**Palaeoenvironmental reconstruction of Late Glacial-Holocene environmental change for Patagonia, southern South America**

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STATEMENT OF ORIGINALITY

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Date: 30th April 2020

**ABSTRACT**

Patagonia is the only continental landmass to intersect the entire migratory track of the Southern Westerly Winds (SWWs), which are a component of the global atmospheric system that has governed the palaeo and modern climate of Southern South America between 30°S and 60°S. Palaeoenvironmental proxies can be used to determine past changes in the migration patterns of the SWW’s and how this migration effects the timing and nature of climatic changes during the Late glacial and Holocene. Three deep basin peat-sediment cores were taken from an extensive latitudinal transect (~47-55°S) on the eastern flanks of the Andean Cordillera in Patagonia. By reconstructing the latitudinal changes from the vegetation response to these migrating fronts the spatial and temporal shifts in the SWWs were determined. Palynological and lithostratigraphic evidence provided by records from Cerro Ataud (47°17’ S 72°39’ W), Lago Fox (53°52’S, 70°26’W) and Punta Burslem (54°54’ S, 67°57’ W) were correlated with other palaeoenvironmental data from proximal sites in central and southern Patagonia and constrained by radiocarbon dating and tephrochronology. The records indicate that deglaciation began sometime before c. 17 kcal yr BP at Pta Burslem, c. 15.7 kcal yr BP at Lago Fox and c. 13.4 kcal yr BP at Cerro Ataud all reflecting warmer interstadial temperatures in the Late glacial. A period of forest expansion by c. 11.5 kcal yr BP at Lago Fox, c. 10.3 kcal yr BP at Pta Burslem and c. 9.5 kcal yr BP at Cerro Ataud as a consequence of increased humidity from the poleward shift in the SWWs was followed by an arid phase and forest contraction between c. 6-9 kcal yr BP at all sites as the SWWs continued to migrate poleward. Arboreal cover increased again between c. 6.4-5 kcal yr BP in response to increasing humidity from an equatorward shift in the SWWs as global temperatures began a cooling trend in the Mid to Late Holocene. A period of climatic instability is then seen from c. 5 kcal yr BP to the present at all three sites as the SWWs shifted into their contemporary position of ~50°S. While the key findings reinforce a prevailing set of ideas about the movements of the SWWs, importantly this study identifies that the SWWs remained beyond the South American continent influencing the ocean-atmosphere system of the Southern Ocean for ~ 3000 years. This is a significant finding for future global warming scenarios.

**GLOSSARY OF TERMS**

**Spanish Geographical names**

Bahía: Bay Lago: Lake

Caleta: Small cove Paso: Narrow channel

Canal: Channel Puerto: Port

Cordillera: Mountain range Punta: Point

Estancia: Farm or ranch Río: River

Estrecho: Strait Volcán: Volcano

Isla: Island

**ABBREVIATIONS**

ACC: Antarctic circumpolar current LGM: Last Glacial Maximum

ACR: Antarctic cold reversal LPAZ: Local pollen assemblage zone

AVZ: Austral volcanic zone NPI: North Patagonian Icefield

Cal yr BP: Calibrated years before present Pta: Punta

(relative to AD 1950) SPI: South Patagonian Icefield

Cta: Caleta SST’s: Sea surface temperatures

CLD: Chilean Lake District SWWs: Southern westerly winds

JRI: John Ross Island SVZ: Southern volcanic zone

LGIT: Last Glacial/Interglacial Transition TLP: Total Land Pollen

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# Introduction

Patagonia is the most southerly landmass on Earth, with the exception of Antarctica. This region of southern South America encompassing the high latitudes of Chile and Argentina protrudes into the Drake Passage at ~56°S, flanked by the Atlantic and Pacific Oceans. Its southerly maritime location makes it especially sensitive to changes in climate with evidence suggesting that during the late Quaternary, Patagonia has experienced successive glaciations that have eroded the landscape and left a suite of glacial landforms and ice scoured troughs and also a record of changing vegetation in response to changing climate (McCulloch et al., 2005a).

The climate of Patagonia is dominated by the Southern Westerly Winds (SWWs) (Section 1.3) which form between the temperature gradients of the warm mid-latitudes and the colder polar regions (McCulloch, 2010). The contemporary core of the SWWs, where the highest wind velocities and precipitation occur, lies at ~50°S but they continually migrate latitudinally, governed by global temperatures with a colder environment triggering an equatorward migration and a contrasting poleward migration during warmer temperatures (Bertrand et al., 2014). Such migrations occur on an annual cycle between Austral summer and winter on a scale of ~5° of latitude, however when global temperature oscillations augment it leads to greater migratory range, forcing the SWWs further north or south (McCulloch et al., 2000; Toggweiler et al., 2006). During extended cold periods, equatorward migrations of the SWWs bring increased amounts of moisture to northern Patagonia allowing ice sheets to be sustained further north than the current North Patagonian Icefield (NPI).

This scenario is inferred during the LGM as the SWWs migrated north by ~10° bringing additional moisture that allowed the formation of a continuous ice sheet extending from the Chilean Lake District (CLD) to Tierra del Fuego (Hulton *et al*., 2002). The warming trend in the Late-glacial, evidenced by James Ross Island (JRI) ice core records (Mulvaney et al., 2012) and sea surface temperatures (SSTs) (Lamy et al., 2010) instigated a poleward migration of the SSWs causing the ice sheet to retreat into smaller discrete ice sheets like the contemporary NPI, South Patagonian Icefield (SPI) and the smaller Cordillera Darwin Icefield (CDI) as they were deprived of moisture from the core of the SWWs. In extended warm periods the SWWs can migrate beyond the southernmost landmass extremities and into the Southern Ocean, amassing the levels of atmospheric CO2 through increased degassing from an augmented Antarctic Circumpolar Current (ACC) causing a positive feedback mechanism for global temperatures (Anderson et al., 2009; Turney et al., 2016). Increasing global temperatures raise SSTs in the Southern Ocean that can reduce sea ice around Antarctica and force the SWWs to migrate further south (Bentley et al., 2009).

The Andean Cordillera extends along the entire western side of the South American continent; the product of plate tectonics as the Nazca and Antarctic oceanic plates subduct under the South American plate (Stern, 2004). As the SWWs move in from the Pacific and reach this mountainous barrier it produces a striking longitudinal orographic precipitation gradient resulting in hyper humidity west of the Andes (> 6000 mm) with rapidly decreasing humidity in the lee of the mountains (<300 mm in Patagonian Steppe) (Schneider *et al.,* 2003; Garreaud *et al.,* 2013). The ecotones along this precipitation gradient, ranging from forest to steppe are some of the most sensitive on Earth with vegetation responding to small changes in climate. Therefore, the ecological response of vegetation in these ecotones can be linked to regional and therefore global patterns of climate change.

The SWWs are therefore the main factor in controlling precipitation and moisture regimes in Chilean Patagonia (Quintana and Aceituno, 2012; Bertrand et al., 2014) resulting in ecotone and ecosystem variation in response to their latitudinal position and intensity. This natural variability can be seen in palaeoenvironmental records, with wet and dry signals evident within the stratigraphy of the record. This can help circumscribe the spatial and temporal characteristics of the SWWs migration in the mid-high latitudes of Patagonia during the Late glacial and Holocene (McCulloch *et al*., 2000; Sugden et al., 2005).

## Format of Thesis

This thesis will be organised into seven chapters;

### Chapter One

Presents a general overview of our current understanding of southern hemisphere ocean atmosphere systems and why Patagonia plays a key role for palaeoenvironmental and climatic reconstruction at global, hemispheric and regional levels. It also states the aims and objectives of the thesis.

### Chapter Two

Describes the field sites and methodologies employed in this study. It also describes the techniques used to construct a high-resolution palaeoenvironmental record of each site, including; field coring, palynology, lithostratigraphy, radiocarbon dating and tephrochronology.

### Data Chapters

The three data chapters are represented by a discrete chapter for each study site and are presented in the style of a publication; with an introduction, methods, results, discussion and conclusion for each site. To reduce unnecessary repetition the introductions will set a brief general context with a focused rational of the discrete sites and how the proposed research can help to build a greater understanding of how the climate of each region is influenced by the SWWs. The methods sections will be a concise version of the techniques used at each study site. The main results and discussion section of the thesis will be split over the three sites and contained within the individual chapters, followed by individual conclusions.

#### Chapter Three

Presents the palaeoenvironmental evidence from Cerro Ataud and discusses the climatic inferences for the site with regard to the migration of the SWWs and how this affected the moisture regime of the northerly extents of its migration in this region.

#### Chapter Four

Presents the palaeoenvironmental evidence from Lago Fox and discusses the climatic inferences for the site with regard to the latitudinal migration of the SWWs as they passed through this region on their journey between the northern and southern study sites.

#### Chapter Five

Presents the palaeoenvironmental evidence from Punta Burslem and discusses the climatic inferences for the site with regard to the southerly extent of SWWs poleward migration at this site. It also looks at whether they continued their migration into the Southern Ocean, with implications for CO2 degassing into the atmosphere and ice shelf melting in Antarctica.

### Chapter Six

Provides a synthesis of the palaeoenvironmental results from all three sites and evidence from the literature to present contemporary climatic inferences for each region and to reconstruct the temporal and spatial migration of the SSWs during the Late glacial and Holocene.

### Chapter Seven

Provides a conclusion of this study and how it has increased the knowledge of palaeoenvironmental changes in Patagonia and contributed to the global and interhemispheric global debate.

## Mechanisms for Interhemispheric Climate Change

Debate over the synchroneity of global climate change centres around two main hypotheses; climate change is globally synchronous, or it is hemispherically asynchronous (McCulloch et al., 2000; Blunier and Brook, 2001). During the Last Glacial Maximum (LGM) a combination of ice core records from Greenland with palaeoenvironmental records and glacial chronological evidence from the southern hemisphere suggest that northern and southern hemispheres appeared to have Millennial scale climatic synchrony (Grootes et al., 2001). Glacial chronologies and moraine exposure dates from New Zealand and Chile also suggest that climate change was globally synchronous driven by variations in the atmospheric composition of naturally occurring greenhouse gases such as water vapour in the tropics (Anderson et al., 1999; Denton et al., 1999a; Ivy-Ochs et al., 1999; Moreno et al., 1999).

Contrasting evidence suggests the brief return to cooler temperatures in the southern hemisphere’s Antarctic Cold Reversal (ACR) and Bølling Allerød warm phase in the northern hemisphere occurred concomitantly providing further inference for the interhemispheric link of abrupt climate change (Denton et al., 2010). The driving mechanisms and positive feedback processes linking temperature oscillations in discrete hemispheres generally known as the Bipolar Seesaw suggests that the oceans and atmosphere are key to redistributing heat around the globe (Broecker, 1998; Wang et al., 2015). This theory generally infers that a cooling in one hemisphere leads to warming in the other. As northern and southern hemispheres appeared to experience millennial scale anti-phase shifts in global climate during the LGM and into the Late glacial (Barker et al, 2009) it inferred interhemispheric heat transfer through Thermohaline Circulation.

Greenland and Antarctic ice core records not only show rapidly changing Quaternary climate in terms of Glacials and Interglacials but also show significantly cool stadial and warm interstadial episodes, often centennial in resolution. Records from the Greenland Ice Sheet suggest a number of rapid interstadial episodes that indicate decadal increases in temperature of ~10°C prompting accelerated climatic changes in the northern hemisphere (EPICA Community Members, 2006; Kindler et al., 2014). These periods of abrupt climatic reorganisation in the northern high latitudes are known as Dansgaard-Oeschger (D-O) events and occurred repeatedly during the LGM (Dansgaard et al, 1993; Rasmussen et al., 2014). In contrast, D-O events were not seen in Antarctic ice core records. Climatic changes in the southern hemisphere were gradual and out of phase with the northern hemisphere D-O events and were centennial to millennial compared to decadal in the north (Lemieux et al., 2010).

As northern hemisphere ice sheets advanced in the LGM the increasing albedo effect caused temperatures to drop further, accelerating their growth. The development of these ice sheets led to decreasing eustatic sea levels that enabled ice sheets to advance beyond existing shorelines creating a positive feedback mechanism that augmented the effect of Milankovitch Cycles. The accumulative mass of these ice sheets began to trigger inherent instabilities as increased pressure caused melting of the basal section and destabilisation of the substrates below reducing the frictional force acting on the ice leading to a more rapid advancement (Bond et al., 1993; Broecker, 1994; Hemming, 2004). This binge-purge mechanism of glacial development known as Heinrich Events released substantial amounts of ice rafted detritus into the North Atlantic leading to large scale decreases in salinity that slowed thermohaline circulation (Vidal et al., 1997; Stanford et al., 2011). The weakening of deep-water formation in the North Atlantic, led to the warming of the southern hemisphere through reduced Thermohaline transport of heat from the South Atlantic (Denton et al., 2010). This has been inferred from climate simulation models using the Meteorological Office’s Hadley Centre climate model (HadCM3) which is a global ocean-atmosphere model (Gordon et al., 2000; Vellinga and Wood, 2002).

The warming trend during the Last glacial-interglacial transition (LGIT) was interrupted by a brief but intense return to colder conditions during the Younger Dryas stadial in the northern hemisphere (between c. 12.8-11.8 kcal yr BP) (Rasmussen et al., 2006). As temperatures rose in the LGIT, meltwater from the retreating ice sheets drained into the North Atlantic substantially lowering the salinity of the water leading to a reduction of its density. Meltwater input had the effect of slowing the downwelling of water in the engine room of thermohaline circulation reducing the transport of heat to the north. Deprived of this heat the ice sheets in North America and Northern Europe began to re-advance. The reduced transport of heat to the north led to the warming of the Southern Atlantic and the southern hemisphere during this northern hemisphere stadial. There is tenuous evidence that the Younger Dryas may have been a global phenomenon (Denton and Hendy, 1994; Renssen, 1997; Ivy-Ochs et al., 1999; Andres et al., 2003) however the consensus of scientific opinion now indicates that it was confined to the northern hemisphere as there is limited evidence to suggest that the Younger Dryas extended to the southern hemisphere (Blunier et al., 1997; McCulloch et al., 2000; Barrows et al., 2007).

