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Late Quaternary climatic inferences from southern Patagonia (~53°S): A holistic palaeoecological approach to tracking the behaviour of the southern westerly winds.

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Abstract

The glacial and vegetation patterns of Patagonia are strongly correlated to the behaviour of the Southern westerly winds (SWWs) with palaeoenvironmental evidence for the behaviour of the SWWs interpreted as past changes in southern hemisphere climate and ocean currents. To fully define shifts in the position and intensity of the SWWs palaeoenvironmental data sets must be generated from climate sensitive proxies with sites located in regions that are responsive to changes in effective moisture. Here we present a c. 15,700 yr-old record from a peat bog at Punta Arenas (53°09'S) which was analysed for pollen, pollen preservation, charcoal and organic content to reconstruct changes in the surrounding vegetation, fire history and mire surface wetness. The peat bog lies in a closed basin and so environmental changes likely reflect changes in effective moisture primarily driven by fluctuations in precipitation. During the Late glacial the landscape was virtually treeless and dominated by cold-tolerant steppe/tundra vegetation. This was followed by substantial vegetation changes as *Nothofagus* woodland expanded and the local site transitioned from a small lake to a fen and later a raised mire. The Early and Mid-Holocene (11,600-6000 cal a BP) was marked by a period of sustained drier conditions evidenced by reduced pollen preservation and increased fire activity. After c. 4600 cal a BP there was a shift to increased effective moisture superimposed with higher magnitude and higher frequency changes in precipitation. The palaeoenvironmental record presented here is used to better define the nature and timing of latitudinal shifts in the position of the SWWs. Careful interpretation of the *Nothofagus* pollen signal is required as during drier periods small increases in humidity can drive large woodland responses in the pollen record while during periods of higher humidity the woodland may appear to be unresponsive to climatic changes.

Keywords:

Pollen analysis, pollen preservation, peat bogs, *Nothofagus*, forest-steppe ecotone.

1 Introduction

Palaeoenvironmental reconstructions from southern South America (Patagonia) are of global importance to our understanding of past changes in southern hemisphere climate and ocean currents (Kilian and Lamy, 2012). The principal component of the Southern Ocean climate is the southern westerly winds (SWWs) (Garreaud et al., 2013) which drive the Antarctic Circumpolar Current and have a key role in the ventilation of CO_2 (Toggweiler et al., 2006). The SWWs are presently focused at ~50-55°S and seasonally migrate (Lamy et al, 2010). During the austral summer they shift polewards, are stronger, and are more zonally (latitudinally) restricted, and during the austral winter they move equatorwards, are distributed wider latitudinally and are weaker (Garreaud et al., 2013). The range and focus of the SWWs was likely shifted equatorward during glacial periods; probably >5° of latitude equatorward during the last glacial maximum (Lamy et al., 2015).

The glacial and vegetation patterns of Patagonia are strongly correlated to the behaviour of the SWWs that intersect the southern Andean cordillera leading to orographic rainfall and a hyperhumid environment along the western flanks of the Andes. On the lee side of the Andes there is a very rapid reduction in precipitation with distance from the crest of the Andes towards the Atlantic coast (see Kilian and Lamy, 2012) (Fig. 1b-c). This extreme precipitation gradient is reflected in the complex biogeographical patterns of Patagonia, with the dominance of hygrophilous plant and

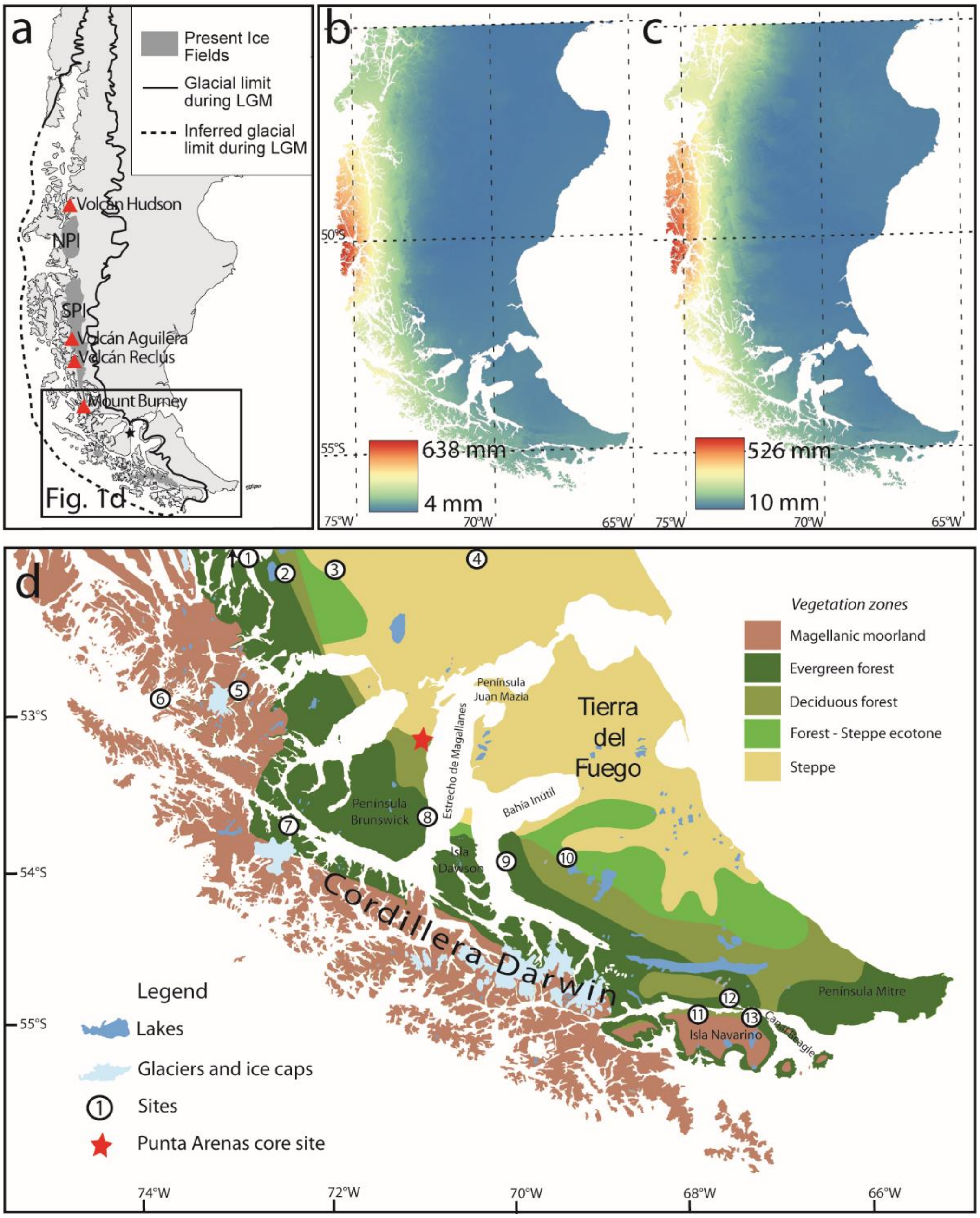

Fig. 1. 1a approximate extent of the Last Glacial Maximum Patagonian ice sheet and location of volcanoes (red triangles) mentioned in the text; 1b January and 1c July precipitation. Data from WorldClim v. 2.1 30 s. data for 1970-2000 (Fick and Hijmans, 2017) and plotted using QGIS; 1d Fuego-Patagonia. The principal vegetation zones are from Tuhkanen et al. (1989–1990) modified with vegetation mapping by Pisano (1994). Palaeo records mentioned in the text are: ① Lago Cipreses (51°S); ② Lago Pintito; ③ Río Rubens; ④ Lago Potrok Aike; ⑤ GC2, Gran Campo Nevado; ⑥ Palm2; ⑦ Lago Ballena; ⑧ Puerto del Hambre; ⑨ Punta Yartou; ⑩ Lago Lynch; ⑪ Punta Burslem; ⑫ Puerto Harberton; ⑬ Caleta Eugenia.

forest communities to the west and more xeric open steppe taxa to the east (Pisano, 1977; Moore, 1983; Tuhkanen, 1989-1990) (Fig. 1d). The forest-steppe ecotone between these two extremes is dominated by the interactions between microclimate, fire, and woodland resilience (Iglesias et al. 2014, 2018; Nanavati et al. 2019). The ecotone lies at the range edge of temperate woodland and the tree cover is highly fragmented and likely susceptible to recruitment and dispersal stresses (Davies, et al., 2017). Therefore, the forest-steppe ecotone is particularly sensitive to relatively small-scale changes in the latitudinal position and intensity of the SWWs (Mansilla et al., 2018). By reconstructing past vegetation patterns, we can better understand the evolution of the Patagonian landscape and infer the climatic drivers of vegetation change.

Holocene pollen records from Patagonia have the advantage that they represent the natural landscape unaltered by agriculture until European colonisation in the late 19th and early 20th centuries (Flantua et al., 2016). Fire, as evidenced through charcoal particles in the sedimentary records, is the only tentative signal of human agency in palaeoecological records (Holz et al., 2016). However, there appears to be a stronger relationship between fire frequency and drier climate, in particular, changes driven by greater seasonality (Markgraf and Huber, 2010, Whitlock et al., 2007; Holz et al., 2017; Nanavati et al., 2019).

