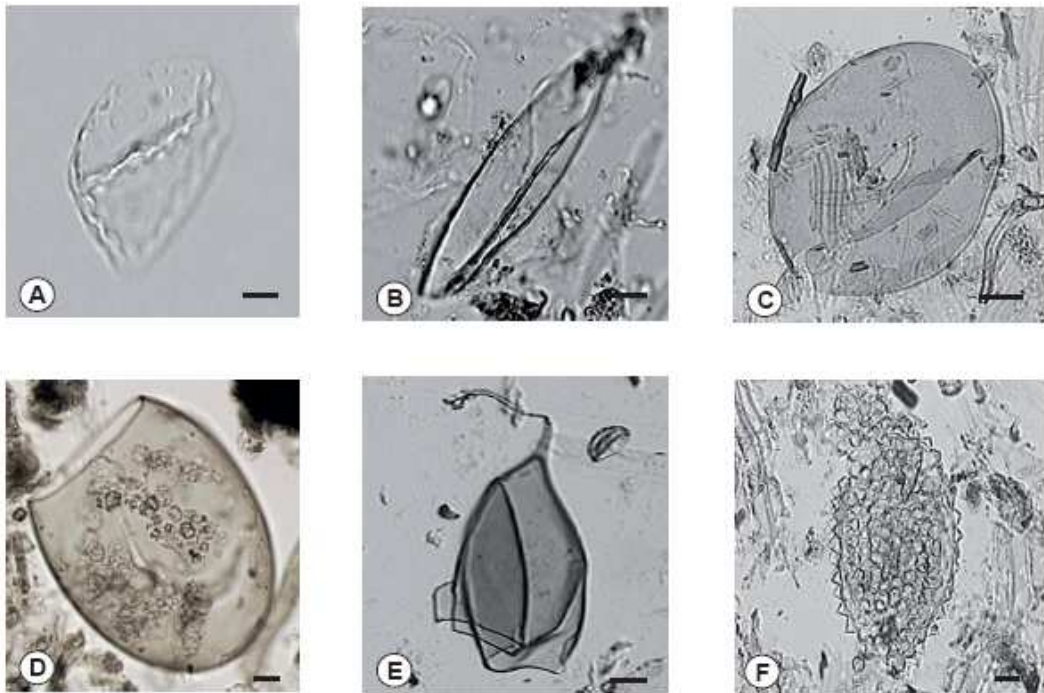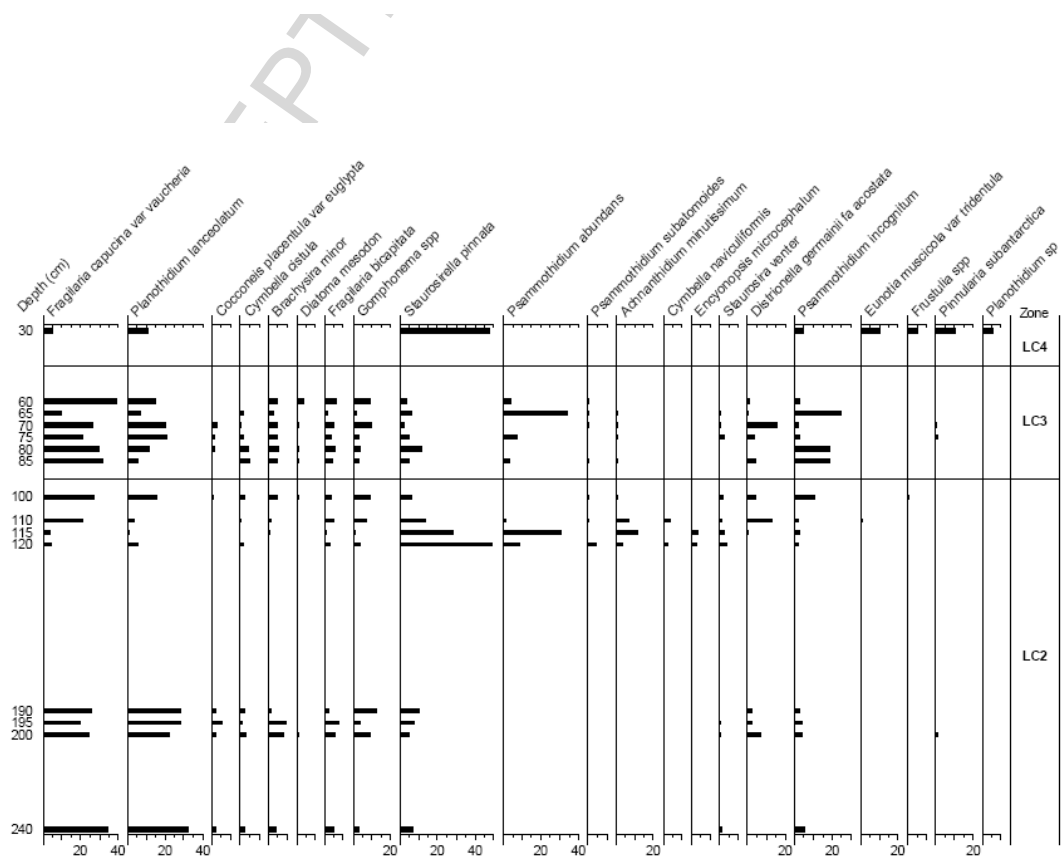| Depth (cm)	Laboratory No	^{14}C yr BP	Calibrated yrs BP (median probability)	1σ range	2σ range	Material
40 - 45	AA62817	412 ± 35	440	444-495	428-501	peat
85 - 90	AA70440	762 ± 39	665	646-685	632-726	peat
90 - 95	AA70441	781 ± 39	679	657-689	639-733	peat
115 - 120	AA78877	1065±37	931	908-964	899-980	organic matter
195 - 200	AA78878	2406±52	2399	2320-2471	2301-2520	organic matter
270 - 275	AA78879	2562±39	2584	2493-2600	2455-2742	peat
410 - 415	AA78880	5804±51	6548	6489-6574	6412-6664	peat
470 - 475	AA62823	7043 ± 47	7821	7758-7867	7700-7933	basal peat