Antarctic ice core records (Gest et al., 2017) and cosmogenic exposure records in Torres del Paine and the Magallanes region of southern South America (SSA) (García et al., 2012) show the ACR preceded the northern hemispheric Younger Dryas by ~1800 years. However, palaeoenvironmental evidence for the ACR is ambiguous in SSA (Mansilla et al., 2018), with ice core records (JRI, 57°41’S) (Mulvaney et al., 2012) and glacier re-advances in the Magellan Straits generating the bulk of the supporting evidence (McCulloch et al., 2005a). A return to colder and possibly drier conditions during the ACR should have triggered a vegetational response in SSA, however the evidence for this has been unclear (Pedro et al., 2016). The limited palaeoenvironmental evidence creates a gap in our understanding of how the timing of this Antarctic climatic event affected the vegetation of the region.

Thermohaline circulation is also influenced by contrasting landmass extents in the mid-high latitudes of the Earth leading to distinctive climates in the northern and southern hemispheres. Where the Arctic Ocean is surrounded by the northern continents facilitating ice sheet advances and sea ice formation, the dominating feature of the southern mid-high latitudes is the Southern Ocean which isolates Antarctica from distal landmasses allowing the prevailing SWWs almost uninterrupted passage to circumnavigate the continent. The frictional agitation of the surface waters of the Southern Ocean by the SWWs generate the ACC (Lamy *et al.,* 2002; Mayewski et al., 2009). The absence of any landmass barriers allows the SWWs to control the strength of the ACC. The Southern Ocean contains a high amount of respired CO2 at depth and the ACC creates an upwelling of this CO2, degassing it into the atmosphere (Anderson et al., 2009; Turney et al., 2016).

CO2 is an important greenhouse gas and its atmospheric concentration is intrinsically linked to global temperatures (Pearson and Palmer, 2000) with ice core records showing levels of CO2 are greater during interglacials and lower during glacials (Broecker, 1982; Sigman and Boyle, 2000). The oceans can hold around ~50 times as much CO2 as the atmosphere which is readily diffused at the surface regulating atmospheric composition (Raven and Falkowski, 1999). The composition of ocean-atmosphere CO2 is regulated by oceanic biogeochemistry. Phytoplankton help the transfer of atmospheric CO2 into the oceans by photosynthesis and carbon is transported to the ocean floor when they die, where it is respired through decomposition (Turney et al., 2016). Thermohaline circulation facilitates this regulation by distributing CO2 from deep water to the surface or back down again and one of the main areas for this upwelling is around Antarctica where surface currents such as the ACC help to diffuse it into the atmosphere (Marshall and Speer, 2012). Increasing concentrations of atmospheric CO2 lead to augmented global temperatures therefore the SWWs are recognised as a fundamental component of the global atmospheric system (Toggweiler et al*.*, 2006; Rojas et al., 2009; Fletcher and Moreno 2011; Fogwill et al., 2019).

## The Southern Westerly Winds

The prevailing winds or air circulating in areas poleward of the subtropical high-pressure zones in the northern and southern hemispheres generally blow in a westerly direction, giving rise to the name westerly winds. The SWWs are formed when a temperature gradient develops between the warm mid latitudes and the colder polar regions. These polar fronts develop when warm air is forced up and over the cold air creating baroclinic instability leading to a region of low-pressure systems (McCulloch, 2010). The contemporary latitudinal positioning of these polar fronts in the southern hemisphere have a wide range of between ~30-60°S (Garreaud et al., 2009). The core of the SWWs lie ~50°S and this is where the highest precipitation and wind velocities occur (Garreaud et al., 2013), however the SWWs display latitudinal variations over seasonal to glacial cycles.

### Migration of SWWs

During the Austral winter (June-August) decreasing southern hemisphere temperatures cause Antarctic sea ice to expand into the Southern Ocean while Arctic ice retreats in the warmer temperatures of the northern high latitudes. This situation is reversed in the Austral summer (December-February) as colder northern hemisphere temperatures cause Arctic sea ice to advance with a coeval retreat in Antarctica (Williams and Bryan, 2006; Lamy et al., 2010; Garreaud et al., 2013). This interhemispheric seasonal expansion and contraction of sea ice forces a latitudinal shift in the position of the subtropical high-pressure systems and a subsequent migration of the SWWs in the southern hemisphere (Yuan and Martinson, 2000). In Austral winter the SWWs migrate north by ~5° expanding their latitudinal range and weakening the core of the storm tracks as advancing Antarctic sea ice pushes the polar fronts equatorward bringing increased humidity to northern regions of SSA (Schneider et al., 2003; Toggweiler, 2009). In Austral summer the advancing Arctic sea ice and retreating Antarctic sea ice causes the subtropical high systems to push the SWWs south. This has the effect of squeezing the SWWs latitudinal range and increasing the precipitation and intensity of the storm tracks in SSA (Lamy et al., 2010) (Fig.1.1).

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| A close up of a sign  Description automatically generated  Figure 1.1. Southern Hemisphere Climatology (1981-2010)  Wind velocity at 850 hPa (NCEP/NCAR reanalysis) showing a contracting of SWWs and increased wind speeds in Austral summer – June, July and August (JJA) (a) and weakening of SWWs and expanding latitudinal range in winter – December, January and February (DJF) (b) from Bertrand et al., 2014. |

During the colder global temperatures of the LGM the SWWs shifted ~10° north of their present location but as temperatures rose in the Late glacial, they began to migrate poleward (Hulton et al., 2002). This is a recognised trend between the latitudinal positioning of the SWWs and global Quaternary climate where poleward migrations are associated with warmer global temperatures and equatorward migrations during colder phases (Kohfeld et al., 2013). This is supported by recent empirical data over the past 40 years suggesting a current poleward migration as global temperatures continue to rise (Toggweiler, 2009; Thompson et al., 2011). Inter-annual variability in the strength and position of the SWWs is expressed as the Southern Annular Mode (SAM), with a positive mode characterised by a poleward shift and a negative mode an equatorward shift (Abram et al., 2014). Atmospheric variability in the Southern Hemisphere is dominated by the SAM and any change infers a key shift in the hemispheric climate (Marshal, 2003).

This alternating migration is part of another interhemispheric feedback mechanism involving the combination of ocean currents, prevailing wind systems, oceanic biogeochemistry and the atmospheric composition of CO2 all interacting with orbital forcing (Toggweiler et al*.*, 2006). Phases of warmer global temperatures induce a positive SAM with a poleward migration of the SWWs generating a greater upwelling of respired CO2 from deep water by a strengthened ACC as they contract and intensify in the Southern Ocean (Turney et al., 2016). Higher atmospheric concentrations of CO2 augment global temperatures causing a more southerly migration of the SWWs producing more CO2 degassing and additional increases in global temperatures, resulting in raised sea surface temperatures (SST) and a reduction of sea ice around the Antarctic Peninsula (Bentley et al., 2009). A caveat to these rising SST’s is that the immediate effect of upwelling would probably lead to reduced SST’s as colder water is drawn up from the deep Southern Ocean and brought to the surface, lowering the SST (Lovenduski and Gruber, 2005; Sydeman et al., 2014). As global temperatures continue to rise the SST’s will also eventually rise through a lagged temporal response. The melting sea ice produces a surface layer of freshwater due to its lower density that should inhibit diffusion of CO2 into the atmosphere, however the southerly positioning of the SWWs generates an increased ACC that overcomes this barrier. This feedback mechanism also works during colder phases where an equatorward migration weakens the ACC and traps more CO2 in the deep water leading to decreased concentrations of atmospheric CO2 and further cooling. Decreasing global temperatures lead to a more northerly migration of the SWWs and to the advancement of sea ice in the Southern Ocean sealing the surface and further reducing the diffusion of CO2 into the atmosphere.

Research into interhemispheric climate change has prompted extensive palaeoenvironmental and palaeoclimatic studies in the northern hemisphere in recent decades enabling a robust regional chronological record of inferred climate change. In contrast, there has been a relative paucity of research in the southern hemisphere that has hampered our knowledge of the interhemispheric synergy involved in global climate change. Fortunately, this trend is gradually starting to change as the importance of the southern hemisphere in the global ocean atmosphere climate system is being recognised.

## Background

### Patagonia

Patagonia plays a key role in southern hemisphere palaeoenvironmental research as it is the only continental landmass to intersect the entire migratory track of the SWWs and so is an important area to study past changes in their migration and how it effects the timing and nature of climatic changes during the Late glacial and Holocene. Except for Antarctica, Patagonia is the most southerly landmass on earth, defined as the territory located between The Chilean Lake District (CLD) (~37°S) and Cabo de Hornos (Cape Horn) (~56°S) (Rabassa, 2008a). It is flanked by the Pacific and Atlantic oceans and is separated from the Antarctic peninsula by the Drake Passage and the Scotia sea (Fig.1.2). The southerly maritime location means Patagonia is particularly sensitive to latitudinal shifts in the Polar Front that determines the latitudinal position of the SWWs.

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| A close up of a map  Description automatically generated  Figure 1.2. Map of Patagonia, southern South America  Showing study sites; Cerro Ataud, Lago Fox and Punta Burslem |

### Topography

The prominent topographical feature in Patagonia is the Cordillera de los Andes, formed (and still forming) by the eastern Pacific Nazca and Antarctic tectonic plates subducting under the South American plate. This extensive mountain chain is the longest on the planet extending adjacent to the west coast along almost the entire length of South America. In Patagonia the Andean Cordillera follows a north-south trend with diminishing altitude from a mean of ~4000 m in the CLD to less than ~500 m in the Magallanes region (~52°S). It then veers south east into Tierra del Fuego, where altitude again rises in excess of ~2000 m in the Cordillera Darwin.

At these latitudes the Patagonian and Fuegian Andes form a significant barrier to the moisture laden SWWs moving in from the warm south eastern Pacific. This barrier generates a longitudinal precipitation gradientwith the highest levels of humidity on the western flanks of the Andean Cordillera (Fig.1.3). The orographic nature of the precipitation creates a significant rain shadow effect in the lee on the eastern flanks leading to a positive correlation between decreasing humidity and longitude, producing increasingly arid conditions into the Patagonian Steppe (Lenaerts et al., 2014). Due to the steep orographic nature of the Andean barrier, the SWWs are the main factor in controlling precipitation and moisture regimes of Chilean Patagonia (Quintana and Aceituno, 2012).

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| A close up of a map  Description automatically generated  Figure 1.3. Modelled wind and orographic precipitation in Patagonia  a) Correlation model between annual mean 850-hPa zonal wind and precipitation [r(U850, P)], the scale-bar at the bottom is the correlation coefficients; b) Longitudinal profile of terrain elevation (shaded area, scale at left), long-term-mean annual precipitation (black line, scale at left in mm/yr), and the r(U850, P) correlation, averaged between 42°S and 52°S (from Garreaud *et al.,* 2013). |

A swathe of volcanoes lies along the extent of the Andean Cordillera created by the subduction of tectonic plates along the western seaboard of the continent. Patagonia lies within the Austral Volcanic Zone (AVZ) between ~49-55°S and also the Southern Volcanic Zone (SVZ) between ~33-46°S (Fig.1.4). These are active volcanic zones where ~74 volcanoes have shown signs of activity since the LGM (Fontijn et al., 2014). Volcanoes in the AZV are proximal to the convergent plate boundary between the oceanic Antarctic plate and continental South American plate, with the oceanic plate subducting beneath the continental plate at a relatively low convergence velocity of ~2 cm/year (Stern and Kilian, 1996). The AVZ contains both Volcán Reclús and Mount Burney that are pertinent to this study. Two more volcanoes relevant to this study are Volcán Hudson and Volcán Mentolat that are part of the SVZ which is a product of the subduction of the oceanic Nazca plate beneath the continental South American plate at a faster rate of ~7-9 cm/year (Stern, 2004). Tephra deposited from volcanic eruptions can be very useful in building stratigraphical chronologies when reconstructing palaeoenvironmental records. Tephra layers are temporally synchronous as they result from one isolated event; the atmospheric fallout from a discrete volcanic eruption. Each eruption produces pyroclasts with unique geochemistry covering an extensive geographical area so can be used as an isochronous marker horizon throughout the expanse of its fallout area (Haberle & Lumley 1998; Dugmore et al., 2005). This will be discussed in more detail in section 2.6.2.

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| A close up of a map  Description automatically generated  Figure 1.4. Southern and Austral Volcanic Zones in Patagonia  Schematic map of Southern South America and the oceanic plate, modified from (Alemán and Ramos, 2000) |

### Glaciation

Formation of glaciers and ice fields in Patagonia is supported by topography and climate where the Andean Cordillera intersects the migratory track of the SWWs. The combination of high relief and precipitation is able to sustain the current NPI and its larger neighbour the SPI which are the largest ice fields outside of Antarctica and Greenland. It also supports the smaller Cordillera Darwin ice fields of Fuego Patagonia in the south. These climatic conditions support maritime ice sheets and glaciers that have positive mass balance from ample winter snow accumulation at higher altitudes that exceeds the rates of ablation in the summer (Matsuoka and Naruse, 1999). This high turnover of ice makes them susceptible to basal sliding, increasing their sensitivity to small changes in climate (Benn and Evans, 2013). As a result, the regional moisture regimes and precipitation variability in Patagonia is one of the main controlling factors in glacial mass balance (Boex et al., 2013).

By studying past oscillations of ice sheet and glacier coverage, relationships can be seen with the latitudinal positioning of the SWWs. Glacial modelling and palaeoecological evidence suggest the SWWs migrated equatorward by an additional ~5° during the LGM as Antarctic sea ice advanced much further into the Southern Ocean. The influence of the SWWs during the LGM brought sufficient moisture to the northern regions of Patagonia to cause the expansion of glacial mass and sustain one continuous ice-sheet stretching across the axis of the Andean Cordillera from the CLD to Tierra del Fuego (McCulloch et al., 2000; Hulton et al., 2002). Moreover, the coalescing of glaciers into one continuous ice-sheet blocked the drainage system of major river systems towards the Pacific and redirected them east across the continent into the Atlantic (Turner et al., 2005).

The onset of warming temperatures in the Late glacial caused the ice sheet to retreat, which was illustrated by geomorphic, stratigraphic and radiocarbon-based chronologies from northwest Patagonia (Denton et al., 1999b; Moreno et al., 2015). Disintegrating ice led to the collapse of ice-dammed lakes in the central and southern regions that eventually drained into the Pacific along the Rio Baker and Estrecho de Magallanes (Magellan Straits) respectively as the ice sheet separated into the contemporary NPI, SPI and smaller icefield on Cordillera Darwin in the south (Thorndycraft et al., 2019).