Finding suitable sites for reconstructing Quaternary environments in Fuego-Patagonia is a challenge. Although peat bogs and lakes are prevalent in the wetter west, they tend to be hydrologically complacent in the climate signal recorded and difficult to access (Lumley and Switsur, 1993). Vegetation reconstructions from palynological records obtained from sediments within the belt of temperate forest also tend to be dominated by *Nothofagus dombeyi* type pollen which may attenuate any climatic signal. Sites to the east of the Andes also tend to be temporally shortened by desiccation caused by the negative moisture balance due to the enhanced SWWs in the lee of the Andean Cordillera; the crater lake record from Potrok Aike (51°58'S, 70°22'W) (Zolitschka et al., 2013) being a notable exception. There is a 'sweet spot' along the forest-steppe ecotone that provides access to peat bogs and lake records within a sensitive ecosystem. However, the geographical complexity of the region, including the latitudinal asymmetry in the distribution of the SWWs, the very steep east-west precipitation gradient, high relative relief, and successional patterns of ecosystem development around ice sheets and glaciers, makes it difficult to characterise the Fuego-Patagonia landscape, even over relatively short distances, from the few extant pollen records.

Pioneering work in the field of palynological reconstructions of vegetation and palaeoclimate from Fuego-Patagonia was conducted by Auer (1958) and later by Heusser (1989, 1995, 1998), Ashworth et al. (1991) and Markgraf (1993). In the early 1980s Calvin Heusser sampled three peat bogs from southern Patagonia: Torres del Paine, Punta Arenas and Puerto del Hambre (Porter et al., 1984; Heusser, 1995). The climate history of the area around Parque Nacional Torres del Paine has since been studied in more detail by Moreno et al. (2012, 2021) and Villa-Martínez et al. (2007). Puerto del Hambre has been investigated further by Heusser (1999) and McCulloch and Davies (2001). Heusser's (1995) pollen record from Punta Arenas is of particular interest because it indicates a high proportion of *Nothofagus dombeyi* type pollen (>50% of TLP) during the Late glacial period. This suggests the local presence of open *Nothofagus* forest in refugia around the northern area of the Peninsula Brunswick and Punta Arenas, which has not been identified by previous studies in the region (McCulloch and Davies, 2001; Markgraf and Huber, 2010). Here we present a new palaeoenvironmental record from the Punta Arenas mire providing valuable insights into the vegetation dynamics and climate drivers during the Late glacial and Holocene.

2 Materials and methods

2.1 Study area: Punta Arenas

The core site (53°09'16.79"S 70°57'06.43"W Alt: 80m asl.) is a mire within a former glacial meltwater channel flowing parallel to the shore of the Estrecho de Magallanes. The channel runs alongside the moraine limit associated with Glacial Stage D (> c. 17 ka) (Bentley et al., 2005; Fig. 2). The channel has been subsequently intersected by the Río de los Ciervos to the south and by the Río de las Minas to the north, both flowing perpendicular to the shore. The small catchment suggests that the Punta Arenas mire will be sensitive to changes in precipitation.

The city of Punta Arenas (at the airport) has the longest continuous meteorological record in the region (since 1950) which indicates a mean annual temperature of 6.5°C and an annual precipitation of ~400mm a-1 (Stolpe and Undurraga, 2016). This has been estimated to be ~8% of the annual precipitation falling over the Andean mountains to the west (Schneider et al., 2003). Pervasive winds at Punta Arenas are predominantly westerly with winds ranging from the north-east to south-east being rare. Although similar precipitation amounts can be recorded at Punta Arenas from westerly and easterly air flows. However, stronger westerly air flows are typically associated with föhn (foehn) winds leading to increased drying and adiabatic warming on the lee side of the Andes (Schneider et al., 2003).

The mire is dominated by *Empetrum rubrum* and with scattered small scrub of *Nothofagus betuloides* on the drier surfaces. The drier slopes of the meltwater channel and the surrounding area was covered by *Chiliotrichum-Berberis* scrub, adjacent to mixed forest of deciduous *Nothofagus pumilio* and evergreen *Nothofagus betuloides* on the eastern slopes of Cerro Mirador above the city of Punta Arenas. However, the area surrounding the mire has been extensively cleared for urban

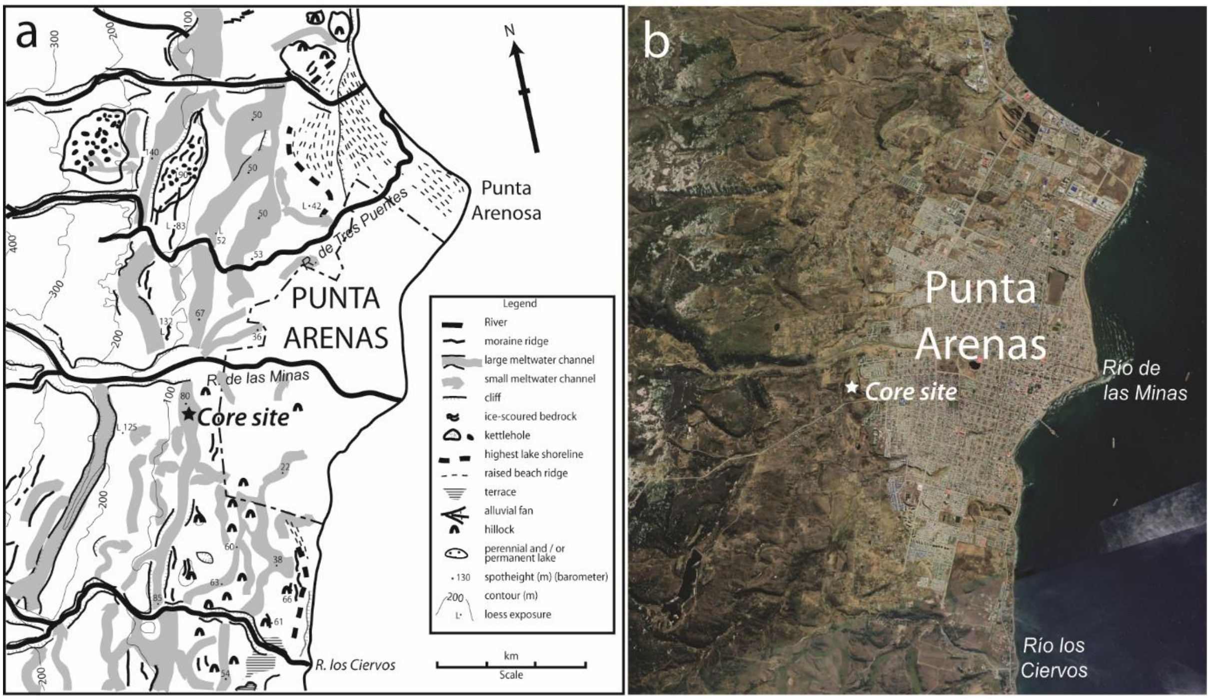

Fig. 2. 2a Extract of glacial geomorphological map indicating lateral flowing meltwater channels associated with Glacial Stage D (from Bentley et al., 2005) and the subsequent perpendicular incision to the coast of the Río de las Minas and the Río de los Ciervos; 2b Google Earth image of the location of the mire site on the margins of the city of Punta Arenas.

expansion. The mire had been cut in two by the construction of Calle Independencia and the southern section had been extensively commercially harvested. It was noted in 1982-1983 that the surface of the mire was 'dessicated' (Heusser, 1995) and this was also the case when the mire was sampled for this study in 1998.

2.2 Sediment coring and laboratory methods

Porter et al. (1984) state a Hiller Borer was used to sample the mire at Puerto del Hambre and although not explicitly stated in Heusser (1995) we believe that a Hiller Borer was also used to sample the mire at Punta Arenas during the same field campaign. While use of a Hiller Borer enabled Heusser to core deep peat bogs, it has a critical drawback as the rotational movement of the borer, as it drives downwards, disturbs the stratigraphy and may carry sample material downwards, thus potentially contaminating underlying layers (Jowsey, 1966). Comparison of the Punta Arenas pollen record from Heusser (1995) and more recent records obtained from the Magellan region led to the speculation that at least the Late glacial section should be interpreted with caution (Kilian and Lamy, 2012).

For this study, a 50 cm long D-section Russian corer 5.5 cm in diameter (Jowsey, 1966) was used to obtain a 632 cm continuous core from the mire at Punta Arenas. The Russian corer is a side filling chambered-type sampler which preserves the depositional structures of sediments and minimises smearing of the sample with extraneous material. The cores were sealed in layflat tubing, returned to The University of Edinburgh, and stored at a constant 4 °C.

The percentage organic content was estimated by loss-on-ignition with 2 cm thick contiguous samples dried and then combusted at 550°C for 4 h (LOI_{550}). Sub-samples (1 cm^3) were taken from the core and prepared for pollen analysis using standard techniques (Moore et al., 1991). Basal mineral rich samples were treated with 40% Hydrofluoric acid. The identification of pollen grains and spores was supported by a pollen reference collection and supplemented by microphotographs (Heusser, 1971; Villagrán, 1980; Wingenroth and Heusser, 1984; Moore et al., 1991). A minimum sum of 300 land pollen (TLP) grains was identified from each sample, excluding Cyperaceae, aquatics, spores, and algae. The pollen percentage data was divided into local pollen assemblage zones (LPAZs) determined by stratigraphically constrained cluster analysis (CONISS) (Grimm, 1987). The percentage pollen results are presented using Tilia software version 3.0.1 (Grimm, 2011). Our interpretation of the arboreal content of the Punta Arenas record is informed by modern pollen rain sampling by Burry et al. (2006) to identify steppe (<13% *Nothofagus*); woodland (~18-40% *Nothofagus*); open canopy forest (~54-63% *Nothofagus*) and closed canopy forest (>70% *Nothofagus*). Here we use 'woodland' to describe the forest-steppe ecotone (also described as 'park forest' by Tuhkanen et al., 1989-1990).