Table 2
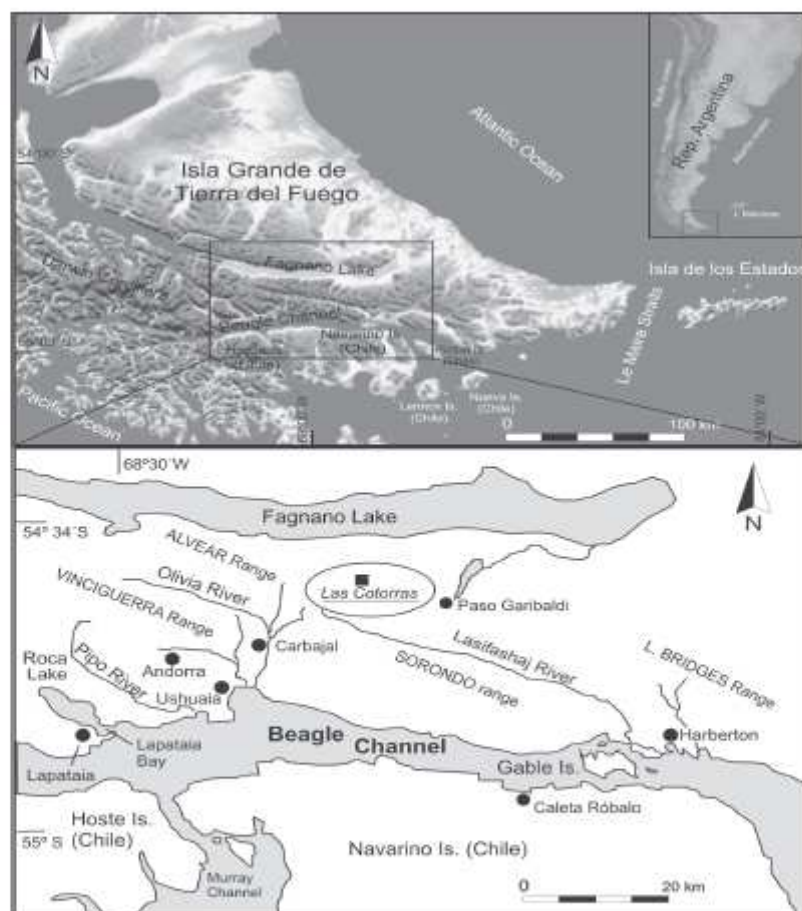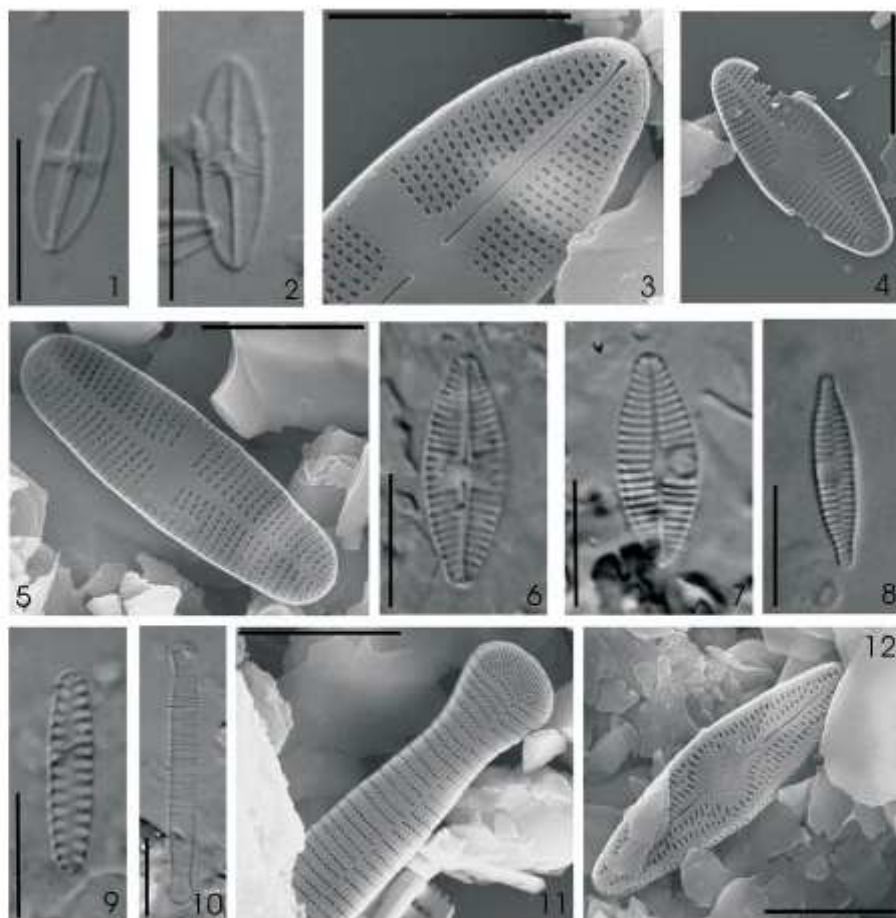
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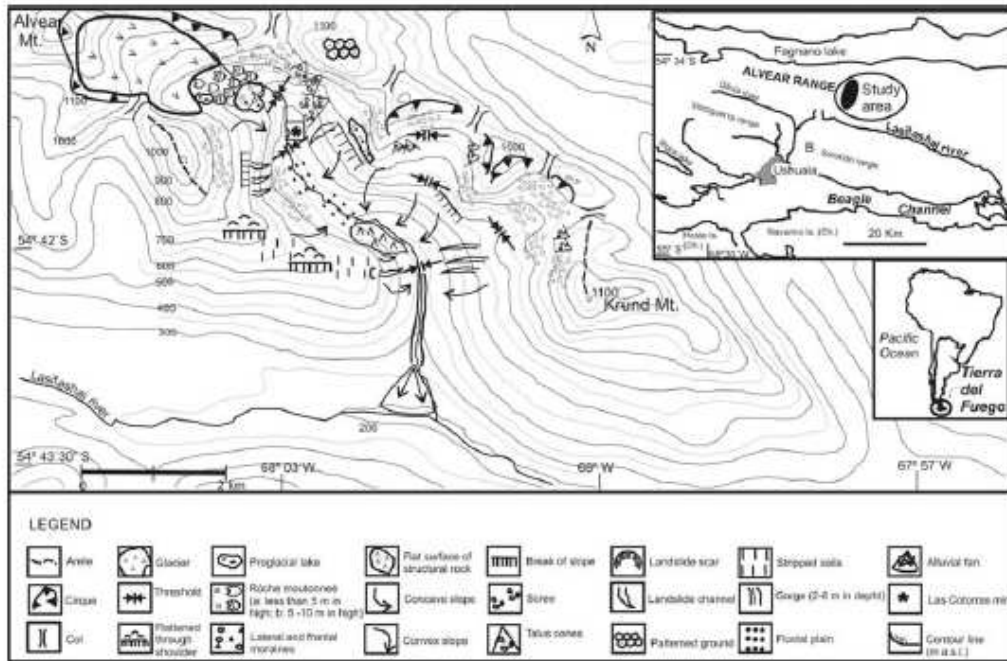
Figure 2