## Vegetation

### Present Vegetation

The flora of Patagonia reflects the variable climatic conditions of the region, ranging from warm-temperate in the north to sub-polar in the south. Mesophytic species are found in the CLD with treeless Magellanic moorland in the western archipelago and southern regions where precipitation ranges between ~2000-7000 mm per annum and wind velocity is higher. More verdant species are found as the longitudinal precipitation decreases with evergreen forest in the central inland areas where rainfall is between ~800-4000 mm; while deciduous forest prefers drier conditions of ~400-800 mm.

The present-day vegetation patterns of Patagonia are significantly influenced by the high levels of precipitation delivered by the SWWs. Vegetation composition strongly reflects the trans-Andean precipitation gradient creating a climatic divide with ecotones showing a longitudinal transformation from Magellanic Moorland on the western flanks of the Andean Cordillera through to Mixed Evergreen and Deciduous Forest in the lee of the mountains to Patagonian Steppe on the gentle Atlantic slopes in the east where precipitation is below ~400 mm per annum (McCulloch et al, 2005b; Markgraf and Huber, 2010).

### Ecotones

The vegetation of Patagonia is classified into separate ecotones across the west-east precipitation gradient (Fig.1.5 and 1.6). Each ecotone is defined by the distinct vegetation within its boundaries that are existing within the limits of their ecological distribution. The limiting factors are usually climatic and therefore changing climatic conditions can alter the location of these ecotones at a regional scale, especially at the transition zones where the vegetation community is already at the limit of their distribution, often integrating with other ecotone vegetation and is particularly sensitive to even small changes in moisture or temperature. Here a summary of the main types of ecotone are presented based on several previous studies (Godley, 1960; Pisano, 1977; 1983; Moore, 1979, 1983; Boelcke et al., 1985; Ruthsatz and Villagran, 1991; Tuhkanen et al., 1992; Luebert and Pliscoff, 2006; Kleinebecker et al., 2007; Garcia and Luebert, 2008; Villa-Martínez and Moreno, 2007).

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| A close up of a map  Description automatically generated  Figure 1.5. Magallanes Vegetation Map  Fuego-Patagonia. The principal vegetation zones and isohyets are from Tuhkanen et al., (1989–1990) modified with vegetation mapping by Pisano (1994). Palaeoecological sites mentioned in the text are: ① Lago Fox; ② Rio Grande; ③ Estancia Esmeralda; ④ Punta Burslem; ⑤ Caleta Eugenia; ⑥ Punta Yartou; ⑦ Lago Lynch; ⑧ Puerto del Hambre |

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| A close up of a map  Description automatically generated  Figure 1.6. Aysén Vegetation Map  Aysén Region of northern Chilean Patagonia. Simplified vegetation map (modified after Luebert and Pliscoff, 2006; Manzini et al., 2008; Vandekerkhove et al., 2016) indicating Northern Patagonian Icefield (NPI), main volcanoes and towns. The Southern Volcanic Zone (SVZ) is indicated in the inset map. Palaeoecological sites mentioned in the text are: ① Cerro Ataud; ② Lago Edita; ③ Lago Augusta; ④ La Frontera; ⑤ Mallín Pollux |

#### Magellanic Moorland

This is located in the extreme western and southern regions of Patagonia on the Pacific coast and archipelagos (~47-56°S). It has an oceanic climate with high precipitation (~2000-6000 mm/yr) from the saturated SWWs first landfall from the Pacific Ocean with low temperatures (5-6°C) and little difference between moderately cold winters and cool summers. It is a mainly treeless environment although some trees and conifers can colonise in sheltered areas such as *Nothofagus betuides*, *Drimys winteri* and *Pilgerodendron uviferum* (Cupressaceae) with *Podocarpus nubigena* and *Lepidothamnus fonkii* in lower latitudes. High winds and precipitation generally restrict this ecotone to sparse populations of dwarf shrub such as *Empetrum rubrum* and *Embothrium coccineum* with *Berberis ilicifolia* in better drained areas between heathland & evergreen forest.

However, this ecotone is dominated by bog communities (blanket peat and cushion bog) with species such as; *Sphagnum magellanicum, Astelia pumila, Donata fascicularis, Bolax caspitosa, Drapetes muscosus, Caltha dioneifolia, Caltha appediculata* (Ranunculaceae) with *Oreobolus obtusangulus, Tetroncium magellanicum* in lower latitudes (Figure 1.7). Some heathland can be associated with grassland communities such as; *Acaena pumila, Drosera uniflora, Prezia magellanica, Myrteola nummularia*.

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| A close up of a flower garden  Description automatically generated  Figure 1.7. Magellanic Moorland (© C.A.Mansilla) |

#### Evergreen Forest

This is located with diminishing longitude along the precipitation gradient from Magellanic Moorland where precipitation is lower but still ranges between ~1500-4500 mm/yr with relatively cool temperatures. This ecotone is almost completely dominated by *Nothofagus betuloides* forest with some *Nothofagus antarctica* dominating proximal to ice margins in higher latitudes. Forests in Central Patagonia are also primarily colonised by *Nothofagus betuloides* and *Nothofagus nitida* with *Pilgerodendron uviferum* in more waterlogged areas. These forest communities generally have a dense layer of bryophytes and ferns in their understory but towards the drier extremities of this zone species including *Drimys winteri, Maytenus magellanica* and *Embothrium coccineum* can prevail. The composition of the forest begins to change in these less humid conditions with a mixed evergreen and deciduous mosaic where *Nothofagus pumelo* is now more dominant. The shrub and herb layer also become modified with *Empetrum rubrum, Gunnera magellanica, Berberis icicifloria*, and *Seneco acanthiflius* forming part of the understory, especially in the more open canopy.

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| A group of giraffe standing on top of a lush green forest  Description automatically generated  Figure 1.8. Evergreen Forest (©Jim Blaikie) |

#### Deciduous Forest

This is found further along the precipitation gradient on the eastern flanks of the Andean Cordillera between the Evergreen Forests and Patagonian Steppe. Levels of precipitation in this ecotone have dropped to ~400-800 mm/yr (up to an altitude of 500 m) and temperatures are still relatively cool. There is a lower diversity in these deciduous *Nothofagus* forests with an almost exclusive dominance of *Nothofagus pumelo* that intermingles with *Nothofagus antarctica* in less humid areas in the south and *Nothofagus betuloides* further north to form a mosaic with evergreen forests. The species poor understory in these areas include the shrub taxa *Berberis iliciflolica* and herb taxa *Ribes magellanicus* (Saxifragaceae). The hemi-parasite *Misodendrom spp* is found in the more mesic areas of this ecotone, taking advantage of stressing factors that open up the forest canopy. In these more open areas Poaceae is also prevalent with shrubs such as *Gunnera magellanica, Berberis buxifolia* (Berberiaceae), *Senecio acanthifolius, Rubus geoides, Acanea ovalifolia* and at the forest margins *Chiliotrichum diffusum* (Asteracea, subfamily Asteroideae) and *Pernettya mucronate* are also prevalent.

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| A tree in a forest  Description automatically generated  Figure 1.9. Deciduous Forest (©Jim Blaikie) |

Heathland is also common in this ecotone with *Sphagnum magellanicum* and *Marsippospermum grandiflorum* bogs frequently seen where there is sufficient water available. Where the surface of these *Sphagnum* bogs has partially dried out *Empetrum rubrum* is commonly found on the hummocks. At increased altitude in more open areas the free draining soils allow a greater diversity within the bog communities where *Empetrum rubrum* merge with *Bolax gummifera, Myrteola nummularia, Pernetta pumila* and *Lycopodium magellanicum*.

#### Steppe

This ecotone is found on the margins of the precipitation gradient distal from the Andean Cordillera. These are generally flat and low-lying areas located in Tierra del Fuego, east and south eastern Chile and most of Argentine Patagonia. These regions are characterised by low humidity (~200-500 mm/yr) with strong winds and warmer temperatures. This is generally an arid scrubland where vegetation needs adaptive strategies for water retention to survive in such a dry environment. Although dominated by grassland species of the Poaceae family including; *Festuca gracillima, F. magellanica* and *F. pyrogea* with *Stipa brevipes* prevalent in central Patagonia, the Steppe ecotone is relatively diverse.

Grassland species in scrubland close to the margins of the deciduous forests are associated with shrub taxa including *Chiliotrichum diffusum*, with *Mulinum spinosum* and *Acaena Splendens* more prevalent in lower latitudes. Herb taxa within these areas include; *Galium fuegianum* (Rubiaceae), *Acaena ovalifolia* (Roseceae), *Acaena chilensis, Anemone multifida* (Ranunculaceae), *Calceolaria* (Calceolariaceae), *Aster vahlii* (Asteracea, Asteroideae), *Cerastium arvence* (Cariophyllaceae), *Gentianella magellanica* (Gentianaceae).

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| A view of a large mountain in the background  Description automatically generated  Figure 1.10. Patagonian Steppe (©Jim Blaikie) |

In more xeric conditions (~200 mm/yr) the grassland species are associated with; *Acaena poeppigiana, A. platyacantha, A. pinnatifica, Galium fuegianum* (Rubiaceae), *Nassauvia spp* (Asteraceae, Subfamily Mutisioideae), *Azorella caespitose* (Araliaceae), *Leucheria spp* (Asteraceae, Subfamily Mutisioideae), *Baccharis magellanicum* (Asteracea, Asteroideae), and *Taraxacum gilliesi* (Asteraceae, Subfamily Cichorieae).

On coastal scrubland Poaceae is combined with Acaena *pinnatifida, Berberis empetrifolia* & *Oxalis enneaphylla*. Heathland is occasionally found in this ecotone on shallow free draining acid soils characterised by *Empetrum rubrum, Baccharis magellanica* and *Azorella caespitose*.

#### High Andean Vegetation

This is a sparsely vegetated community above the arboreal limit of ~900-1000 m in central regions and ~500-600 m in higher latitudes. This is a harsh environment for vegetation that have to adapt to higher wind speeds, lower temperatures, the nature of the substrate and availability of water. In southern regions some dwarf arboreal growth is occasionally seen with *Nothofagus pumelo* and *Nothofagus antarctica* present in Tierra del Fuego. In lower latitudes Andean vegetation is dominated by herbs from the Poaceae, Apiaceae, Cyperaceae and Asteraceae families, with some dwarf shrub taxa such as *Empetrum rubrum*. At this altitude and latitude arboreal growth is not common with only very occasional instances of *Nothofagus antarctica* seen.

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| A picture containing mountain, outdoor, grass, nature  Description automatically generated  Figure 1.11. High Andean Vegetation and timberline (©Jim Blaikie) |

### Past Vegetation

The rapid retreat of ice is ideal for studying environmental change in the mid-high latitudes as the sensitivity of these maritime glaciers to climate change can provide a record of transformation during the Late glacial and Holocene and can be tracked by studying the vegetation response to their retreat (McCulloch et al, 2005b).

There are relatively few continuous and high resolution palaeoenvironmental records encompassing the vegetational response to post glacial climate change in southern Patagonia during the Late glacial and Holocene, and significantly less in central Patagonia. Of these, many indicate a similar pattern of rapid colonisation of deglaciated landscapes east of the Andean Cordillera. The pollen records indicate an open and treeless environment during deglaciation, dominated by several pioneer species such as *Gunnera, Acaena,* Asteraceae, *Empetrum* heathland and expansion of grassland species. This is followed by slowly developing arboreal taxa such as *Nothofagus*, developing into open canopy forest by the Early to Mid-Holocene and eventually out competing grassland species as the forest became fully established thereafter (Heusser, 1995; McCulloch and Davies, 2001; Huber et al., 2004; Markgraf et al., 2007; Mancini, 2009; Moreno et al., 2009, 2010; Borromei et al., 2010; Markgraf and Huber, 2010; Ponce et al., 2011; Villa-Martínez et al., 2012; Mansilla et al., 2016, 2018; Moreno et al., 2019). These authors interpret this vegetation succession as a response to changing moisture regimes from cold and relatively dry climate in the Late glacial which was unsuitable for arboreal colonisation, into the warmer and more humid Holocene which was ideal for forest development.

An association can be made between the proportion of arboreal pollen and the landscape ecology with ~20% of Total Land Pollen (TLP) characteristic of the Forest/Steppe ecotone. As it reaches ~40% it is representative of open canopy forest, with > 63% symbolic of closed forest (Trivi and Burry, 2006; Burry et al., 2006). Palaeoenvironmental records from southern and central Patagonia indicate the establishment of *Nothofagus* forest (~20% TLP) occurred at; Lago Augusta (47°05’ S, 72°23’ W) around c. 13.2 kcal yr BP (Villa-Martínez et al., 2012), Lago Edita (47°8’ S, 72°25’ W) around c. 13 kcal yr BP (Henríquez et al., 2017), Lago Lynch (53°51’ S, 69°26’ W) around 12.7 kcal yr BP (Mansilla et al., 2018), Rio Grande (53°39’ S, 70°30’ W) around c. 12.5 kcal yr BP (Mansilla, 2015), Punta Yartou (53°51’ S, 70°08’ W) around c. 12.5 kcal yr BP (Mansilla et al., 2016), Puerto del Hambre (53°36’ S, 70°55’ W) around c. 11.7 kcal yr BP (McCulloch and Davies, 2001), Ushuaia II (54°47’ S, 68°18’ W) around c. 11.5 kcal yr BP (Heusser, 1998), Puerto Harberton (54°53’ S, 72°25’ W) around c. 11 kcal yr BP (Markgraf and Huber, 2010) and in the drier areas; Caleta Eugenia (54°55’ S, 67°20’ W) around c. 10.5 kcal yr BP (McCulloch et al., 2019), Mallín Pollux (45°41’ S, 71°50’ W) around 10 kcal yr BP (Markgraf et al., 2007) and Estancia Esmeralda (53°30’ S, 70°35’ W) around 8.5 kcal yr BP (McCulloch and Davies, 2001).

The Evergreen and Deciduous forests of Patagonia represent the southernmost forest ecosystem on the planet. As this region was one of the last areas of the world to be peopled, these forests have possibly gone without anthropogenic interference until recently making them ideal for studying their natural response to climate change (Fesq-Martin et al., 2004).