Pollen concentrations were estimated by adding a known quantity of *Lycopodium clavatum* to each sample obtained from the University of Lund (Stockmarr, 1971). The pollen concentration values (grains cm^3) and estimated sediment accumulation ($cm\ a^{-1}$) were used to calculate the pollen and charcoal accumulation rates (influx: grains or particles $cm^2\ a^{-1}$). Charcoal particles between 10 and 180 µm were counted alongside the pollen and spores on the microscope slides as an indicator of past fire activity (Whitlock and Larsen, 2001).

The physical condition of the pollen grains was also assessed as a further indicator of the environmental conditions in which it was deposited (Cushing, 1967; Berglund and Ralska-Jasiewiczowa, 1986; Tipping, 1987). Pollen grains are well-preserved in acidic and anaerobic conditions such as lakes and waterlogged mires. Corroded and degraded pollen grains suggest degrees of chemical deterioration and microbial digestion which indicate a drier aerobic environment. Broken and crumpled pollen suggest mechanical damage, most probably due to abrasion during transportation. The state of preservation of land pollen was assigned to a single hierarchical category: normal, broken, crumpled, corroded, and degraded from lowest (normal) to highest (degraded) (McCulloch and Davies, 2001). This tends to emphasise the higher deterioration types (corroded / degraded) (Lowe, 1982), but can be applied quickly and consistently and does not contain subjective elements (Tweddle and Edwards, 2010).

Cryptotephra layers were identified during pollen identification and as mineral residue during the LOI_{550} assays. Visible and cryptotephra layers were concentrated by acid digestion of the organic content (Dugmore et al., 1992) and the mineral content of each sample was then assessed using light and polarising microscopy. Volcanic glass shards were identified based on morphology, vesicularity and isotropism under plane-polarised light. The major element geochemical composition of each tephra sample was determined by electron microprobe analysis using the SX100 Cameca Electron Microprobe at The University of Edinburgh (Hayward, 2012). A minimum of 10 glass shards were analysed to provide a representative geochemical signature (Hunt and Hill, 1993). Tephra identification was conducted through comparisons with geochemical data from previous studies (McCulloch and Bentley, 1998; McCulloch and Davies, 2001; Mansilla, et al., 2016, 2018; McCulloch et al., 2021) (Supplementary material).

3 Results and analysis

3.1 Stratigraphy

The Punta Arenas stratigraphy (Fig. 3) comprised grey coarse silts and sands (632-627 cm) probably deposited during the waning stages of flow through the meltwater channel. This was overlain by a lacustrine mud with increasing organic content (>40% LOI_{550}) between 626 and 531 cm. At 578-575 cm there was a discrete creamy-white silty tephra layer containing clear vesicular glass. Above 531 cm the organic content of the sediment fluctuates and declines, reaching a nadir of ~11% LOI_{550} between 459 and 435 cm before increasing again to >40% LOI_{550} between 435 and 360 cm. At 360 cm there was a marked increase in organic content transitioning to peat (>80% LOI_{550}). The peat continues to the surface interrupted by the deposition of a mineral layer at 338-332 cm and two visible tephra layers, a pale greenish-brown silty layer at 308-312 cm and a creamy-white silty layer at 223-226 cm. Two cryptotephra layers were also identified at 361-362 cm and 269-270 cm as peaks of mineral residue in the LOI_{550} samples. At the surface of the mire the sample material increased in mineral content, probably due to mineralisation of the peat and/or increased dust from the urban expansion of the city of Punta Arenas.

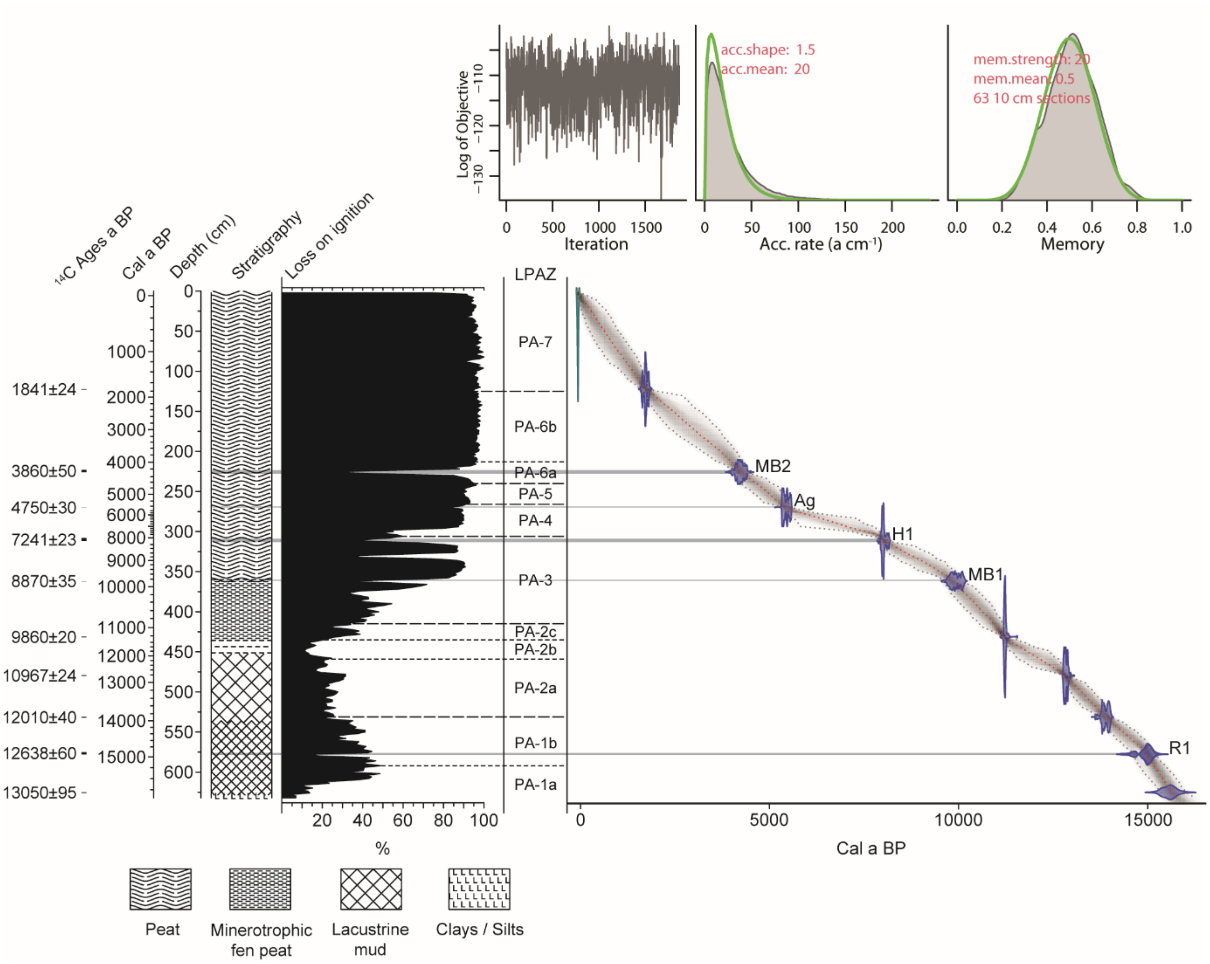

Fig. 3. The Punta Arenas profile: sediment stratigraphy, organic content determined by LOI_{550}, and the LPAZs determined from the percentage pollen diagram using CONISS (Fig. 4) alongside the BACON age-depth model (Blaauw and Christen, 2011). Details of the ^{14}C ages are given in Table 1.

3.2 Chronology

The chronology of the Punta Arenas mire record is constrained by 5 AMS radiocarbon dates from 1cm thick, ~2 cm^3 samples processed by Beta Analytic, the Scottish Universities Environmental Research Centre (SUERC) and the University of Arizona AMS laboratory and supplemented by the ages of the five tephra layers (Table 1). The tephra layers at 223-226 cm and 361-362 cm are geochemically correlated to Holocene eruptions of Mount Burney and dated to 3860 ± 50 ^{14}C a BP (MB2, McCulloch and Davies, 2001) and 8870 ± 35 ^{14}C a BP (MB1, Mansilla et al., 2016) respectively. The cryptotephra at 269-270 cm is geochemically correlated to an eruption of Volcán Aguilera dated to 4750 ± 30 ^{14}C a BP (McCulloch et al., 2021). The tephra layer at 308-312 cm is geochemically correlated to an eruption of Volcán Hudson, located ~ 800 km to the north of Punta Arenas, and dated to 7241 ± 23 ^{14}C a BP (H1) (Stern et al., 2016). The tephra layer at 575-578 cm is geochemically

Table 1. Conventional radiocarbon ages, calibrated age ranges and median ages for the Pta. Arenas record. The SHCal20 calibration curve was applied (Hogg et al. 2020) and using Bacon ver. 2.5.5 (Blaauw and Christen, 2011), as described in the main text.

Laboratory code	Depth (cm)	Material	^{14}C a (1σ)	δ^{13}C(‰)	Calibrated age range (95.4%) cal a BP*	Calibrated age range (wma) at 95% confidence (cal a BP)**
SUERC-82833	122-123	Bulk peat	1841 ± 24	-27.2	1615-1818	**1626-(1748)-1866**
MB2[1]	223-226	tephra	3860 ± 50	n/a	4015-4412	**4004-(4232)-4440**
Ag[2]	269-270	tephra	4750 ± 30	n/a	5322-5578	**5327-(5471)-5581**
H1[3]	308-312	tephra	7241 ± 23	n/a	7939-8164	**7876-(8003)-7876**
MB1[4]	361-362	tephra	8870 ± 35	n/a	9700-10,151	**9613-(9854)-10,124**
SUERC-82834	431-432	Bulk sed.	9860 ± 20	-27.4	11,209-11,256	**11,172-(11,247)-11,360**
SUERC-105462	479-480	Bulk sed.	10,967±24	-29.5	12,768-12,902	**12,765-(12,833)-12,939**
Beta-505606	531-532	Bulk sed.	12,010 ± 40	-27.7	13,767-14,024	**13,693-(13,911)-14,049**
R1[5]	575-578	tephra	12,627 ± 48	n/a	14,578-15,181	**14,582-(14,931)-15,126**
R1[6]	575-578	tephra	12,638 ± 60	n/a	14,554-15,225	
AA-30919	625-626	Bulk sed.	13,050 ± 95	-23.6	15,271-15,860	**15,346-(15,672)-16,029**

* Calibrated age ranges using Calib 8.20 (Stuiver and Reimer, 1993).