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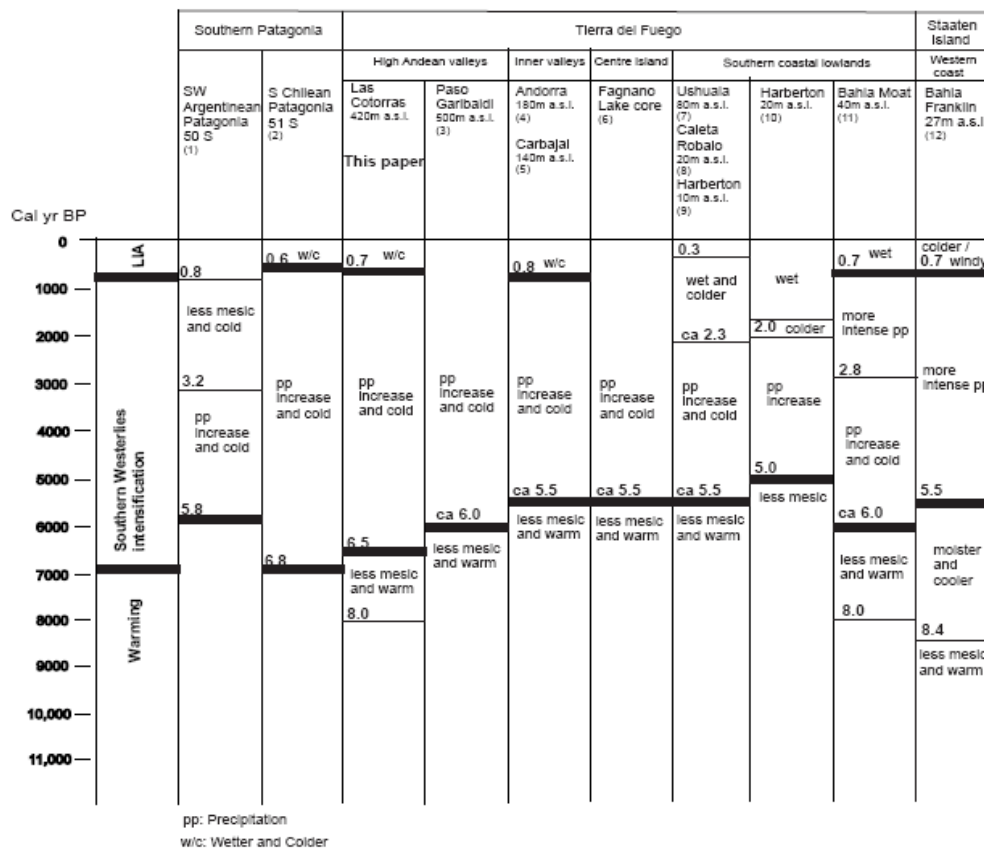
	Southern Patagonia		Tierra del Fuego							Staaten Island
			High Andean valleys		Inner valleys	Centre Island	Southern coastal lowlands			Western coast
Cal yr BP	SW Argentinean Patagonia 50 S (1)	S Chilean Patagonia 51 S (2)	Las Cotorras 420m a.s.l. (3) This paper	Paso Garibaldi 500m a.s.l. (3)	Andorra 180m a.s.l. (4) Carbajal 140m a.s.l. (5)	Fagnano Lake core (6)	Ushuaia 80m a.s.l. (7) Caleta Robalo 20m a.s.l. (8) Harberton 10m a.s.l. (9)	Harberton 20m a.s.l. (10)	Bahia Moat 40m a.s.l. (11)	Bahia Franklin 27m a.s.l. (12)