### *Nothofagus*

*Nothofagus* has been the dominant vegetation throughout central and southern Patagonia during the Quaternary and remains a key species fundamentally linked to the moisture regimes of the region (Mansilla et al., 2016;2018). It is thought to have survived in numerous refugia during the LGM allowing colonisation of post glacial landscapes in the Late glacial and Holocene (Markgraf, 1993; Markgraf and Huber, 2010; Premoli et al., 2010). This arboreal taxon is a key marker for identifying climatic changes in Patagonia so is of particular interest when reconstructing past vegetation from the fossil pollen record. It is particularly sensitive to humidity and can flourish in climates that exhibit a precipitation range of ~400-1000 mm/yr (Quintanilla, 2005).

### Pollen Analysis

Just as the vegetation reflects current climatic conditions, it most likely responded and adapted to palaeoclimatic changes, therefore reconstructing palaeoecological distribution of Patagonian flora could infer changing palaeoclimatic conditions. To reconstruct the Late glacial and Holocene environments of this region the project will produce records of vegetation change using pollen analysis (Palynology) from the selected peat sites. Pollen analysis is regarded as arguably the most versatile and widely used technique in reconstructing Quaternary environments due to the spatial nature of the data and the temporal continuity in the records. Using pollen grains preserved in peat bogs and lacustrine sediments enables a picture of palaeoenvironmental change to be constructed (Fægri et al., 1989). In this study approximately 200,000 pollen grains and spores (approx. 60 species) were visually identified from 260 samples taken from 26 m of peat cores to reconstruct the vegetation change in the Late glacial – Holocene environment.

## Aims and Objectives

### Track the Migration of SWWs since LGM to Present

Variations in the intensity and latitudinal position of the SWWs have been invoked as key drivers of climate change in the southern hemisphere and as part of the larger bipolar seesaw mechanism of global climate change (Broecker, 1998; Toggweiler et al*.*, 2006; Wang et al., 2015; Fogwill et al., 2019). Their seasonal shifts create varying climatic patterns with increased storm activity in southern Patagonia during the Austral summer as the core of the SWWs converge on its annual meridional migration, with less turbulent winters as the SWWs migrate equatorward (Schneider et al., 2003; Toggweiler, 2009; Lamy et al., 2010). There have been several studies on the migratory shifts in the SWWs and their influence on palaeoclimate (McCulloch et al., 2000; McCulloch and Davies, 2001; Haberle and Bennett, 2004; Moreno et al., 2009; Sepúlveda et al., 2009) contributing to the hypothesis that the SWWs migrated north by an additional ~5° during the LGM leading to expansion and coalescing of ice-sheets and glaciers into one continuous ice-sheet (Hulton et al., 2002). It has also been suggested they were influential in the internal feedback mechanism that contributed to the last glacial termination on their poleward migration, considering their effect on the ventilation of CO2 from the deep waters in the Southern Ocean influencing global ocean-atmosphere systems and global temperatures (Toggweiler et al*.*, 2006; Turney et al., 2016; Fogwill et al, 2019).

Yet, not all palaeoenvironmental research is in agreement with these hypotheses. The relative paucity of research in the central Patagonian region makes the northerly extent of the SWWs migration largely uncertain with some suggesting a more northerly position of the SWWs during the Holocene (Markgraf et al., 2003; Villa-Martínez and Moreno, 2007). Another scenario is that the SWWs did not migrate poleward at all but merely weakened (Moreno et al., 2010; Fletcher and Moreno, 2011).

It is therefore important to build on such research to improve our understanding of the spatial and temporal migration of the SWWs during the Late glacial-Holocene and how it shaped palaeoclimate in the southern hemisphere and the subsequent implications for global climate change. This study hopes to increase our understanding by providing palaeoenvironmental evidence of the vegetational response to the shifting moisture regimes and precipitation gradients created by the migrating SWWs. It is important to note that past migrations of the SWWs would be difficult to reconstruct using the records from only one site. Therefore, three deep basin peat-sediment cores taken from an extensive latitudinal transect (~47-55°S) on the eastern flanks of the Andean Cordillera will help to circumscribe the spatial and temporal shifts in the SWWs by reconstructing the latitudinal changes in the vegetation response to these migrating fronts. The study sites are all selected at the western (wetter) end of the precipitation gradient, proximal to the eastern flanks of the Andean Cordillera for consistency, making them less sensitive to small changes in humidity and therefore will be more robust in testing the intensity of the SWWs at different latitudes. By using additional study sites from the drier regions of the precipitation gradient the relationship between the strength and latitudinal position of the SWWs and the orographic precipitation gradient can also be analysed. Peat bogs were selected over lake sites mainly as peatlands not only reflect a regional pattern of palaeoenvironmental change but also capture local changes from the bog surface.

### Track the migration of SWWs to Southernmost Extent

This study will also circumscribe the southerly extent of the SWWs poleward migration in the Holocene by coring one of the most southerly accessible peat bogs in the southern hemisphere on Isla Navarino, south of the Beagle Channel (~55°S). An integrated palaeoenvironmental approach using palynological analysis constrained by radiocarbon dating and tephrochronology will establish a climatic record for this region indicating whether the core of the SWWs reached these latitudes or continued past into the Southern Ocean. There is increasing evidence that current global warming is driving a sustained phase of positive SAM (Toggweiler, 2009) but contemporary records are short, so it is important to reconstruct and understand the likely regional impacts of a sustained poleward shift of the SWWs. If the core migrated into the Southern Ocean, this could suggest possible increased sea surface temperatures (SST) influencing ice shelves on the Antarctic Peninsula (Bentley et al., 2009). SWWs encroaching into the Southern Ocean could also augment CO2 venting into the atmosphere with implications for global temperatures and could reflect possible future global warming scenarios.

# Methodology

This chapter will outline the site selection process and methodologies used to provide palaeoenvironmental information in this study. Three cores obtained from peat mires over a north-south transect of ~950 km (~8**°** of latitude) were used to construct a high-resolution pollen and charcoal record depicting environmental and climatic change during the Late glacial and Holocene; with specific attention to tracking the southerly migration of the SWW’s.

## Site Selection

All three sites are located within the latitudinal migratory range of the SWWs allowing the migration to be spatially and temporally tracked on a north-south transect from 47°S to 55°S during the Late glacial and Holocene. Peat bogs were chosen over lakes as they could provide local and regional palaeoenvironmental information and the sites were all selected for their proximal location to the orographic barrier of the Andean Cordillera, placing them in the more humid part of the precipitation gradient for continuity. The wide latitudinal spread of the sites will also define the northern response to the SWWs and their southerly extent. The specific locations were identified as locations where it was more likely to find deep peat sites to provide high resolution records. The palaeovegetation records from these closed deep basin sites will not only provide site-specific and regional palaeoenvironmental records but will focus on the latitudinal shifts (c. 8°) from the relatively warm northern climate of the Aysén region to that of the sub-polar environment of the Magallanes province in the south and to the southernmost extents of landmass on Isla Navarino. The palaeoenvironmental data from the three cores will circumscribe the timing and extent of the shifting focus of precipitation during the Late glacial and Holocene at sub-centennial scale and how far south the core of the SWWs migrated during this period.

Additional sites were cored; one in Aysén (Rio Lincol), one on Isla Dawson (Lago Fox I) and two on Isla Navarino (Pantalon and Cerro Bandera), all of which were discounted from this project (Appendix D). Rio Lincol was unlikely to have Late glacial stratigraphy, Lago Fox I did not contain a visual Reclús tephra layer, the basal layer of Pantalon was dated at 9800 ± 30 14C yrs BP and would not have met the Late glacial – Holocene criteria for the project and the Cerro Bandera core was unconsolidated with gloopy Sphagnum which could not have been analysed.

### Cerro Ataud

The study site is a fen peat bog located southwest of Cochrane in the Aysén Region of Patagonia (47°17’53.2” S 72°39’18.6’ W, altitude 348 m asl) (Fig.1.2). The bog is situated in a kettle hole northwest of Lago Esmeralda on the western flanks of Cerro Ataud (876 m). It is a pear-shaped basin (~270 x 175 m) situated on an old lake terrace (2 km x 350 m) formed by an ice-dammed lake during the LGM (Turner et al., 2005) (Fig.2.1). A 582 cm core was sampled to an impenetrable base. There is a transition between 560-552 cm between bluish-grey clays and silts to the base and overlying organic sediments. The present-day bog was partially flooded, covered mostly by Cyperaceae in the shallow water with sporadic stands of deciduous *Nothofagus antarctica* trying to colonise the drier parts of the surface (Fig.2.2). The margins were characterised by dry scrubland slopes colonised by deciduous *Nothofagus antarctica*, almost certainly post fire regeneration. Much of the surrounding slopes consisted of exposed cobbles and gravels from the lake terrace and glacial till from an ice marginal moraine that formed the southern rim of the bog (Turner et al., 2005) and these areas supported tussock grasses, *Acaena*, Saxifrages and Asters. The only patches of soil on the slopes was held together by *Empetrum*, creating their own moisture retention. Mean annual precipitation for the Cochrane area is 805 mm and temperature is 7.6 °C (Tomé et al., 2007).

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| A large mountain in the background  Description automatically generated  Figure 2.1. Cerro Ataud fen bog showing core location (© R.D. McCulloch) |

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| A close up of a lush green field  Description automatically generated  Figure 2.2. Surface of Cerro Ataud fen bog partially flooded and colonised by Cyperaceae  (© R.D. McCulloch) |

### Lago Fox

Isla Dawson lies in the south-central section of the marine flooded glacial trough that forms the Straits of Magellan (Fig.1.2). The west coast of Isla Dawson is flanked by Paso del Hambre and the east coast by Canal Whiteside. The northern tip of Isla Dawson is a low altitude peninsula which rises southward to ~110 m asl. The peninsula preserves many glacial landforms associated with the retreat of the Magellan glaciers after the LGM in the form of moraines, palaeo-meltwater channels and kettle holes now occupied by lakes and bogs (McCulloch and Bentley, 1998; Bentley et al., 2005).

Lago Fox is an ombrotrophic mire on Isla Dawson, 200 m south west of Lago Fox (53°52’06.5” S, 70°26’47.5” W, altitude 52 m asl). The mire is oval shaped (~320 x 150 m) and was surveyed to determine the deepest point (Fig.2.3). A 950 cm core was sampled to an impenetrable base. There is a sharp contact at 936 cm between bluish-grey clays and silts to the base and overlying organic sediments. The eastern flank of the bog has steep relief colonised by *Nothofagus betuloides* forest with low gentle slopes surrounding the remaining perimeter (Fig.2.4). The present-day mire is characterized by a hummocky surface with pools of standing water. The wet peat bog surface vegetation is dominated by *Sphagnum magellanicum* (Sphagnaceae) and some moorland species are present, such as *Astelia pumila* (Asteliaceae), *Donatia fascicularis* (Stylidiaceae) and *Drosera uniflora* (Droseraceae). *Empetrum rubrum* (Ericaceae) is also dominant along with sedges such as Cyperaceae increasing towards the periphery. Dead stands of *Nothofagus* are found in the wetter margins of the bog.

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| A path with trees on the side of a mountain  Description automatically generated  Figure 2.3. Lago Fox bog showing core location (© J. Blaikie) |

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| A close up of a dry grass field  Description automatically generated  Figure 2.4. Hummocky surface of Lago Fox bog dominated by *Sphagnum* and *Empetrum*  (© J. Blaikie) |

### Punta Burslem

Isla Navarino is located south of the Canal Beagle (~55°S) with only Cape Horn (Cabo de Hornos) and the Drake Passage separating it from Antarctica (Fig.1.2). It is one of the largest islands in the Tierra del Fuego archipelago, the largest of which, Isla Grande de Tierra del Fuego lies directly to the north of the Canal Beagle, a marine flooded ice-scoured trough formed from glacial abrasion from the proximal Cordillera Darwin (Rabassa et al.,2000). The study site is an ombrotrophic bog located near Pta Burslem on the northern coastline (54°54’05.62” S, 67°57’11.39” W, altitude 54 m asl) approximately 25 km west of Puerto Williams (Fig.2.5). The bog was probably formed as a kettle hole at the end of the LGM and is bounded within an oval shaped basin (~230 x 160 m) with the enclosed character suggesting it will be sensitive to changes in precipitation. The mire was surveyed to determine the deepest point and an 1100 cm core was sampled to an impenetrable base. The surface of the bog is characterised by a complex of hummocks that are mostly covered with *Empetrum rubrum* and *Gaultheria microphylla* and hollows mostly filled with pools of water and *Sphagnum* moss (Fig.2.6). The southern rim of the bog has steep relief with gentler slopes around the remaining edges mostly colonised by *Nothofagus antarctica* with *Chilliotrichum spp* shrubs colonising the margins of the bog. Open canopy *Nothofagus pumilio* forest surrounds the basin with a profusion of the hemi-parasite *Misodendrum* and a scattering of *Ribes magellanicum* and *Berberis microphylla* in the more open spaces.

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| A sign on a grassy field  Description automatically generated  Figure 2.5. Punta Burslem bog showing core location (© J. Blaikie) |

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| A river running through a field of grass  Description automatically generated  Figure 2.6. Surface of Pta Burslem dominated by *Empetrum* and *Sphagnum*  Characterised by a complex of hummocks and pools of standing water (© J. Blaikie). |

## Field Sampling

The cores were sampled from each site using a 50cm long, 5cm diameter Russian corer (Jowsey, 1966). This provided sufficient sample size for pollen analysis, 14C dating and Loss On Ignition (LOI) but was also light enough for two people to transport in the field over great distance with extension poles sufficient for coring up to a depth of 10.5 m. Logistics prevented extensive mapping of each bog therefore a rudimentary 10 point x-y transect was employed, using a gouge, to estimate the location of the deepest point; from where the core was retrieved. To obtain a stratigraphically intact and continuous record, two boreholes (15 cm apart) were used alternately to retrieve consecutive core sections (Fig.2.7). Gross stratigraphy of each core was documented in situ, recording the characteristics of the sediment and any visible tephra layers. They were labelled and placed in clean plastic guttering to protect its physical integrity and sealed in lay-flat tubing to prevent moisture loss. Samples were then shipped back to The University of Stirling and stored at a constant 4**°**C pending lab analysis.