** Probability interval of calibrated ages and weighted mean ages (wma) using BACON (Blaauw and Christen, 2011).

[1]Age for Mount Burney tephra layer MB2 (McCulloch and Davies, 2001).
[2]Age for Volcan Aguilera tephra layer (McCulloch et al., 2021)
[3]Age for Volcán Hudson tephra layer H1 (Stern et al., 2016).
[4]Age for Mount Burney tephra layer MB1 (Mansilla et al., 2016).
[5]Age for Volcan Reclus tephra layer R1 (Sagredo et al., 2011).
[6]Age for Volcan Reclus tephra layer R1 (McCulloch et al., 2005).

correlated to the eruption of Volcán Reclus, which has been previously dated to between 12,638 ± 60 (McCulloch et al., 2005) and 12,627 ± 48 ^{14}C yr BP (Sagredo et al., 2011). The Punta Arenas age-depth model was constructed using the Bayesian chronological package Bacon ver.2.5.5 (Blaauw and Christen, 2011) and implementing the southern hemisphere calibration curve SHCal20 (Hogg et al., 2020) with instantaneous events such as the tephra layers removed (Fig. 3). The weighted mean ages from the BACON age–depth model are used to provide the age–depth axis (cal a BP) for the pollen diagrams (Figs. 4-6).

3.3 Pollen Stratigraphy

Seven Local Pollen Assemblage Zones (LPAZs) are indicated by CONISS based on the percentage pollen data (Fig. 4) and these LPAZs are applied to the pollen influx (Fig. 5) and pollen preservation data (Fig. 6) to aid comparison.

3.3.1 LPAZ PA-1 (632 - 531 cm; c. 15,765 - 13,885 cal a BP)

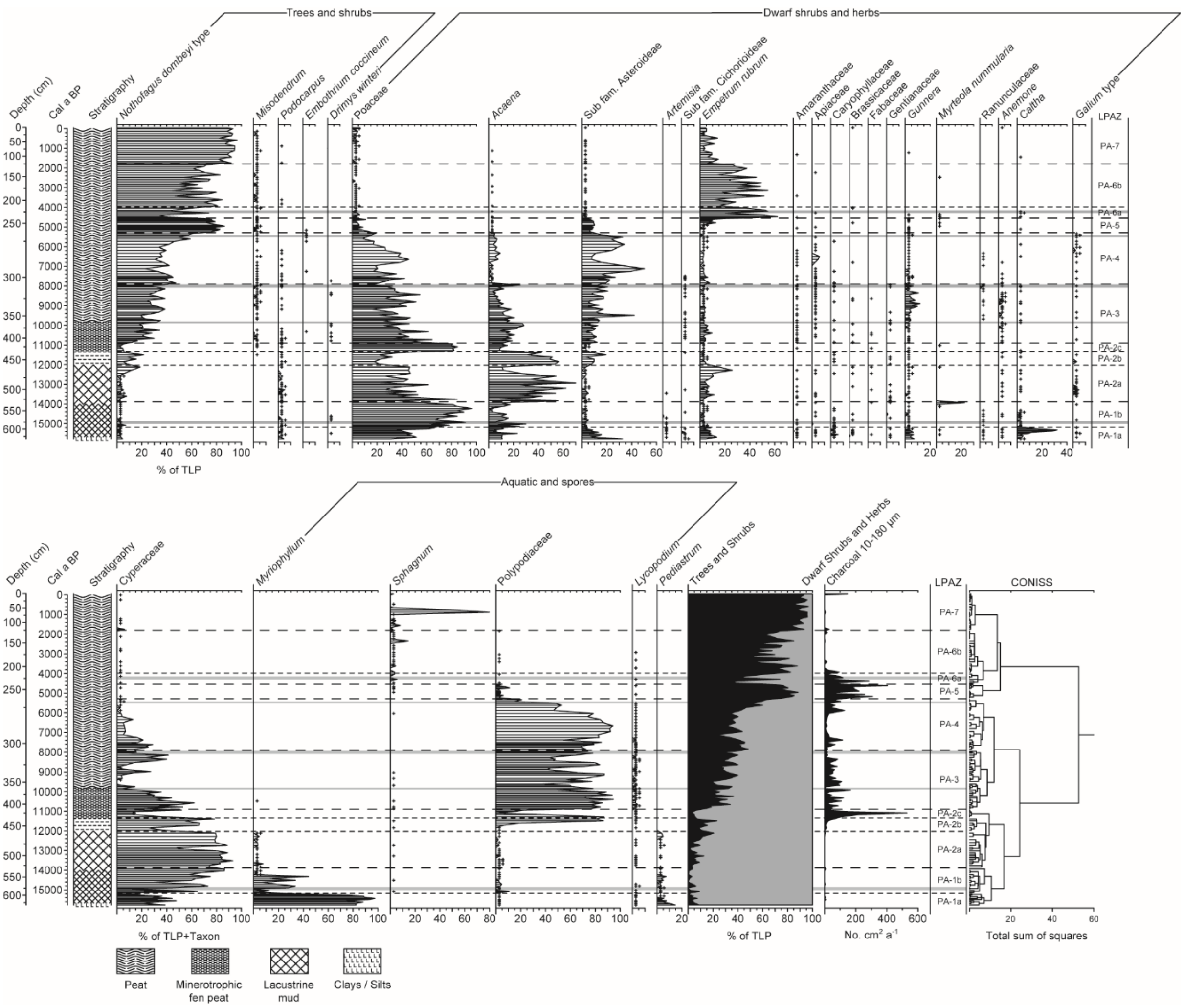

Fig. 4. Punta Arenas summary percentage pollen and spore diagram. *Misodendrum* is included in the trees group as it is a hemiparasite of *Nothofagus* trees.

LPAZ PA-1 is divided into two sub-zones; sub-zone PA-1a (c. 15,765 – 15,170 cal a BP) comprises the basal land pollen assemblage dominated by Poaceae and Sub. Fam. Asteroideae with lesser amounts of *Acaena, Empetrum rubrum* and *Gunnera*. There is a high diversity of open ground taxa including trace amounts of Amaranthaceae, Sub. Fam. Cichorioideae, Caryophyllaceae and Brassicaceae, and pollen influx values initially are low (~120 – 2000 cm^2 a^{-1}). The arboreal content is limited to trace amounts of *Nothofagus dombeyi* type (hereafter referred to as *Nothofagus*), *Podocarpus* and single grains of *Drimys winteri*. The continuous presence of *Artemisia* along with the treeless open grassland taxa is indicative of a cold-tolerant steppe / tundra vegetation following deglaciation. The site itself was dominated by the shallow rooting aquatic *Myriophyllum* and small proportions of the freshwater algae *Pediastrum* (Komárek and Jankovská, 2001). In sub-zone PA-1b (15,170 – 13,855 cal a BP) there is a marked increase in Poaceae and decline in taxa diversity, although pollen influx values increase to ~6000 cm^2 a^{-1}. At the same time there is a rapid decline in *Myriophyllum* (from >80% to ~10% of TLP+taxon) and *Pediastrum* continues in trace amounts. During this transition there was a brief peak in the wetland herb *Caltha* and a rise in Cyperaceae (to >80% of TLP+taxon) towards the upper zone boundary at 13,855 cal a BP. These changes probably reflect a rapid shallowing of the water level and a hydroseral succession of taxa in response to the decreasing water level culminating in the brief peak of *Myrteola nummularia*, a wetland/bog taxon that probably expanded across the emergent surfaces as the lake dried out indicated by the virtual disappearance of *Myriophyllum*. It is not clear to what extent this shift in the local hydrology of the site was driven by climate or natural infilling from increased bioproductivity and sediment accumulation. There is no marked response to the deposition of the Volcán Reclus (R1) tephra layer at c. 15,000 cal a BP.