Left vertical labels: LIA — Southern Westerlies intensification — Warming

Column content:

SW Argentinean Patagonia 50 S (1): 0.8 — less mesic and cold — 3.2 — pp increase and cold — 5.8

S Chilean Patagonia 51 S (2): 0.6 w/c — pp increase and cold — 6.8

Las Cotorras 420m a.s.l. (3) This paper: 0.7 w/c — pp increase and cold — 6.5 — less mesic and warm — 8.0

Paso Garibaldi 500m a.s.l. (3): pp increase and cold — ca 6.0 — less mesic and warm

Andorra / Carbajal: 0.8 w/c — pp increase and cold — ca 5.5 — less mesic and warm

Fagnano Lake core (6): pp increase and cold — ca 5.5 — less mesic and warm

Ushuaia / Caleta Robalo / Harberton: 0.3 — wet and colder — ca 2.3 — pp increase and cold — ca 5.5 — less mesic and warm

Harberton 20m a.s.l. (10): wet — 2.0 colder — pp increase — 5.0 — less mesic

Bahia Moat 40m a.s.l. (11): 0.7 wet — more intense pp — 2.8 — pp increase and cold — ca 6.0 — less mesic and warm — 8.0

Bahia Franklin 27m a.s.l. (12): colder / 0.7 windy — more intense pp — 5.5 — moister and cooler — 8.4 — less mesic and warm

pp: Precipitation
w/c: Wetter and Colder

Figure 11