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| A picture containing bicycle, grass, sitting, brown  Description automatically generated  Figure 2.7. Core section from Cerro Ataud  Showing organic sediments in sharp contact with basal clays |

## Pollen Analysis

Pollen analysis is regarded as arguably the most versatile and widely used technique in reconstructing Quaternary environments due to the spatial nature of the data and the temporal continuity in the records (Bennett and Willis, 2001). Using fossilised pollen grains preserved in peat bogs and lacustrine sediments enables a picture of palaeoenvironmental change to be constructed. Ombrotrophic mires are excellent archives of palaeoclimatic and palaeoenvironmental change as they are hydrologically isolated from their surroundings and receive water and nutrients purely from precipitation. The exclusive relationship with the atmosphere allows efficient capture of atmospheric particles such as pollen, tephra and dust with the anoxic conditions ensuring the slow decay of vegetation allowing pollen to be preserved for identification. The principles of pollen analysis assume there is an explicable association between this preserved pollen and the surrounding vegetation communities that produced it (Birks and Birks, 2000). However, the interpretation of the pollen assemblage has to be taken with a degree of caution as not all plant species produce the same amount of pollen. This could lead to some high producing species being over-represented and low producers being under-represented. *Nothofagus* is a monoecious genus producing both male and female flowers at different times as a generative strategy to produce more pollen grains. These grains can be transported large distances from its source and therefore *Nothofagus* can be over-represented in pollen diagrams.

Cores from peat bogs reflect the vegetation response at a regional scale and provide an insight into vegetation history and dramatic transformation during periods of climatic change. They also reflect vegetation response at a local scale which can relate to species composition from the bog surface (Seppä, 2007).

### Preparation

The aim of pollen preparation is to produce a sample that is as clean as practically possible to ease visual identification and counting of individual pollen grains. In order to achieve this, the removal of excess organic and mineral matter is required through a series of laboratory techniques, leaving a relatively high concentration of pollen and spores. The procedures used in this study are a modified version of the industry standard techniques (Moore *et al*. 1991).

Cores were removed from protective covering and the exposed uppermost layer cleaned to eliminate any possible contamination that may have occurred during the coring process in the field. Samples were initially taken at intervals of 32 cm throughout the whole core and subsequently at a reduced increment (2-16 cm) in key areas to achieve higher resolution. 1cm3 samples were taken from each defined depth for preparation and analysis.

Each 1cm3 sample was measured by displacement in 3ml of Hydrochloric acid 10% v/v (HCL 10%) and this also removed calcium carbonates (CaCO3) from the sample. To then remove the humic acids and disaggregate the material, the centrifuge tubes were filled with Sodium Hydroxide 10% v/v (NaOH 10%) and placed in a boiling water bath for 20-30 minutes.

To remove any course debris or mineral sediment remaining within the samples they were passed through a 180μm sieve to physically separate course debris greater in size than the largest pollen grain. Fine mineral sediments, smaller than the smallest pollen grain such as clays and fine silts, were removed by passing through a 10μm nylon sieve mesh. The retained residue on the mesh now contained the pollen and other material >10m and <180m. If the samples were glacial or lake sediments (high silica content) the mesh residues can still contain significant minerogenic content and these samples were treated with Hydrofluoric Acid 40% SLR (HF 40%)

Acetolysis was used to hydrolyse the cellulose content within the samples. The Acetolysis solution contains Sulphuric acid concentrate >98% SLR (H2SO4 98%) which reacts fiercely with water therefore dehydration is required prior to mixing. This is achieved by adding 4ml of Acetic acid Glacial >99% SLR (CH3CO2H 99%) and centrifuge at 3000rpm. The Acetolysis solution, which contains 9 parts Acetic anhydride acid >97% SLR to 1-part H2SO4 98% is added and centrifuge tubes placed in a boiling water bath for 3-4 minutes.

To prepare samples for storage in silicone oil they are firstly dehydrated by adding 2ml of Tert-Butyl Alcohol (TBA) >99% SLR, stirred and centrifuged.

### Identification

An Olympus BX41 light microscope at x400 magnification was used to identify and count the pollen grains. A minimum of 300 pollen grains were counted per sample excluding aquatics, spores and Cyperaceae. The omission of these taxa from peat mire records is to facilitate the interpretation of the pollen diagram, which can be problematic due to the over representation of mire taxa. This is not an issue in *Sphagnum* dominated mires as these spores will be omitted from the pollen sum, however it can be problematic with non-bryophyte mire taxa such as Cyperaceae that can dominate the local pollen signal and so are often omitted from the pollen sum (Chambers et al., 2011). Lake sites have no local pollen signal so are dominated by the regional pollen which can often misrepresent the true nature of the landscape around the mire, especially if these taxa produce disproportionate amounts of pollen such as *Nothofagus* (Section 2.3). Based on palaeoenvironmental evidence from several lake sites in the Aysén region of Patagonia that showed *Nothofagus* overwhelming the pollen signal in the record (Villa-Martinez et al 2012; Henríquez et al., 2017; Moreno et al., 2019) and the ephemeral nature of standing water at the Cerro Ataud site it was decided to include Cyperaceae in the pollen sum to boost the local pollen signal. The identification of pollen grains and spores was supported by a pollen reference collection (McCulloch, 1994) and supplemented by microphotographs (Heusser, 1971; Villagrán, 1980; Wingenroth and Heusser, 1984; Moore et al., 1991).

Another limitation of pollen analysis is realised when identifying *Nothofagus* to species level. It is hampered by the morphological similarities between the pollen grains of the species, preventing their identification and palaeoenvironmental interpretation (Moore et al., 1991; Fontana and Bennett., 2012). In Patagonia there are up to ten different species of *Nothofagus* that flourish in varying climates and environments and if identified could be used to infer the climate of the region. However only two types can be reliably identified though light microscopy; *Nothofagus dombeyi* (representing; *N. dombeyi, N. antarctica, N. betuloides, N. pumelo, N. alessandri and N. leonii*) and *Nothofagus* *obliqua* (representing; *N. obliqua, N. alpine, and N. glauca*) (McCulloch, 1994). Although a disadvantage, these two types prosper in differing climates; *N. dombeyi* in cooler, humid conditions with *N. obliqua* in warmer drier conditions and so are still key markers in palaeoenvironmental reconstruction.

The pollen percentage data was divided into Local Pollen Assemblage Zones (LPAZ) based on major changes in Land Pollen and constrained by cluster analysis on Total Land Pollen (TLP) >2% (Grimm, 1987). The pollen results are presented using Tilia and Tilia-Graph software version 2.6.1 (Grimm, 2011). A problem with representing pollen in percentage form is that individual taxa are interdependent, meaning a rise in one species will lead to the suppression of another. This can exhibit significant variations in the pollen diagram that do not necessarily represent ecological variations. One way to overcome this is to also represent the changing pollen concentration.

### Concentration

Pollen concentration diagrams are based on variations in the number of pollen grains per unit volume of sediment which is estimated by adding a known quantity of *Lycopodium clavatum* to each sample during the preparation process (Stockmarr, 1971). The concentration values (No. grains cm-3) and sediment accumulation (cmyr-1) were used to calculate the pollen and charcoal accumulation rate (influx: No. grains or particles cm-2yr-1) to compliment the percentage pollen diagrams.

### Preservation

The physical condition of fossil pollen within the sediment was assessed as a further indicator of the environmental conditions in which it was deposited. Normal pollen grains are well-preserved in acidic and anaerobic conditions such as waterlogged mires and are physically undamaged. Corroded pollen grains have perforations and degraded pollen grains have noticeably altered exines suggesting degrees of chemical deterioration and microbial digestion which indicate a drier aerobic environment at the mire surface. Broken pollen grains have one or more ruptures in their exines, and crumpled pollen grains are folded or twisted suggesting mechanical damage, most probably due to abrasion during the transportation process from plant to sediment. Each land pollen grain was placed into one of five hierarchical preservation categories; normal, broken, crumpled, corroded and degraded (Berglund and Ralska-Jasiewiczowa, 1986; Tipping, 1987; Mansilla et al., 2018) (Fig.2.8).

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| A picture containing bird  Description automatically generated  Figure 2.8. The five categories of preservation for pollen grains  The grains shown are *Nothofagus dombeyi* type photographed at x400 magnification. A) shows normal pollen grains, B) shows pollen grains that have been subjected to mechanical damage and C) shows pollen grains that have succumbed to biochemical deterioration |

## Charcoal Content

Particulate charcoal found within the sediment is produced by the incomplete combustion of organic material and is evidence of fire activity produced by natural sources including lightning strikes, or anthropogenic means (Patterson et al., 1987). Post fire dispersal of particulate charcoal is deposited in lakes and peat bogs and is preserved as a fossilised record that can be analysed to reconstruct a chronology of fire history (Conedera et al., 2009). This approach has been employed since the pioneering work by Iversen (1941) and remains a powerful proxy for past fire activity that can infer increasing temperatures and drier environmental conditions that led to increased frequency of forest or grassland fire activity at the study site.

Charcoal particles are generally black and opaque with an angular and elongate shape but have variable morphology (Scott, 2010). Their size can be used to infer dispersal distance from the fire source with larger (heavier) particles likely to have originated from a proximal source. Smaller (lighter) particles may have been windborne and travelled a greater distance from its source and can therefore reflect regional fire activity (Blackford, 2000). Particles from 10-200 μm are classed as microcharcoal and >200 μm is macrocharcoal (Clark et al., 1998). During the preparation process for pollen analysis, sediment samples are sieved to segregate larger and smaller particles therefore only charcoal particles between 10-180 μm were counted alongside the pollen and spores on the microscope slides as an indicator of past fire activity. This prevents any firm inferences about the proximity of fire, however reliable palaeofire records require contiguous sampling and most palynological microcharcoal analysis cannot fulfil this requirement due to intense laboratory time limitations. Sampling at > ~30 years can leave gaps that make it difficult to estimate the frequency of past fire activity but recent studies suggest that counting charcoal particles using the pollen-slide method is sufficient to gain insight into extended fire trends within ~20-100 km around a site (Finsinger and Tinner, 2005; Conedera et al., 2009). Charcoal content within the record cannot be compared to pollen as they are produced in very different ways therefore it is presented as influx in the pollen diagram.

## Organic Content

A further measurement of environmental conditions can be made by calculating the amount of organic matter within the record. The amount of organic carbon within the sediment can be used as an approximate representation of site productivity. A profile of organic content can therefore be produced to complement the stratigraphic evidence (Santisteban et al., 2004).

An estimation of the organic content within the sediment can be obtained by the percentage weight lost after heating. The Loss on Ignition (LOI) percentage value is inversely proportional to the inorganic weight (Beaudoin, 2003). The cores were sampled contiguously every 2cm and each sample placed in a weighed crucible and dried in an oven at 80° for a minimum of 24 hours. The weight loss was measured once the water content had been removed. They were then placed in a furnace at 550° for four hours to remove the carbon content. After cooling the dry weight lost on ignition can be calculated.

LOI is a widely used method and regarded as reliable, nevertheless it can be subject to error. Factors like differences in exposure time at high temperatures and sample size can all have an effect on the results. Sediment with higher organic or ‘mixed’ content can also be susceptible to inconsistent outcomes, therefore consistent methods are key to overcoming these issues (Heiri et al., 2001). Low organic content can indicate increased minerogenic inputs to peatlands which could suggest inwashing, highlighting a possible issue with the overall suitability of the study site. However, the site selection process for this study specifically identified ombrotrophic bogs to avoid the possibility of inwashing.

## Chronologies

In order to create a comprehensive pollen diagram a robust chronology must be created. This involves the construction of age-depth models from radiocarbon dating and tephrochronology to estimate the calendar age of specific depth horizons within the stratigraphy of each core.

### Radiocarbon Dating

Radiocarbon (14C) dating was employed to date relevant sediment horizons within the stratigraphy of the Cerro Ataud, Lago Fox and Punta Burslem records. It is necessary to calibrate radiocarbon dates using carbon proxies that have been directly incorporated from the atmosphere at the time of its formation. Tree rings, speleothems and plant macrofossils have all been used to reconstruct past changes in atmospheric 14C and create an internationally accepted calibration curve; IntCal13, Marine13, and SHCal13 (Riemer et al., 2013). All calibrated calendar dates are measured in years before present (BP) with present being 1950.

#### Radiocarbon Sampling

Samples were obtained from bulk sediment and taken immediately below (<1 cm) significant stratigraphic events in each record relating to changes in pollen, charcoal, organic content or tephra horizons. The samples were very carefully removed to eliminate possible contamination that could introduce older or younger organic material that would distort the results. Samples from Punta Burslem were processed at The Keck Carbon Cycle AMS Laboratory, University of California. Samples from Cerro Ataud were processed at the Centre for Applied Isotope Studies, University of Georgia. Samples for Lago Fox were prepared to graphite at the NERC Radiocarbon Facility-East Kilbride and passed to the SUERC AMS Laboratory for 14C analysis.

All three facilities followed standard procedures for processing the samples by pre-treating with acid digestion (HCl) and rinsing with deionised water, followed by further digestion in KOH and rinsing. Samples were further digested in HCl and rinsed free of acid, dried and homogenised. The dry samples were combusted at 900°C in an evacuated sealed quartz ampoule in the presence of CuO. The gas was converted to graphite by Fe/Zn reduction and ages estimated by Accelerator Mass Spectrometry (AMS).

Using bulk material for radiocarbon dating comes with a caveat that it may contain many different ages of 14C, with roots penetrating from above or stems from below providing an average age that may not accurately represent the time when the sedimentary layer formed. Re-working of sediments may also affect bulk ages especially in lacustrine environments. Terrestrial plant macrofossils provide a more targeted age as they represent the time in which they were photosynthesising and assimilating atmospheric carbon. Nevertheless, these can also represent inaccuracies due to time lags from transportation of the material to sedimentation. Aquatic plant macrofossils can also incorporate ‘old carbon’ from lignite in coal beds, depending on whether they were emergent or submergent that can distort the age (Hatté et al., 2013). All of these issues advocate the use of terrestrial plant macrofossils for radiocarbon dating but they are not always available in the sediment. The basal samples of the three cores in this study did not appear to have terrestrial plant macrofossils in the sediment and due to the small sample sizes, if it had been sieved, the sample would have been lost. In material that has accumulated so rapidly (in this study, cores of up to 11 m) the age difference between plant fibres and the fine fraction will most probably not significantly differ much in age. In some cases, a tephra layer was available to constrain a certain layer within the core.