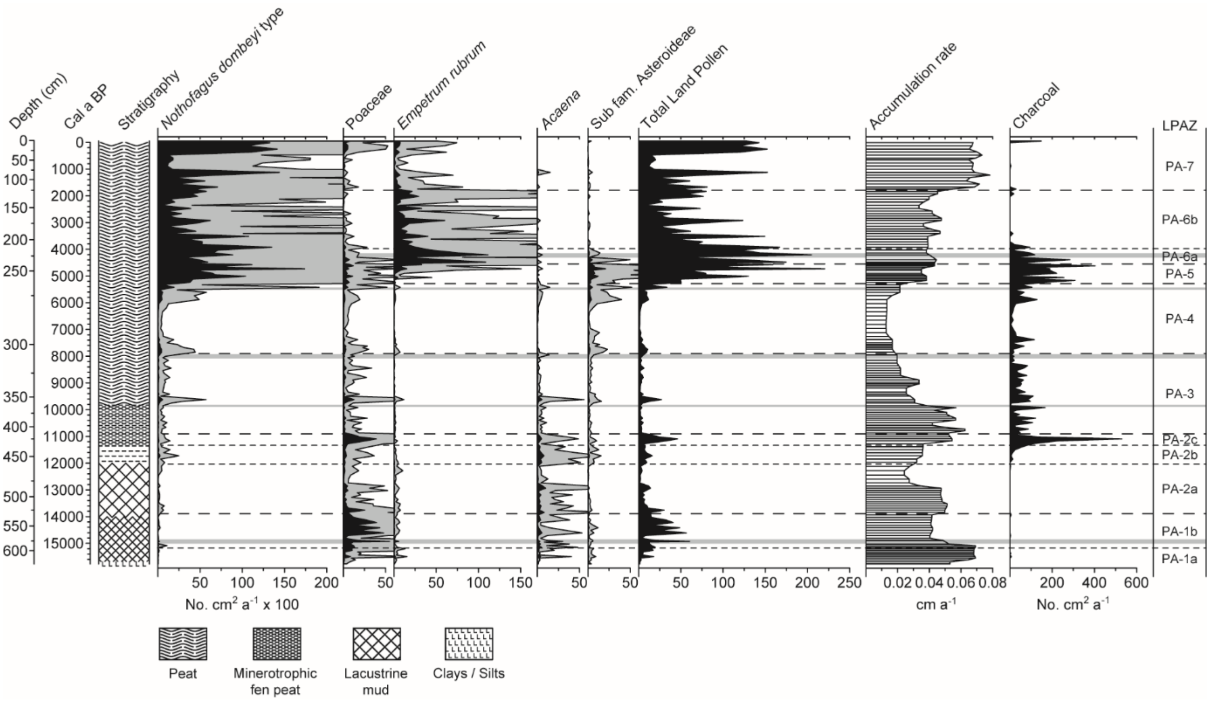

Fig. 5. Punta Arenas pollen accumulation rate (influx) for selected taxa. Grey shading = 10 x exaggeration.

3.3.2 LPAZ PA-2 (531 - 415 cm; c. 13,885 – 10,905 cal a BP)

LPAZ PA-2 is divided into three sub-zones; sub-zone PA-2a (c. 13,885 – 12,035 cal a BP) is dominated by a gradual and fluctuating increase in *Acaena* (with a corresponding decrease in Poaceae), peaking at c. 12,940 cal a BP followed by a gradual decline in *Acaena,* but this time replaced by *Empetrum rubrum*. During this sub-zone *Nothofagus* was present in small amounts ~5% and at c. 12,116 cal BP steadily increased to ~21%, contributing to the decline in *Acaena*. It is likely that the small expansion of *Nothofagus* represents the spread of woodland from glacial refugia facilitated by increased humidity (Premoli et al., 2010; Mansilla et al., 2016). At this stage the pollen values probably represent isolated scrubby stands of *Nothofagus*. The site itself was dominated by Cyperaceae (>80% of TLP + taxon) and together with the normal pollen at ~50% suggests the mire site continued to be relatively wetter. Sub-zone PA-2a encompasses the most part of the time periods of the Antarctic Cold Reversal (Chowdhry Beeman et al., 2019) and the Greenland stadial GS-1 (Younger Dryas) (Walker et al., 2019). However, apart from the continued dominance of steppe / tundra vegetation, the low proportions of arboreal pollen and a small decrease in organic content, it is difficult to identify an unambiguous response to climate cooling, but the vegetation changes were probably driven by changes in effective moisture, probably as the focus of the SWWs shifted poleward during the last glacial – interglacial transition (McCulloch et al., 2020; Moreno et al., 2021).

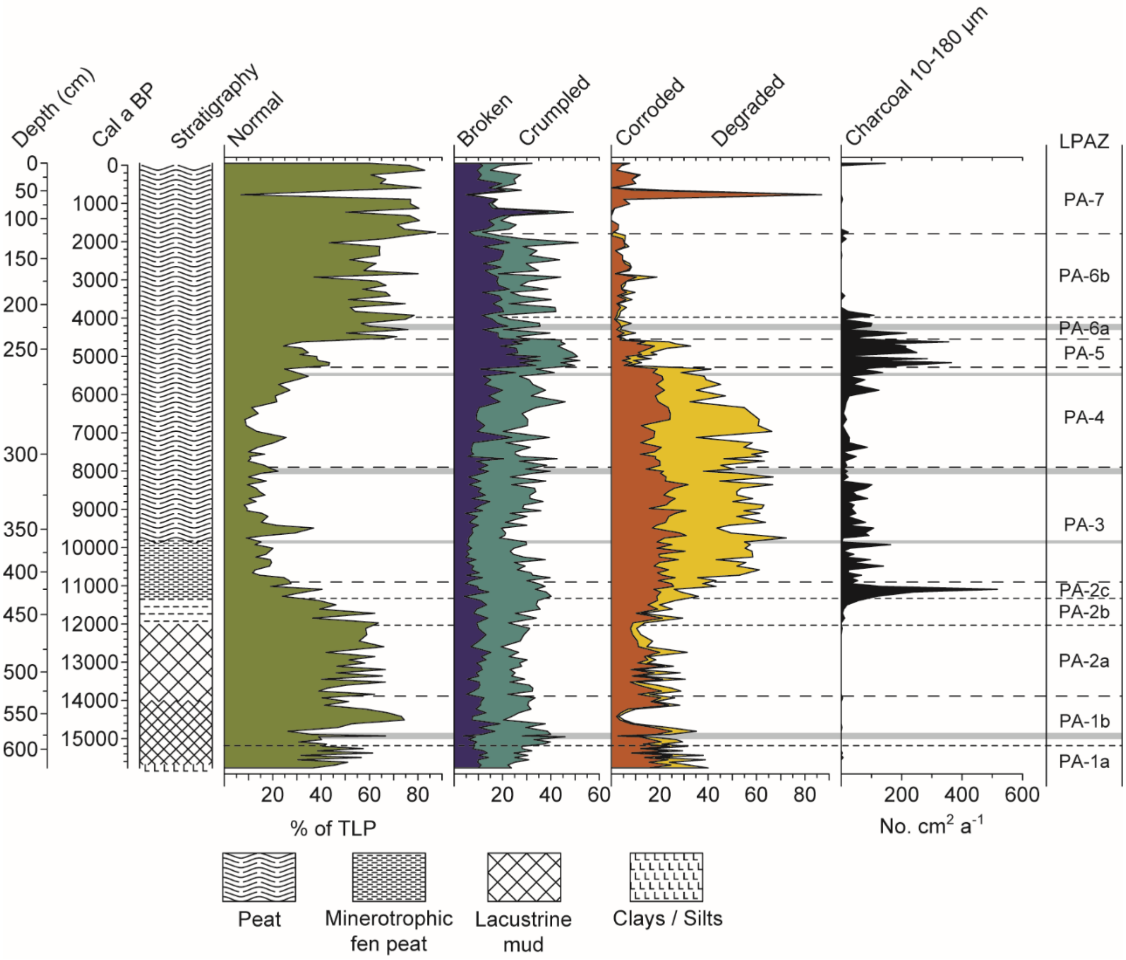

Figure 6. Punta Arenas percentage pollen preservation diagram and charcoal accumulation rate (influx).

Sub-zone PA-2b (c. 12,035 – 11,330 cal a BP) is marked by a rapid re-expansion of *Acaena* and corresponding decline in Poaceae with smaller increases in *Nothofagus* and Sub fam.

Asteroideae. Organic content reaches extremely low values at c. 11,500 cal a BP. At the start of the sub-zone there was a marked drop in the dominance of Cyperaceae but by c. 11,700 cal a BP, sedges had recovered together with a rapid rise in Polypodiaceae (polypod ferns). The latter suggests sufficient warmth and effective moisture for the development of an increased diversity of understorey vegetation (Rosas et al., 2019). Although during sub-zone PA-2b there was a gradual decline in the proportion of normal pollen and a corresponding increase in corroded and degraded pollen (Fig. 6). This suggests that the increase in temperature may have resulted in the onset of drier mire surface conditions and the increase in Polypodiaceae may also reflect the spores' resistance to deterioration (Bunting and Tipping, 2000). It is notable that the expansion of polypod ferns occurs at c. 11,600 cal a BP and coeval with the end of GS-1).

Sub-zone PA-2c (c. 11,330 – 10,905 cal a BP) was dominated by a rapid increase in Poaceae to ~80% of TLP and virtually all dryland declined. Most notable is the marked contraction of *Nothofagus* and the virtual disappearance of *Empetrum rubrum* and sub fam. Asteroideae. Cyperaceae, polypod ferns and the proportion of normal pollen also dramatically declined during this sub-zone. Contemporary with these major vegetation changes is the largest charcoal peak in this ~15,000 yr-long record. The vegetation changes and reduced pollen preservation suggests a shift to drier conditions leading to the replacement of the sedges with grasses across the mire site and increased fire activity enabled by the availability of drier fuel. The reduction in effective moisture and increased burning likely led to the contraction of the scrubby *Nothofagus* tree cover, favouring the expansion of Poaceae.

3.3.3 LPAZ PA-3 (415 - 306 cm; c. 10,905 – 7900 cal a BP)

After the drier period during sub-zone PA-2c, LPAZ PA-3 reflects a period of more sustained stability with only modest centennial scale fluctuations. *Nothofagus* recovers to values between ~20 and 40% of TLP. The frequent, although intermittent, presence of the hemiparasite *Misodendrum* (which continued to the top of the pollen record) indicates variability in tree density and overall local growing conditions of *Nothofagus*. *Acaena* and sub fam. Asteroideae increase to >10% of TLP and during the latter-half of the LPAZ *Gunnera* increases. Poaceae was correspondingly reduced to ~30 – 40% of TLP. Cyperaceae steadily declines towards the midpoint and the organic content rises to >80% indicating the transition to a raised peat bog. Polypod ferns rapidly expanded at the start of LPAZ PA-3 suggesting a greater availability of habitat. The increase in *Lycopodium* likely reflects the colonisation of drier parts of the bog surface by club mosses. Taken together the pollen evidence suggests a return to relatively more humid and warmer conditions than sub-zone PA-2c. However, a sustained shift to drier conditions is indicated by the significant reduction in the proportions of normal pollen and the increase in corroded and degraded pollen due to aerobic conditions persisting at the mire surface. Again, this may have amplified the mire taxa, such as Polypodiaceae, that are more resistant to deterioration. A brief small increase in mire surface wetness (MSW) occurred at c. 9500 cal a BP and is also reflected in the small peak in *Acaena* at that time. The influx of charcoal particles during LPAZ PA-3 fluctuates but was relatively continuous reflecting the continued availability of drier fuel.

3.3.4 LPAZ PA-4 (306 - 266 cm; c. 7900 – 5285 cal a BP)

At the start of this LPAZ there was a small step increase in *Nothofagus* to ~40% of TLP and the continued dominance, though with highly variable proportions, of Poaceae and sub fam. Asteroideae. Aridification resulted in *Gunnera* and *Acaena* reduced to trace amounts, although the latter recovered to ~5% of TLP towards the top of the LPAZ. Furthermore, the low proportions of normal pollen and the continued fluctuating influx of charcoal particles suggests the continuation of the extreme drier conditions that developed during the previous zone, LPAZ PA-3. This is also reflected in the much-reduced rate of peat accumulation (~ 0.013 cm a^{-1}) (Fig. 5). However, the proportions of corroded and degraded pollen begin to decline towards the upper LPAZ boundary suggesting a shift to cooler and/or wetter conditions and increased MSW that probably prompted the increase in *Nothofagus* and decline in Polypodiaceae at the end of the LPAZ.

3.3.5 LPAZ PA-5 (266 - 240 cm; c. 5285 – 4550 cal a BP)

This LPAZ was distinguished by the development of closed *Nothofagus* forest with only lesser amounts of Poaceae and sub fam. Asteroideae (probably *Chiliotrichum* scrub) persisting. This is supported by the substantial increase in the influx of land pollen mostly composed of *Nothofagus* (Figs. 4, 5). The trend in improving pollen preservation that started towards the top of LPAZ PA-4 underwent a brief reversal in LPAZ PA-5 at c. 4730 cal a BP. There was also a small increase in the proportion of broken and crumpled pollen but as the organic content reflects the continued accumulation of undisturbed peat and the absence of any fluvial sediments to the core site this may have been due to increased wind transport (Fig. 6). At c. 4730 - 4670 cal a BP there was a small reduction in humidity and MSW inferred from the increase in corroded and degraded pollen. The sustained influx of charcoal suggests that the relatively drier conditions continued to favour fire activity.

3.3.6 LPAZ PA-6 (240 - 125 cm; c. 4550 – 1790 cal a BP)

LPAZ PA-6 is marked by the continued dominance of the surrounding *Nothofagus* forest interplaying with *Empetrum rubrum* on the mire to the virtual exclusion of all other taxa (Fig. 5). Sub-zone PA-6a (c. 4550 – 3980 cal a BP) is marked by the higher proportions of *Empetrum* and a corresponding reduction in *Nothofagus*, perhaps in response to increased fire activity (Fig. 5). This interplay between *Nothofagus* and *Empetrum* is also reflected in the pollen influx data. At c. 4210 cal a BP there was a brief peak in total land pollen influx, substantially composed of *Empetrum*. This probably indicates that the deposition of the MB2 tephra layer and/or fire activity had a significant impact on the ecology of the bog. Sub-zone PA-6b (c. 3980 – 1790 cal a BP) reflects a higher proportion of *Nothofagus* developing into a closed forest. The proportion of well-preserved pollen (normal ~60%) throughout LPAZ PA-6 indicates a significant increase in MSW, also suggested by the return of trace amounts of *sphagnum* spores. These patterns, combined with the virtual absence of charcoal after c. 4015 cal a BP, despite the greater availability of woody fuel, strongly suggests a shift to increased humidity at that time.

3.3.7 LPAZ PA-7 (125 - 0 cm; c. 1790 cal a BP - present)

This LPAZ is marked by the almost total dominance of closed *Nothofagus* forest to the virtual exclusion of all other land pollen taxa, except for *Empetrum rubrum* which persists in reduced amounts (~5% of TLP). The rate of peat accumulation reached its highest levels of the entire record (~0.07 cm a^{-1}) and the percentage land pollen assemblage suggests a period of stability. However, at c. 890 cal a BP there was a brief peak in *Sphagnum* from which we infer a shift to wetter conditions, and this was closely followed by a dramatic switch to extreme drier conditions inferred from the peak in corroded and degraded pollen at c. 770 cal a BP. This evidence for shortlived intense changes in MSW suggests that centennial scale high-magnitude climate shifts may not always be identifiable from the percentage land pollen data alone.

4 Landscape change at Punta Arenas and climatic inferences

4.1 Late glacial landscape (c. 15,765 – 11,600 cal a BP)

During the Last Glacial Maximum, a large glacier advanced northward along the central section of the Estrecho de Magallanes, culminating in several advances to the Peninsula Juan Mazia (Segunda Angostura) between c. 25,000 and 21,000 cal a BP (McCulloch et al., 2005) (Fig. 1a). The last major advance of the Magellan glacier occurred sometime before c. 17,500 cal a BP and formed the glacial moraine limit running offshore just north of the city of Punta Arenas (Stage D, Bentley et al., 2005). A meltwater channel, now occupied by the raised mire that is the focus of this study, ran parallel to the Stage D moraine limit. Present day drainage of the slopes of Cerro Mirador now runs perpendicular to the shore through the incised channels, such as the Rio de las Minas and Rio de los Ciervos (Fig; 2).

Abandonment of the meltwater channel was likely soon after glacier retreat from the Stage D limits sometime after c. 17,500 cal a BP (McCulloch et al., 2005). Therefore, the basal age of c. 15,600 and c. 15,800 cal a BP obtained by this study and Heusser (1995) respectively are unlikely to be close minimum ages for deglaciation. It is probable that the rainwater flow continued to scour the abandoned meltwater channel until it was beheaded by the incision of the Rio de los Ciervos. Also, radiocarbon minimum ages from sites on the margin of the western steppe boundary probably reflect a later increase in humidity that enabled an increase in organic productivity and preservation of datable material rather than the timing of ice retreat (McCulloch et al., 2005).

Comparison of our palaeoenvironmental record presented here and the previous record from Punta Arenas provided by Heusser (1995) suggests broad similarities but key differences. Our record indicates that the landscape at Punta Arenas between c. 15,765 and 12,100 cal a BP was dominated by a treeless steppe/tundra vegetation with low pollen productivity. This picture is consistent with other palaeoenvironmental studies from the region (McCulloch and Davies, 2001; Huber and Markgraf, 2010; Mansilla et al., 2016, 2018) and it is likely that any woodland refugia of *Nothofagus* were more distant (McCulloch et al., 2022). Our findings suggest that the use of a Hiller Borer by C. Heusser vertically smeared the previous pollen record leading to the transfer of Holocene *Nothofagus* pollen into the Late glacial sediments.

The vegetation changes that occurred during the Late glacial likely reflect shifts in the site hydrology following glacial abandonment and a transitional phase as the SWWs migrated polewards in response to Southern Hemisphere warming (Lamy et al., 2010) (Figure 7b, e, f). However, river incision and isolation of the initial small lake basin followed by gradual infilling and development of a minerotrophic fen complicates the picture of climate change. There is no clear vegetation response to acute cooling coeval with the Antarctic Cold Reversal (ACR) and / or Greenland Stadial 1 (GS1; Younger Dryas) although it is likely that colder 'glacial-like' conditions persisted during the Late glacial. This is also suggested by the prevalence of cold-tolerant diatom assemblages at Lago Cipreses between c. 14,000 and 11,900 cal a BP (Villacís et al., 2023) (Figure 7d). A shift to warmer conditions is marked by the expansion of *Nothofagus* woodland and the rapid expansion of polypod ferns between c. 12,100 and 11,600 cal a BP respectively. The establishment of *Nothofagus* is later than at Río Rubens (52°13'S, 71°52'W) (c. 13,200 cal a BP, Markgraf and Huber, 2010), Punta Yartou (53°51'S, 70°08'W) (c. 12,900 cal a BP, Mansilla et al., 2016) and Lago Lynch (53°54'S, 69°26'W) (c. 13,300 cal a BP, Mansilla et al., 2018) which may reflect a larger distance to refugial areas of forest (Premoli et al., 2010). The timing of the rapid rise in warming and the increase in Polypodiaceae is closely coeval with the end of the deglacial warming recorded in Antarctic ice cores and the onset of Holocene-like conditions between 11,700 and 11,500 cal a BP (Chowdhry Beeman et al., 2019).