### Tephrochronology

Tephrochronology is often used as a means for stratigraphic correlation in a broad range of disciplines including paleoecology (Mansilla et al., 2016; McCulloch et al., 2016). It can be used in conjunction with AMS dates to develop a more robust chronology. Tephra layers are temporally synchronous as they result from one isolated event; the atmospheric fallout from a discrete volcanic eruption. Each eruption produces pyroclasts with unique geochemistry covering an extensive geographical area so can be used as an isochronous marker horizon throughout the expanse of its fallout area (Haberle & Lumley 1998; Dugmore et al., 2005, Lowe, 2010). This fallout is dependent on wind direction and speed to determine the fallout area so many locations will not be included in this isochron marker. There are many techniques employed to distinguish and separate different tephra deposits, one of which is mineral abundance. However, the mineral abundance within each tephra deposit changes with distance from the source through differing atmospheric settling rates, causing proximal deposits to contain greater amounts of denser minerals. This can be problematic when the source is distal to the study site as it would contain a reduced amount of denser minerals. This issue can be overcome by analysing the glass shard component of the tephra which does not vary with distance from source allowing analysis of discrete shards hundreds of kilometres from the source, as is the case for these study sites in Patagonia (Dugmore et al., 1992). Each eruption has its own geochemical fingerprint that can be constrained by establishing the major element geochemistry of the glass component using Electron Probe Microscopy (EMP) (Hunt and Hill, 1993; Hayward, 2012). The EMP’s extremely small beam size of 3 m allows analysis on individual shards down to 10 m. The advantage of this very precise analysis on discrete shards is the avoidance of possible cross contamination with the material the shards are enclosed within.

Patagonia lies within the Austral Volcanic Zone (AVZ) between ~49-55°S and also the Southern Volcanic Zone (SVZ) between ~33-46°S (Fontijn et al., 2014). Many volcanoes from these zones have been known to produce large eruptions such as; Mentolat (~45°S), Volcán Hudson (~46°S), Volcán Reclús (~51°S) and Mt Burney (~52°S) (Stern, 2008; Stern et a., 2016) (Section 1.4.2).

Geochemical fingerprinting combined with AMS dating from palaeoenvironmental studies have refined the accuracy of tephrochronology by radiocarbon dating organic material in sharp contact with these isochrons (McCulloch 2005; Stern, 2008; Villa-Martínez et al., 2012; 2016; McCulloch et al., 2016; Mansilla et al., 2016; 2018). The potential of tephrochronology is now being realised through the frequency and quality of tephra data from increasing palaeoenvironmental studies. This is improving the geochemical information for tephrostratigraphy in SSA, which had, until recently, been limited.

#### Tephra Layers

Four macrotephra layers were visible in the cores retrieved from Cerro Ataud and Lago Fox from which the thickness, colour and texture were recorded.

One thick tephra layer was visible in the Cerro Ataud core and was predicted to originate from Volcán Hudson (H1) (~46°S) located less than 150 km north west in the SVZ. Three additional cryptotephra layers were revealed through the analytical process.

Three tephra layers were visible in the Lago Fox core and were thought to be from Volcán Reclús (R1)(~51°S) and Mt Burney (~52°S)(MB2) both of which are part of the AVZ and relatively close to the study site (within ~300 km north west). The other visible tephra layer was thought to be from Volcán Hudson (H1) (~46°) which is much further away in the SVZ (>800 km). No tephra layers were visible in the Pta Burslem core but one cryptotephra layer was revealed during the analytical process.

#### Preparation

The current tephrochronology of SSA was used to constrain known tephra layers within the three cores (Weller et al., 2015; Mansilla et al., 2016; 2018; McCulloch et al., 2005a; 2016; Stern, 2008; Stern et al., 2016). Additional methods were used to focus the search for tephra layers, especially in the very long cores from Lago Fox and Pta Burslem. LOI data was used to locate areas of the core with unusually low organic content plus layers were recorded where tephra shards had been identified during the pollen analysis. The cores were also analysed by magnetic susceptibility to identify minerogenic horizons within the sediment that could possibly be tephra deposits. This can be a useful non-destructive method to locate micro horizons due to the contrast of iron rich tephra to the surrounding organic rich sediment. Areas of the core singled out by the aforementioned analysis were sub-sampled contiguously for examination.

An acid digestion technique was employed to disaggregate the glass shards from the organic content within the sediment in preparation for EMP analysis (Dugmore et al., 1992). Each 2 cm3 sample was placed in an Erlenmeyer flask and concentrated Sulphuric acid 98% SLR was added (~75 ml). The flasks were placed on a hotplate and simmered at 280° for ~2 hours. A few drops of Nitric acid S.G. 1.42 68-72% SLR were added to the dark liquid of each flask until it turned transparent. The samples were left to cool for ~1 hour before distilled water was slowly added to fill the flask and left to settle overnight. A gentle water vacuum pump was used to draw off the supernatant with a pipette, to avoid disturbing the residue on the bottom of the flask. The remaining fluid and sediment were transferred to a 50 ml falcon tube and centrifuged at 2,500 rpm for 5 minutes. This procedure was repeated until the remaining acid was removed from the sample.

#### Identification

The samples were then optically examined to ensure glass shards were present in sufficient size and quantity for EMP analysis. The colour and morphology of the shards were recorded and compared with known tephra layers from the literature.

#### Geochemical Analysis

Tephra samples then had to be prepared for EMP geochemical analysis (Steele and Engwell, 2009) by mounting onto a frosted glass slide prepared by gently grinding one face using 600 carborundum powders on a flat glass plate allowing the resin to properly bond to the slide. The slide is then ultrasonically cleaned and rinsed with acetone to remove any residual coarse carborundum from the surface. Areas were then marked out on the slide for the addition of the tephra samples (4 per slide). A thin film of resin is spread on each individual area of the slide and tephra samples sprinkled on top with a few drops of resin added to prevent shards floating to the surface and were left to cure overnight.

Slide samples then had to be carefully ground to expose the shards using a range of different grades (400, 800, 1200 and 2500). This had to be done progressively to ensure a uniformly flat surface to a thickness of no less than 0.1 mm. A final polishing was then performed on the slide samples using a 6 μm polishing lap and ultrasonically cleaned in pet-ether before repeating with a 1 μm polish. The quality of the surface polish was then checked under a reflected light microscope before slides were carbon coated prior to EMP analysis.

A minimum of ten individual glass shards per sample were then analysed by EMP at the Tephra Analysis Unit at Edinburgh University’s School of Geosciences. The volcanic origin of the tephra was determined by major element geochemical composition measuring ten major elements (Sodium oxide, Magnesium oxide, Aluminium oxide, Silicon dioxide, Potassium oxide, Calcium oxide, Iron oxide, Phosphorus pentoxide, Titanium dioxide and Manganese oxide). The 3 μm beam used by the SX100 Cameca EMP allows the analysis of very fine grained and highly vesicular distal tephra (Hayward, 2012).

The major element geochemical composition of each tephra sample was categorized by EMP analysis using the SX100 Cameca Electron Microprobe at The [University of Edinburgh](http://www.ed.ac.uk/) (Hayward, 2012). A minimum of 10 tephra shards were analysed to provide a representative geochemical signature (Hunt and Hill, 1993). Tephra identification was carried out through comparisons with geochemical data from previous studies (McCulloch, 1994; Stern, 2008; Mansilla, et al., 2016, 2018) to determine absolute dates, which were added to the chronological data.

### Age Depth Modelling

Age depth modelling is vitally important in reconstructing palaeoenvironmental records. The statistically generated model provides a relationship between the depth of a core and the calendar age at any given depth. Building a chronology using AMS radiocarbon dating and tephrochronology can be problematic. Owing to time and budget constraints and available material, it is not realistic to date every level in a sediment core which necessitates some form of age-estimation for the many more layers that have not been dated (Heegaard et al., 2005). An age-depth graph using only a few radiocarbon or tephra dated layers will show specific depths as calendar ages at a single point, resulting in a line graph that misleadingly exhibits a chronology where the timing of changes is precisely known. This is further complicated by errors on radiocarbon dates and varying sedimentation rates within the sediment core. By applying Bayesian statistics to age-modelling each radiocarbon age is constrained by statistical assumptions on prior and subsequent dates resulting in a more robust chronology (Blaauw et al., 2007).

It was therefore decided the best and most robust option for age-depth modelling for this study would be to use the Bayesian age-depth modelling software, BACON 2.4 (Blaauw and Christen, 2011) using the SH13 calibration curve (Hogg et al., 2013).

The age-depth model for Cerro Ataud was constructed by 6 AMS radiocarbon dates from bulk material and supplemented by 4 known tephra dates. The age-depth model for Lago Fox was constructed by 8 AMS radiocarbon dates from bulk material and supplemented by 3 known tephra dates. The age-depth model for Punta Burslem was constructed by 8 AMS radiocarbon dates from bulk material and supplemented by 1 known tephra date.

# Cerro Ataud

## Introduction

The central region of Patagonia, spanning ~45-48°S is dominated by the presence of the North Patagonian Icefield (NPI) covering the high Andean Cordillera at these latitudes. The NPI is the second largest icefield in the southern hemisphere (excluding Antarctica) and is currently sustained by the moisture from the SWWs through their contemporary migration regime (Hubbard, et al., 2005). As global temperatures cooled during the LGM the SWWs migrated further north bringing sufficient moisture to this region to cause the expansion of glacial mass and sustain one continuous ice-sheet stretching across the axis of the Andean Cordillera from The Chilean Lake District to Tierra del Fuego (McCulloch et al., 2000). The onset of warming temperatures in the Late glacial as the SWWs began their poleward migration to their contemporary position, led to the retreat of the icefield. The retreating ice led to the formation of ice-dammed lakes in the central region that modified the catchment characteristics with lake systems draining east towards the Atlantic Ocean. As the warming trend continued, ice retreated further and these ice dams were breached leading to the contemporary catchment drainage system into the Pacific along the Rio Baker as the ice sheet separated into the contemporary NPI and SPI (Thorndycraft et al., 2019).

The Andean Cordillera and NPI forms a formidable barrier to the moisture laden SWWs sweeping in from the south eastern Pacific. This leads to a steep orographic precipitation gradient demonstrating a positive relationship with zonal wind speeds and precipitation (Moreno et al., 2014), keeping the Pacific coastal regions under the continuous influence of the hyper humid SWW precipitation with diminishing moisture on the eastern slopes (Moy et al., 2009). The correlation diminishes with decreasing longitude from the Andean Cordillera and eventually turns negative with Atlantic moisture having an influence on climate towards the eastern Steppe (Whitlock et al., 2007). This precipitation gradient is very steep in Central Patagonia (Fig.1.3) and is reflected in the ecotones that range from Magellanic Moorland and Evergreen Forest in the west through to Forest-Steppe in the east over a distance of tens of kilometres (Fig.1.6) (Tuhkanen, 1989-1990). Palaeoclimate in this region is less certain, as the steep precipitation gradient in the lee of the Cordillera de los Andes offers a relatively small longitudinal window between the NPI and steppe for the retrieval of sufficiently preserved organic material for palynological study (Hein et al., 2010).

Due to the steep orographic nature of the Andean barrier, the SWWs are the main factor in controlling precipitation and moisture regimes of Chilean Patagonia (Quintana and Aceituno, 2012; Bertrand et al., 2014). The regional vegetation response to the latitudinal shifts in the SWWs and changing moisture regimes along the longitudinal precipitation gradient are therefore important due to the relative paucity of palaeoenvironmental records for Central Patagonia during the Late glacial and Holocene. Our understanding of palaeoenvironmental change in Patagonia is improving with increasing levels of studies (Markgraf et al., 2007; de Porras et al., 2014; Horta et al., 2016; Iglesias et al., 2016; Moreno et al., 2018) but more evidence is required to examine how the SWWs drove climate change particularly toward their northern extent in central Patagonia. The records that do exist for this region depict relatively stable vegetation cover dominated by Southern Beech (*Nothofagus*) forest persisting with little change during this period until the present (Haberle and Bennett, 2004; Markgraf et al., 2007; Villa-Martinez et al., 2012; McCulloch et al., 2016; M; Henríquez et al., 2017; Moreno et al., 2019). However, others suggest a more variable moisture regime (Stine and Stine, 1990; Markgraf et al., 2003; Gilli et al., 2005) creating conflicting hypothesis and therefore more research is required in this region to reaffirm palaeoclimate change. *Nothofagus* has been the dominant vegetation throughout central and southern Patagonia during the Quaternary and remains a key species fundamentally linked to the moisture regimes of the region (Mansilla et al., 2016;2018). It is thought to have survived in numerous refugia during the LGM allowing colonisation of post glacial landscapes in the Late glacial and Holocene (Markgraf, 1993; Markgraf and Huber, 2010; Premoli et al., 2010; Moreno et al., 2019).

A new palaeoenvironmental record of sediment from a mountain kettle hole on the western flanks of Cerro Ataud, less than 50 km east of the current NPI will explore the nature and timing of environmental change in this region since the ice retreated from these latitudes of Central Patagonia. It will explore the resilience of *Nothofagus* seen in this region (Villa-Martinez et al 2012; McCulloch et al, 2016) with regard to the latitudinal positioning of the SWWs through the Late glacial and Holocene and will investigate arboreal stability in regard to the longitudinal precipitation gradient. The close proximity of the NPI ensures the site is within one of the most humid sections of the precipitation gradient on the eastern flanks of the Andean Cordillera. This will determine the nature of the moisture regime in this region and whether it acted as a buffer in the absence of the SWWs as they migrated poleward during the Late glacial and Holocene.

## Materials and Methods

### Study Area

The region is dominated by the presence of the NPI with two large waterbodies of Lago Cochrane and Lago General Carrera extending east into the Patagonian Steppe. The terrain is largely mountainous with valleys and outlet glaciers dissecting the landscape with the catchment area draining into the Pacific through the Rio Baker. The study site is a peat bog located southwest of Cochrane in the Aysén Region of Patagonia (47°17’53.2” S 72°39’18.6” W, altitude 348 m asl) (Fig.1.2 and 1.6). The bog probably formed as a kettle hole northwest of Lago Esmeralda on the western flanks of Cerro Ataud (876 m) (Fig.2.1). It is a fen like bog (~270 x 175 m), precipitation fed with no input from surrounding watercourses and situated on an old lake terrace (~2 km x 350 m) formed by an ice-dammed lake during the LGM (Turner et al., 2005). When the bog was cored it was partially flooded, covered mostly by Cyperaceae in the shallow water with sporadic stands of deciduous *Nothofagus antarctica* trying to colonise the drier parts of the surface (Fig.2.2). However archived aerial photographs of the bog showed a dry surface with no standing water indicating the ephemeral nature of this basin (Fig.3.1).