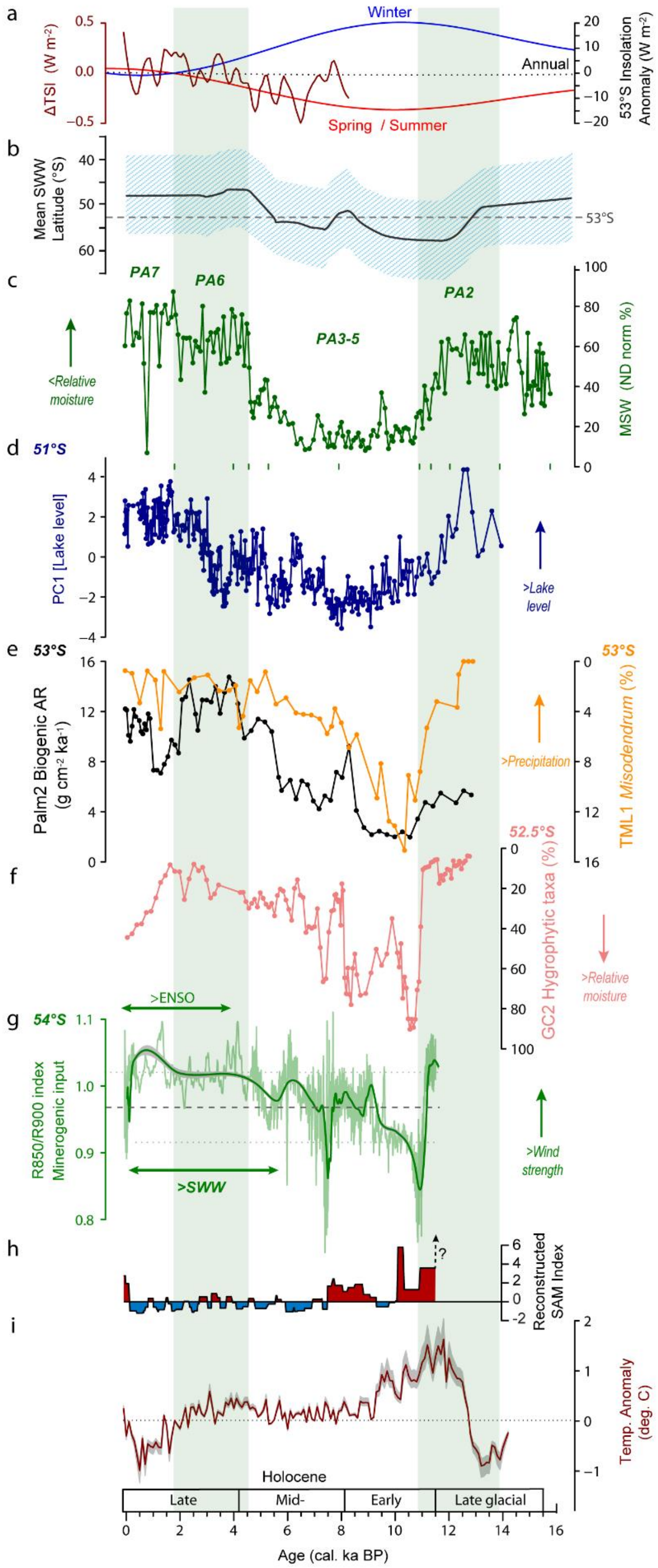

Figure 7. Regional palaeoclimate records. a) Total Solar Irradiance (ΔTSI) anomaly from present day value (Steinhilber et al., 2009) compared with solar insolation received at 53°S during the Holocene (Laskar et al.,

2004); annual insolation = dotted black line, austral spring/summer (SONDJF) insolation = red line; winter (JJA) insolation = blue line. b) Hypothetical representation of changes in the mean annual latitudinal position of the core SWW intensity belt (black line) and the approximate 1σ latitudinal range of enhanced precipitation (light blue stipple) (Ariztegui et al., 2010; Quade and Kaplan, 2017). In reality, the SWWs are more intense and focused during warmer, more positive Southern Annual Mode (SAM) index phases, but weaker, latitudinally broader and less focused during negative (colder) SAM phases shown in (h). c) Mire Surface Wetness (MSW) proxy (this study). LPAZs 1-7 are summarised with light green shading highlighting key changes. d) Diatom-based lake level reconstruction from Lago Cipreses (Villacís et al., 2023); e) Palm2 biogenic accumulation rate, a proxy for changes in SWW wind strength (black; Lamy et al., 2010) and changes in Misodendrum (gold) after Lamy et al. (2010). The Fletcher and Moreno (2012) reflecting changes in wet and dry conditions at the TML1 site is shown here. f) Hygrophytic taxa at the Gran Gampo Nevado (GC2) site, reflecting changes in relative moisture as shown (Lamy et al., 2010); g) Ultra-high resolution (69 µm interval) hyperspectral (SPECIM) R850/R900 data, which is a proxy for mineral input into the Emerald Lake, Macquarie Island at 54°S (Saunders et al., 2018; age model updated to SHCal20), which reflects changes SWW strength; the dark grey horizontal dotted line is the R850/R900 dataset mean and the dark green line a 100-year LOESS smoothing of the R850/R900 with standard errors shaded in grey. h) Reconstructed Holocene SAM-index variability between positive (red) to negative (blue) SAM-like conditions based on Northern Arboreal Pollen data from Southern Chile (Moreno et al., 2018). i) Temperature anomaly relative to pre-industrial reference period (1850–1900 CE) from the James Ross Island (JRI) ice core record, NE Antarctic Peninsula (Mulvaney et al., 2012); grey shading represents the published error range; the dotted line is the 12 ka mean.

4.2 Early Holocene (c. 11,600 – 8000 cal a BP)

The period between c. 11,600 and 8000 cal a BP is generally characterised by the gradual, albeit restrained, expansion of *Nothofagus* woodland versus the steady replacement of open grassland and diverse herbaceous taxa co-occurring with higher fire activity. Between c. 11,300 and 10,890 cal a BP the early woodland expansion suffered a brief setback, probably due to a brief but large peak in fire activity. Thereafter the gradual trend to increased *Nothofagus* continued largely uninterrupted. This would commonly be interpreted as suggesting an increase in effective moisture favouring the development of forest. However, the picture at Punta Arenas is more nuanced as the large increase in aerobically deteriorated pollen grains between c. 11,600 and 8000 cal a BP indicates a sustained period of drier conditions which also favoured the increase in fire activity evidenced by the influx in charcoal. The combined evidence from Punta Arenas also suggests that the Early Holocene dry period can be divided into two phases. The first phase, between c. 11,600 and 10,000 cal a BP, had relatively higher levels of effective moisture that supported woodland growth and also peat accumulation (Figure 7c). The second phase, between c. 10,000 and 8000 cal a BP, continued to have sufficient effective moisture to support continued woodland growth but a reduction in mire surface wetness (MSW) led to slower rates of peat accumulation (Figure 7c). The second phase was also punctuated by a brief period of increased MSW at c. 9500 cal a BP which also saw a short expansion in Sub. fam. Asteroideae, probably *Chiliotrichum* scrub. While it is probable that levels of effective moisture also supported the growth of polypod ferns it is also probable that the higher levels of peat humification led to the differential preservation of the more resistant Polypodiaceae spores (Bunting and Tipping, 2000).

The onset of the early Holocene drier period in Fuego-Patagonia appears to vary according to latitude and environmental proxy. To the west, at Gran Campo Nevado (GC2, 52°48'S, 72°55'W), there was a rapid expansion of hygrophytic taxa (Fesq-Martin et al., 2004) and increased winds and precipitation inferred from reduced fjordal salinity (Palm2, 52°47'S, 73°38'W) at c. 11,000 cal a BP (Lamy et al., 2010) (Figure 7e). Conversely the expansion of Isoetes along the littoral of Lago Pintito (52°02'S, 72°22'W) and the development of a more stratified water column (i.e. reduced mixing) at Lago Cipreses (51°17'S, 72°51'W) at c. 11,300 cal a BP marks the onset of the drier period and a minima in the strength of the SWWs at ~51° - 52°S (Moreno et al., 2021, Villacís et al., 2023) (Figure 7d), although the increase in charcoal accumulation rates also at Lago Pintito occurred at c. 12,900 cal a BP suggesting that the onset of drier conditions may have been earlier. At Río Rubens there was a similar increase in the influx of charcoal particles at c. 12,000 cal a BP (Huber and Markgraf, 2003). Further south at Lago Ballena (53°38'S, 72°25'W) an increase in 'wet-demanding' species (Magellanic rainforest) occurred between c. 10,000 and 9000 cal a BP (Fontana and Bennett, 2012). At Punta Burslem on Isla Navarino (54°54'S, 67°57'W) there is a later increase in charcoal influx at c. 11,000 cal a BP and a more significant shift to drier MSW at c. 9500 cal a BP (McCulloch et al., 2020). This drier MSW period is closer to the period of minimum SWW activity inferred from the Lago Cipreses diatom record between c. 9100 and 7400 cal a BP (Villacís et al., 2023). While the spatial and temporal patterns of fire histories may vary considerably (Moreno et al., 2018) there appears to be a latitudinal and longitudinal relationship with the onset of the Early Holocene drier period occurring later at the southernmost sites in Fuego-Patagonia which suggests a continuation of the east-west precipitation gradient but a polewards migration in the focus of the SWWs (Figure 7b).

4.3 Mid-Holocene (c. 8000 – 4000 cal a BP)

At c. 8000 cal a BP, after the deposition of the H1 tephra layer, there was a small stepwise increase in *Nothofagus* woodland, but the continued higher proportions of aerobically deteriorated pollen indicates that the drier period at Punta Arenas persisted into the Mid-Holocene. The reduction in the diversity of the herbaceous taxa, including the virtual loss of *Acaena* and *Gunnera*, and the lower peat accumulation rates between c. 8000 and 6000 cal a BP also suggest an intensification of the drier conditions during this period, although at c. 7200 cal a BP there was a brief increase in MSW, again reflected by a more sustained increase in Sub. fam. Asteroideae.