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| A picture containing mountain, riding, dirt, man  Description automatically generated  Figure 3.1. Aerial photograph of dried out bog surface at Cerro Ataud (2016)  (© Google Earth) |

The margins are characterised by dry scrubland slopes colonised by deciduous *Nothofagus antarctica*, almost certainly post fire regeneration. Much of the surrounding slopes consists of exposed cobbles and gravels from the lake terrace and glacial till from an ice marginal moraine that formed the southern rim (Turner et al., 2005) and these areas support tussock grasses, *Acaena*, Saxifrages and Asters. The only patches of soil on the slopes are held together by *Empetrum*, creating their own moisture retention. Mean annual precipitation for the Cochrane area is ~805 mm and mean temperature is ~7.6 °C (Tomé et al., 2007). The considerable size of the bog at Cerro Ataud indicates a large pollen source catchment area therefore representing a regional pollen signal (Prentice, 1985).

### Sediment Coring and Laboratory Methods

A 5.82 cm continuous sediment core was obtained from the Cerro Ataud site using a 5.5 cm diameter and 50 cm long Russian corer (Jowsey, 1966). The stratigraphy of each 50 cm core section was recorded before sealing in layflat tubing then kept in cold storage at 4 °C. Organic content was estimated by Loss on Ignition from dried sediment samples combusted at 550°C for 4 hours (LOI550). 79 sub samples (1 cm3) were taken from the core at intervals of between 4-8 cm and prepared for pollen analysis using standard techniques (Moore et al., 1991). A minimum total of 300 land pollen (TLP) grains were identified from each sample excluding aquatics, spores and algae but included Cyperaceae to boost the local pollen signal (Section 2.3.2). This was supported by a pollen reference collection (McCulloch, 1994) and supplemented by microphotographs (Heusser, 1971; Villagrán, 1980; Wingenroth and Heusser, 1984; Moore et al., 1991). Charcoal particles between 10-180 μm were also counted alongside the pollen and spores as an indicator of past fire activity (Whitlock and Larsen, 2001). The pollen and spore data were presented using Tilia software version 2.0.41 (Grimm, 2011). The pollen data are divided into Local Pollen Assemblage Zones (LPAZ) determined by changes in Land Pollen (constrained by cluster analysis on TLP >2%) (Grimm, 1987). Total pollen concentrations were estimated by adding a known quantity of *Lycopodium clavatum* to each sample (Stockmarr, 1971). The pollen and charcoal accumulation rate (influx: No. grains or particles cm-2yr-1) was determined using the the concentration values (No. grains cm-3) and sediment accumulation (cmyr-1).

The environmental conditions in which pollen grains are deposited is reflected in their physical condition within the sediment with each land pollen grain in this study placed into one of five hierarchical preservation categories; normal, broken, crumpled, corroded and degraded (Section 2.3.5) (Berglund and Ralska-Jasiewiczowa, 1986; Tipping, 1987; Mansilla et al., 2018) (Fig.2.8).

One tephra layer was visually identified in the sediment stratigraphy and 3 cryptotephra layers discovered during the pollen analysis and LOI processes (Fig.3.2). The tephra was isolated from the sediment and prepared for optical analysis using an acid digestion process (Dugmore et al., 1992). The volcanic origin of the tephra was determined by major element geochemical composition of the cleaned and prepared glass shards (minimum of 10) by electron microprobe analysis using the SX100 Cameca Electron Microprobe at The [University of Edinburg](http://www.ed.ac.uk/)h (Hayward, 2012; Hunt and Hill, 1993). The geochemical signatures were compared to previous studies to determine the exact eruption from a particular volcano (McCulloch, 1994; Stern, 2008; Mansilla, et al., 2016, 2018) (Appendix A) (Fig.3.3).

## Results

### Sediment Stratigraphy

The basal sediments consist of bluish-grey clays and silts from 582-560 cm. The sediment then grades between 560-552 cm into a lighter more less well humified peat to 475 cm. More humified darker peat then persists through a visible tephra layer (408-395 cm) to 290 cm when lighter less well humified peat is again visible in the core until returning to darker peat at 152 cm. This darker peat persists until 26 cm where it returns to lighter less well humified peat until the surface. The organic content of the peat estimated from loss-on-ignition (LOI550 %) is variable and may be divided into 6 sections: 1) 582-566 cm <5%, 2) 566-408 cm >65%, 3) 396-250 cm >80%, 4) 250-130 cm >60%, 5) 130-26 cm >80% and 6) 26-0 cm >60% (Fig.3.2). This indicates that the sediment is not always above the true classification for peat of > 75-80% organic content (Kazemian et al., 2011) but appears to remain just above and below this threshold throughout the record.

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| A close up of a map  Description automatically generated  Figure 3.2. Cerro Ataud sediment profile  The profile displays organic content determined by LOI550, with the red dashed line indicating the organic content threshold for peat. Sediment stratigraphy and the LPAZ’s determined from the percentage pollen diagram (Fig.3.5) by CONISS with BACON age-depth model (Blaauw and Christen, 2011) are also shown. Tephra layers within the core are linked to the age depth model; Vn Hudson (H1), Vn Mentolat, Vn Hudson (1971) and Vn Hudson (1991). |

### Chronology

The chronology of the Cerro Ataud record is constrained by 6 AMS radiocarbon dates from in-situ peat (Section 2.6.1.2) and supplemented by four tephra dates (Table 3.1).

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| Table 3.1. Radiocarbon ages, calibrated age ranges and median ages for the Cerro Ataud record  A screenshot of a cell phone  Description automatically generated |

Tephrochronology is a powerful dating technique using the identification and correlation of tephra layers, each of which form a time parallel isochron (Dugmore et al., 2005). The Cerro Ataud chronology is enhanced by the results of geochemical fingerprinting of the tephra layers found within the sediment record, which enabled the correlation to previous studies that present 14C dates for eruption events in the published literature. This study found one visible tephra layer at 394-408 cm geochemically linked to the well dated Volcán Hudson (H1) layer at 394-408 cm (7241±23 14C yr BP) (Stern et al., 2016) and was supplemented by 3 cryptotephra layers within the record. Two of these cryptotephra layers are also geochemically linked to Volcán Hudson from eruptions in 1991 at 8 cm and 1971 at 26 cm, and one from Volcán Mentolat at 316 cm (6895±20 14C yr BP) (Best, 1992; Naranjo and Stern, 1998; Stern et al., 2016). Figure 3.3 shows the correlation between the Cerro Ataud Hudson tephras and the Hudson H1 tephra from Punta Yartou (Mansilla et al., 2016) and the 1991 and 1971 tephras (Naranjo and Stern, 1998; Mansilla et al., 2016). The correlation of the Mentolat tephra found at 316 cm is derived from a single geochemical sample from the Cochrane area (Stern et al., 2016), the relative temporal fit within stratigraphical sequence and the glass shard description.

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| A screenshot of a cell phone  Description automatically generated  Figure 3.3. Geochemical analysis of Cerro Ataud tephra  Percentage totals of individual glass shards for SiO2 versus TiO2/Fe showing the correlation of Cerro Ataud tephra; CA8 cm (Hudson 1991), CA26 cm (Hudson 1971), CA316 cm (Mentolat) and CA394-408 cm (Hudson H1) with Hudson H1 tephra data from Punta Yartou (PY H1) (Mansilla et al., 2016), Hudson 1991 and 1971 tephra data (Naranjo and Stern, 1998) and Mentolat tephra from Cochrane (Stern et al., 2016). |

The dark green coarse H1 tephra was clearly visible in the sediment core (Fig.3.4) between 394-408 cm. The andesitic nature of the tephra is supported by the geochemical analysis with green brown platy glass shards (Fig.3.4) showing SiO2 between 62.8-66.8 wt.%, TiO2 ≤ 1.34 wt.% and Fe ≤ 5.58 wt.%. The Mentolat cryptotephra at 316 cm had smaller clear glass shards with unstretched vesicles (Fig.3.4). The geochemical analysis of the Mentolat tephra indicates it is rhyolitic with SiO2 between 72.3-75.4 wt.%, TiO2 ≤ 0.31wt.%, and Fe ≤ 1.87 wt.%.

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| A picture containing grass, sitting, table, food  Description automatically generated  Figure 3.4. Cerro Ataud core section (400-450 cm)  A: H1 tephra layer, B: MEN tephra glass shards and C: H1 tephra glass shard both at x400 magnification. |

There are only three historical accounts of Hudson eruptions; 1991, 1971 and 1891 (Lachowycz, 2016). Although the correlation between the tephra found at 8 cm to the eruption of Volcán Hudson in 1991 was apparent (Naranjo and Stern, 1998), the association of the Hudson tephra found at 26 cm was ambiguous. Reports of an eruption in 1891 are unclear (Caldenius, 1932; Smithsonian Institute, 2020) with this date thought to be incorrectly recorded from an account by Burmeister (1891) who wrote of considerable ashfall in the Santa Cruz valley, drifting south towards Punta Arenas in 1886 (Lachowycz, 2016). Without convincing evidence of the 1891 eruption, the tephra layer at 26 cm is thought to originate from the only other historical record of a Hudson eruption in 1971 (Best, 1992; Naranjo and Stern, 1998).

Age depth modelling is discussed in section 2.6.3 and based on these discussions it was decided that the best and most robust option for the age-depth model for Cerro Ataud would be to use the Bayesian age-depth modelling software, BACON (Blaauw and Christen, 2011) and the pollen diagram was constructed using an age-depth axis (cal yr BP) from the median ages. The age-depth model suggests the basal age is estimated to be c. 13.4 kcal yr BP (Fig. 3.2).

### Pollen Stratigraphy

Seven local Pollen Assemblage Zones (LPAZ’s) were identified for the Cerro Ataud core from the percentage pollen data (Fig.3.5) and constrained cluster analysis (CONISS, Grimm, 1987) and these LPAZ’s are applied to all the stratigraphic figures.

#### LPAZ CA-1 (582-476 cm; c. 13.4-11 kcal yr BP)

The characteristics of this LPAZ is of grasslands and expanding forests with lesser abundance of sedges and ferns. After the ice retreated from the Cerro Ataud kettle hole organic material began accumulating around c. 13.4 kcal yr BP. There was rapid colonisation of *Nothofagus* (~42%) forming open canopy forest and continuing to rise to ~70% by c. 13.2 kcal yr BP. Following a brief period of relative stability, a sharp decline in *Nothofagus* (~57%) is seen at c. 11.6 kcal yr BP before steadily rising to closed canopy (~80%) by the upper boundary at c. 11 kcal yr BP. The cold-adapted arboreal species, *Podocarpus* (Quiroga and Premoli, 2007; Henríquez et al., 2017) is also present at the basal depth (~4%) declining to zero by the upper boundary. There is trace amounts of the hemi-parasite *Misodendrum* throughout the LPAZ*.* This epiphyte is found in more open forest environments that are usually under some level of environmental stress (Markgraf et al., 2002).

Non-boreal taxa are also present in CA-1, the most abundant being Poaceae and follows an almost inversely proportional trend to *Nothofagus* with an undulating but overall downward inclination from ~22-9% with three distinct peaks at c. 13.3, 12.8 and 11.6 kcal yr BP (~21.7, 17.5 and 20.2% respectively). *Empetrum rubrum* and Asteraceae Subf. Asteroideae are very early pioneers in this area starting out at ~7% but they also display an almost instantaneously rapid decline then gradually regress to trace amounts by c. 11 kcal yr BP. *Gunnera* and *Acaena* are present in small amounts as the ice retreated from the region (~7%) but quickly decline to trace amounts by the upper boundary of CA-1. *Gunnera* is a specialist pioneer species following glacial retreat from this region, flourishing in the cold environment (Pisano 1977). There are minor extents of Caryophyllaceae, Saxifragaceae and *Galium type* (<2%) with all virtually disappearing by c. 11 kcal yr BP. There are also trace amounts of *Drapetes muscosa* and Amaranthaceae. An initial presence of Cyperaceae (~5%) rising to ~18% at c. 12.1 kcal yr BP is followed by a decline to ~8% by the upper boundary. After an early spike of ~17%, Polypodiaceae plateaus at ~10%. The only instance of the aquatic *Pediastrum* in the entire record is in the basal section (~9%) but swiftly disappears. *Myriophyllum* is also present but only in trace amounts, which suggests the study site was briefly a freshwater lake environment but rapidly transformed into a bog by c. 13.2 kcal yr BP This is also supported by a lack of lacustrine mud in the stratigraphic record and a carbon content of ~84% at this time. The Land Pollen Influx (LPI) is relatively low (~834 grains cm-2 yr-1) (Fig.3.6) as vegetation slowly colonise the post glacial landscape and the pollen is well preserved at ~92% (normal) and remains so until CA-6 (Fig.3.7). Charcoal particles in the sediment are in relatively high abundance (~885 cm-2 yr-1, peaking at ~2614 cm-2 yr-1) reflecting the availability of fuel in the region (Fig.3.7).

#### LPAZ CA-2 (476-400 cm; c. 11-8.2 kcal yr BP)

This LPAZ is typified by dense forest canopy with decreasing abundance of most other vegetation types. The steady increase of *Nothofagus* seen in CA-1 continues until c. 9.3 kcal yr BP (~94%) where it shows a prolonged decline to ~76% by the upper boundary at c. 8.2 kcal yr BP, opening up the forest canopy somewhat. There is also a minor presence of *Misodendrum* (~1-2%) and trace amounts of *Podocarpus*. The initial closed canopy forest had a negative effect on the grassland species with Poaceae declining from ~10-1% coeval with the apex of *Nothofagus* but recovers to ~10% as *Nothofagus* declines towards the upper boundary. Other grassland and herb species such as Asteraceae Subf. Asteroideae and *Empetrum rubrum* are present at <2% with Asteraceae having a similar presence to CA-1 but *Empetrum* only in trace amounts. There are trace amounts of Caryophyllaceae, Saxifragaceae, *Drapetes muscosa, Acaena* and *Gallium type* with Saxifragaceae and *Drapetes muscosa* maintaining a constant but minor presence similar to CA-1 but *Acaena* and *Gallium type* declining to zero. *Gunnera*, Caryophyllaceae and Amaranthaceae have all disappeared from the site since CA-1. Cyperaceae has continued its decline from CA-1 until c. 9.3 kcal yr BP (~3%) then showed a resurgence towards the upper boundary (~14%) as *Nothofagus* declines. Following an early rise to ~11%, Polypodiaceae declines to ~3% and there are only trace amounts of *Pediastrum* in the early part of this LPAZ. LPI remains relatively low (~795grains cm-2 yr-1) and there are fewer charcoal particles become less (~437 cm-2 yr-1) as the forest begins to contract. CA-2 contains ~8 cm of the 12 cm thick H1 tephra layer (7241±23 14C yr BP) (Stern et al., 2016) at the upper boundary of the LPAZ (Fig.3.2).