The persistence and intensification of the early Holocene drier period at Punta Arenas into the mid-Holocene is broadly contemporary with reduced MSW at Punta Burslem (McCulloch et al., 2020 Fig. 6), windier conditions in the Southern Ocean (Marcott et al., 2013; Saunders et al., 2018) (Figure 7g), ice sheet thinning and ice shelf retreat across the Antarctic Peninsula (Johnson et al., 2020; Hein et al., 2016; Roberts et al., 2008; Verleyen et al., 2017), ice retreat of the South Shetland Islands (Heredia Barión et al., 2023), which has been associated with an extended and pronounced positive phase of the Southern Annular Mode (SAM) (Moreno et al., 2018) (Figure 7h). The high proportions of hygrophytic taxa at GC2 also continued until c. 7000 cal a BP (Fesq-Martin et al., 2004) (Figure 7f) and higher westerly winds inferred from reduced fjordal salinity at Palm2 persisted until c. 5500 cal a BP (Lamy et al., 2010) (Figure 7e). However, both records indicate a significant reversal to drier (GC2) and less windy (Palm2) conditions between c. 8000 and 7500 cal a BP (Figure 7e, f).

The timing of the end of the Early to Mid-Holocene drier period is regionally less precise. By c. 6000 cal a BP at Punta Arenas there was a trend to increasing well-preserved pollen and a corresponding fall in the proportions of aerobically deteriorated pollen grains suggesting a small increase in mire surface wetness. The response of *Nothofagus* cover to the relatively small increase in effective moisture was dramatic as it rapidly developed into closed forest by c. 5300 cal a BP, virtually to the exclusion of grassland taxa. The shift to wetter MSW at Punta Arenas is closely consistent with evidence from the South Shetland Islands that suggests the focus of the SWWs had shifted equatorward by c. 6000 cal a BP (Bentley et al., 2009; Saunders et al., 2018) (Figure 7b). Moreno et al. (2021) argue that the SWWs were reinvigorated at c. 52°S at c. 7500 cal a BP indicated by the rapid decline in the littoral aquatic taxon Isoetes at Lago Pintito. This is close to the resurgence of water column mixing at Lago Cipreses at c. 7400 cal a BP (Villacís et al., 2023) (Figure 7d). At Río Rubens *Nothofagus* forest increased at c. 6800 cal a BP (Markgraf and Huber, 2010) and there was an even earlier expansion of *Nothofagus* forest at Puerto Harberton (54°52'S, 67°19'W) at c. 7300 cal a BP (Markgraf and Huber, 2010) in step with small increases in MSW identified at Punta Burslem but barely registered at Punta Arenas (Figure 7c). We suggest this demonstrates the capacity of *Nothofagus* forest when at its range edge to bounce back in response to relatively small increases in effective moisture. The combined evidence from Punta Arenas spanning this period also demonstrates that we should be cautious in interpreting both the timing of the onset and the magnitude of climate changes from such 'leaps' in pollen percentage data.

The trend at Punta Arenas to increased MSW after c. 6000 cal a BP was interrupted by a reversal to drier conditions between c. 5300 and 4700 cal a BP and an increase in fire activity. This period is closely contemporary with a similar reduction in MSW recorded at Punta Burslem and Caleta Eugenia (54°55'S, 67°20'W), the latter located toward the eastern drier end of Isla Navarino (McCulloch et al., 2019). However, the evidence for drier conditions contrasts with the development of closed *Nothofagus* forest at Punta Arenas, as represented by the percentage pollen data, which suggests an increase in moisture. The forest may have proved to be resistant to this centennial-scale period of drier conditions or it was more open than that suggested by the percentage thresholds used to define the nature of the forest. At c. 4600 cal a BP there was a second and larger improvement in pollen preservation indicating an increase in MSW (Figure 7c). The increase in effective moisture probably led to the expansion of heathland taxa across the mire. The apparent contraction in *Nothofagus* cover at this time is not supported by the pollen influx data, which suggests *Nothofagus* cover also increased at that time, and is more likely to be an artefact of an increased local component (in this case heathland) of the pollen rain.

4.4. Late Holocene (c. 4000 cal a BP – present)

After c. 4000 cal a BP the development of closed *Nothofagus* forest and improved levels of pollen preservation which suggest a shift to a wetter climate. It also appears that the increase in humidity also led to a significant reduction in fire activity following the Early to Mid-Holocene dry period. While the timing of forest expansion varies, regionally the Late Holocene is characterised by the development of closed *Nothofagus* forest which appears to be unchanged during the last 4000 years at Río Rubens and Puerto Harberton. However, the fluctuations in pollen preservation and *Nothofagus* cover at Punta Arenas between c. 4000 and 1800 cal a BP (Figure 7c) suggest frequent centennial small-scale shifts in effective moisture reflecting the sensitivity of the forest-steppe ecotone to shifts in the east-west precipitation gradient.

At c. 1900 cal a BP there was a stepwise improvement in pollen preservation, and this was followed ~100 years later by an increase in the rate of peat accumulation and in the proportions of *Nothofagus,* to the virtual exclusion of all other land taxa, which continued as stable land cover until the present. However, during this period there are two shortlived climate shifts that are not reflected in the percentage TLP data. Firstly at c. 890 cal a BP there was a large but brief expansion of *Sphagnum* suggesting a short increase in mire surface wetness. This event was followed by a dramatic shift to drier conditions inferred from a spike in corroded pollen grains at c. 770 cal a BP. This event is contemporary with a brief reduction in *Nothofagus* at Punta Burslem. It is noteworthy that the forest expansion at Punta Arenas lagged the shift to increased effective moisture and then appears, in the percentage data and despite fluctuations in the influx of *Nothofagus* pollen, to reflect a period of stable climate. However, the pollen preservation data and changes in mire taxa reflect significant shifts between wetter and drier climate. This period (c. 2000 cal a BP to present) provides valuable insight into the complacent behaviour of the *Nothofagus* pollen signal once effective moisture levels place the woodlands comfortably beyond their range edge. This also points to the necessity of supplementing percentage land pollen information with a range of sensitive measures to reconstruct past environmental and climatic changes.

5 Implications for the southern westerly winds

The Punta Arenas record provides a better understanding of the past behaviour of the SWWs. During the Late glacial period there was a transitional phase (c. 14,800 – 11,600 cal a BP) as the SWWs migrated southward from their more equatorward focus during the LGM (Figure 7b). The poleward latitudinal shift does not appear to have been a smooth movement but rather characterised by centennial-scale reversals and competing signals as temperature and precipitation increased in southern Patagonia. At the start of the Early Holocene (c. 11,600 cal a BP) a degree of clarity emerges as the more focused poleward position of the SWWs led to windier and wetter conditions along the western flanks of the southern Andes, but increased Föhn effects led to drying conditions in the lee of the Andes. Here we suggest that the Early to Mid-Holocene drier period does not reflect a general 'minimum' in the SWWs but rather their movement southward that can be tracked through the available palaeoenvironmental records, and their impact identified in the Southern Oceans and along the Antarctic Peninsula (Ingólfsson et al., 2003; Roberts et al., 2008; Bentley et al., 2009). It is likely that the small reduction in atmospheric CO_2 following the Early Holocene peak was caused by an increase in the uptake of terrestrial carbon in the Northern Hemisphere and the Tropics (Schmitt et al., 2012) rather than reduced ventilation of the Southern Oceans (Moreno et al., 2021). The more poleward focus of the SWWs and the sustained positive SAM mode during the Early Holocene (Figure 7) was probably similar to present conditions, as the SWWs move polewards and intensify in response to anthropogenic warming leading to reduced precipitation at Punta Arenas and the desiccation observed at the mire surface.

The timing of the equatorward return of the SWWs is less clear and probably occurred during a transition period between c. 7500 and 5500 cal a BP (Figure 7). As the SWWs shifted northward they also appeared to weaken and stretch wider latitudinally leading to a variety of changes in the extent of *Nothofagus* forest. The changes are related to increases in effective moisture, but the nature and timing of the forest responses were dependent on the latitude and sensitivity of each site and their location along the east-west precipitation gradient. The transitional period was probably not characterised by a smooth migration of the SWWs but again punctuated by centennial-scale reversals.

6 Conclusion

The Punta Arenas palaeoenvironmental record demonstrates the sensitivity of the peat bogs and their surrounding vegetation within the forest-steppe ecotone. Our record from Punta Arenas confirms that the Late glacial landscape was a virtually treeless steppe / tundra under colder and more humid climatic conditions. This suggests that the area was not a glacial refugia for *Nothofagus* woodland. The onset of warmer Holocene-like conditions began at c. 12,200 cal a BP followed by the transition from a lake to a minerotrophic fen. Between c. 12,000 and 11,000 cal a BP there was a shift to drier conditions leading to reduced mire surface wetness that persisted, albeit with brief wetter periods at c. 9500 and 7200 cal a BP, until c. 6000 cal a BP. During this time, the expansion of *Nothofagus* forest was likely moisture limited and the sustained drier conditions favoured increased fire activity. The reduction in effective moisture between c. 11,000 and 6000 cal a BP is consistent with a more poleward shift in the focus of the SWWs leading to increased wetter conditions in the west (e.g. GC2) and increased Föhn effect in the east, thus steepening the precipitation - evaporation balance across the lee of the southern Andes. The Late Holocene was characterised by increased moisture levels leading to more forest cover but also centennial-scale climate variability leading to frequent longitudinal shifts of the forest-steppe margin. The contrast between the climate signals inferred from the pollen (percentage and influx) data and the pollen preservation data (as a proxy of mire surface wetness) demonstrates that small-scale shifts in effective moisture can lead to large-scale changes in the pollen assemblages. Conversely, these shifts can also mask regional signals, leading to a false impression of stability in the landscape. These results highlight the utility of pollen preservation as a tool to support climatic inferences from palynological data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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