#### LPAZ CA-3 (400-346 cm; c. 8.2-7.8 kcal yr BP)

The forest contracts slightly in this LPAZ allowing the expansion of some grassland and sedges. The forest canopy continues to open up through the steady reduction of *Nothofagus*. The decline seen towards the end of CA-2 is maintained until c. 8 kcal yr BP (~50%) then began expanding again with a brief fall again at c. 7.9 kcal yr BP before increasing to ~83% followed by another decline towards the upper boundary (~70%). *Misodendrum* maintains a marginal presence but *Podocarpus* is no longer present in the record at this time. Poaceae continues its gradual steady decline since CA-1 but displays an anti-phase relationship with *Nothofagus*, ranging from ~2-11%. Asteraceae Subf. Asteroideae has retained its constant but small presence similar to CA-1 and CA-2 with only trace amounts of *Empetrum rubrum,* Saxifragaceae*, Acaena* and *Gallium type* with *Drapetes muscosa* no longer present. Cyperaceae continues the rise seen in CA-2 coeval with the decline of *Nothofagus* (~35%) to c. 8 kcal yr BP where it declines sharply (~9%) before stabilising (~16%) towards the upper boundary. LPI increases in this LPAZ through the aggressive growth of *Nothofagus* (~3401 grains cm-2yr-1) (Fig.3.6) with charcoal also rising with more available fuel (~968 cm-2 yr-1, peaking at ~1640 cm-2 yr-1). CA-3 contains ~4 cm of the H1 tephra layer (7241±23 14C yr BP) (Stern et al., 2016) at the lower boundary of the LPAZ.

#### LPAZ CA-4 (346-154 cm; c. 7.8-4.6 kcal yr BP)

This LPAZ is characterised by dense forest throughout the region during this time, with little or no other vegetation. Closed canopy *Nothofagus* forest almost completely dominates CA-4 with an average of ~90% but varying between ~79-98% throughout the LPAZ. *Podocarpus* and *Misodendrum* are present throughout in trace amounts but *Podocarpus* increases to ~3% coeval to a dip in *Nothofagus* around c. 5.8 kcal yr BP. This dominance supresses most of the grassland and herbaceous taxa with Poaceae (~2%) showing only two small spikes to ~6%, contemporary with brief dips in *Nothofagus*. *Empetrum rubrum* has a small presence (<2%) with trace amounts of Asteraceae Subf. Asteroideae, Acaena, Amaranthaceae, Saxifragaceae, *Gunnera* and *Gallium type* exploiting any brief reduction in *Nothofagus* with a small Asteraceae spike (~6%) at c. 5.9 kcal yr BP. Cyperaceae begins at ~12% but falls as *Nothofagus* increases then remains steady at ~5% throughout the LPAZ. Polypodiaceae remains in the record (<2%) briefly growing to ~6% following the Men1 eruption (c. 7.7 kcal yr) and *Myriophyllum* is present in trace amounts in the upper section of the LPAZ. LPI is lower than CA-3 (~1532 grains cm-2yr-1) as is charcoal (~358 cm-2 yr-1), although there is a pronounced spike at c. 5.8 kcal yr BP (~2777 cm-2 yr-1) that coincides with a brief decline in forest cover and a distinct deterioration in pollen preservation to ~50% (Fig.3.7) and rise in Asteraceae Subf. Asteroideae. CA-4 contains the cryptotephra layer associated with an eruption from Volcán Mentolat at 316 cm (6895±20 14C yr BP) (Stern et al., 2016).

#### LPAZ CA-5 (154-108 cm; c. 4.6-3.8 kcal yr BP)

This LPAZ is again dominated by dense forest but there is a brief reduction during the early phase allowing some grass and sedge taxa to expand. Arboreal taxa continue to dominate in this LPAZ, however there is a brief opening of the forest canopy at the beginning of this phase as *Nothofagus* falls to ~74% allowing a short-lived period of development for Poaceae and Cyperaceae (~8% and ~19% respectively). *Misodendrum* also appears in this phase (~1%) but *Podocarpus* only makes one brief appearance in trace amounts. This period is not prolonged as *Nothofagus* increases again (>90%) by c. 4.2 kcal yr BP, inhibiting the growth of most other species with only trace amounts of *Empetrum*, Asteraceae Subf. Asteroideae, Polypodiaceae and *Myriophyllum*. The LPI reflects this sharp arboreal rise (~1984 grains cm-2yr-1). Charcoal is the lowest of the entire record in the LPAZ (<30 cm-2 yr-1).

#### LPAZ CA-6 (108-60 cm; c. 3.8-1.5 kcal yr BP)

Once again, the characteristics of the region are of dense forest cover but in this LPAZ it is gradually contracting, allowing grass and sedges to increase. Although the arboreal dominance continues in CA-6 there is a sharp decline in *Nothofagus* (~72%) at the lower boundary but is quickly followed by a recovery to ~88% and from there it begins a punctuated but protracted decline to the upper boundary (~77%) at c. 1.5 kcal yr BP. *Podocarpus* makes its most conspicuous appearance up to this point in the record fluctuating between ~2-4% while *Misodendrum* appears in trace amounts throughout. The declining *Nothofagus* allows the increase of some grassland herbaceous taxa; Poaceae increases modestly from ~4-6% while *Empetrum rubrum* rises from ~1-2%) and *Acaena* from ~0-3%. There are now trace amounts of Caryophyllaceae, Asteraceae Subf. Asteroideae, Saxifragaceae, *Gunnera* and *Gallium type* at the site. Cyperaceae is increasing modestly but undulates between ~5-17% throughout the LPAZ with Polypodiaceae returning but in small amounts of <2%. *Myriophyllum* has been present in trace amounts in all but one of the LPAZ’s but makes a substantial appearance rising up to ~4% towards the upper boundary indicating pools of water at the site. The LPI is the lowest in the record in this LPAZ reflecting the downward trend of *Nothofagus* (~327 grains cm-2yr-1) with charcoal particles increasing within the sediment from CA-5 (248 cm-2 yr-1). Pollen preservation shows its first decline in the record (~72%) with a nadir of ~57% at c. 3.4 kcal yr BP.

#### LPAZ CA-7 (60-0 cm; c. 1.5 kcal yr BP -present)

Grassland and sedges begin to flourish in this LPAZ as the forest continues to decline. *Nothofagus* continues its gradual decline seen in CA-6 to a much more open canopy (~52%) at c. 900 cal yr BP. The canopy then starts to close again as *Nothofagus* increases steeply reaching ~77% before opening yet again as it wanes towards the surface in the twentieth century. *Podocarpus* makes its most significant rise in the entire record by reaching ~9% at the nadir of *Nothofagus* then levelling out at ~3% to the surface with *Misodendrum* again present in trace amounts. Poaceae rises to ~12% at the same time as *Nothofagus* declines then falls back to ~6% until the surface. *Empetrum rubrum* ranges between~1-2% and there are trace amounts of other grassland and herbaceous taxa coeval to the 1991 Hudson tephra layer like Caryophyllaceae, Asteraceae Subf. Asteroideae, Saxifragaceae, *Acaena*, *Drapetes muscosa*, *Gunnera* and *Gallium type*. Cyperaceae flourishes in this phase reaching ~25% before slowly declining towards the surface and Polypodiaceae is ~2% throughout. *Myriophyllum* is at its most abundant in the entire record in this LPAZ reaching 7% at the surface indicating that pools of water are persisting at the site. The LPI increases sharply in this LPAZ (~2075 grains cm-2yr-1) reflecting the resurgent forest growth, with charcoal and pollen preservation also rising (~79% and 373 cm-2 yr-1 respectively). CA-7 contains two tephra layers from Volcán Hudson eruptions in 1991 at 8 cm and 1971 at 26 cm (Best, 1992; Naranjo and Stern, 1998).

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| A close up of a piece of paper  Description automatically generated  Figure 3.5. Cerro Ataud summary percentage pollen and spore diagram  Cyperaceae including in the TLP to give enhanced local pollen signal |

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| A close up of a map  Description automatically generated  Figure 3.6. Cerro Ataud pollen accumulation rate (influx) diagram for selected taxa |

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| A screenshot of a cell phone  Description automatically generated  Figure 3.7. Cerro Ataud percentage pollen preservation diagram with charcoal influx |

#### Summary of vegetation change

After the ice retreated from the Cerro Ataud site organic sedimentation began around c. 13.4 kcal yr BP with rapid forest development as *Nothofagus* quickly colonised the region. There were other non-arboreal taxa forming a vegetation community like the post glacial landscape specialists *Gunnera* and *Acaena* thatwere quick to colonise but were quickly outcompeted by other grassland taxa like Poaceae, *Empetrum* and Asteraceae. There is evidence to suggest the site was briefly a freshwater lake environment by the presence of the aquatics *Pediastrum* and *Myriophyllum* but this was short lived as these species were soon replaced by terrestrial taxa as the lake was replaced with a fen bog through hydroseral succession supported by the stratigraphy showing peat instead of lacustrine mud.

The record shows a steady decline in non-arboreal taxa as the forest continued to expand until around c. 9 kcal yr BP when it began to decline over the subsequent ~1000 years. During this forest regression there is an upsurge in Cyperaceae and Poaceae that had taken advantage of the increasingly available light from the opening forest canopy. This forest contraction coincides with a deterioration in pollen preservation suggesting a changing moisture regime in the region.

By around c. 8 kcal yr BP this forest decline is reversed with the record showing a sharp increase in *Nothofagus* and improving pollen preservation suggesting the moisture regime has again changed. There is a brief halt to the expanding forest around c. 7.9 kcal yr BP before full development of closed canopy forest by around c. 7.7 kcal yr BP. There was then a period of almost complete arboreal dominance in the region until around c. 5.9 kcal yr BP where the record shows a brief decline in *Nothofagus* that coincided with the lowest pollen preservation and highest charcoal content in the record suggesting another environmental change. There was another brief forest contraction around c. 5.3 kcal yr BP allowing an ephemeral rise in Poaceae and Cyperaceae before full canopy was again resumed by around c. 4.6 kcal yr BP.

The forest cover then began a punctuated but protracted decline lasting to the present which allowed the expansion of other arboreal taxa like *Podocarpus* to expand to its highest abundance in the record. Other grassland and herbaceous taxa like Poaceae and Cyperaceae took advantage of the contracting forest canopy and expanded. There was a brief resurgence of *Nothofagus* between the two Hudson eruptions of 1891 and 1991 but the decline was soon resumed until the present.

## Interpretation of the vegetation record

The early part of the Late glacial is not recorded at Cerro Ataud owing to prolonged ice and glacial lake cover from its proximal position to the NPI. While climatic temperatures increased in this period as evidenced in Antarctic ice core records (Mulvaney et al., 2012; Gest et al., 2017), and sea surface temperatures (41°00’S) (Lamy et al., 2010) the Patagonian Ice Sheet began retreating. At this stage Lago Cochrane and Lago General Carrera were separate ice-dammed lakes draining into the Perito Moreno and Estancia Carracolas channels respectively towards the Atlantic Ocean. As temperatures continued to increase and the ice sheet in the Aysén region retreated further west, the catchment characteristics continued to change with the two lakes uniting and draining through the lower Perito Moreno channel (Turner et al., 2005). The kettle hole at Cerro Ataud most likely formed at this time from an iceberg grounded on the shoreline, leaving an impression that was filled in when the lake level lowered. Further ice retreat resulted in the final stage of the ice-dammed lake conditions as the ice sheet separated into the contemporary NPI and SPI allowing the catchment to drain through the Rio Baker and into the Pacific Ocean leading to the contemporary catchment conditions (Thorndycraft et al., 2019). The basal age of c. 13.4 kcal yr BP therefore represents the onset of organic sedimentation at Cerro Ataud and is not a record of ice retreat, which would have preceded this. The date for the breaching of the ice-dammed lake at Cerro Ataud that discharged into the Pacific via the Rio Baker is c. 13.6 kcal yr BP (Turner et al., 2005) and would be a minimum age for ice retreat in the region but is likely to be sometime before this.

The post glacial landscape of Cerro Ataud was swiftly colonised by cold-tolerant steppe vegetation such as Poaceae, and although relatively abundant, it shows a protracted decline. Other pioneer species such as *Empetrum rubrum,* Asteraceae Subf. Asteroidea and *Acaena* were also quick to colonise the site indicating the cooler than present environment of the Late glacial, but these taxa were also short-lived, indicating rising temperatures in the region (Pizano, 1977). These early pioneers were quickly outcompeted by a rapid expansion of *Nothofagus* as open canopy forest formed by c. 13.2 kcal yr BP with arboreal cover continuing to develop into dense full canopy by c. 11 kcal yr BP. While still relatively cold, the steady warming trend and increasing humidity in the now, well established Late glacial would have been favourable conditions for the sudden establishment of *Nothofagus* forest at Cerro Ataud. The rapid nature of colonisation suggests that multiple *Nothofagus* refugia could have survived in climatically constrained circumstances on the ice margins during the LGM (Markgraf et al, 1995; Mansilla et al, 2016). This is supported by genetic analysis across the entire latitudinal distribution of the *Nothofagus* species inferring a continuous presence of the taxa during the LGM (Premoli et al., 2010).

The rapid nature of forest development as the ice retreated is consistent with similar forest development seen at two lake sites ~20 km north east at Lago Augusta (47°45’ S 72°23’ W, 444 m asl) and Lago Edita (47°8’ S 72°25’ W, 575 m asl) in the Chacabuco Valley (Villa-Martinez et al 2012; Henríquez et al., 2017). Despite the similarities, these records differ from Cerro Ataud as they do not show immediate colonisation of *Nothofagus* but rather an archetypal post glacial landscape of pioneer species comprising dwarf shrubs and herbs but only a small assemblage of *Nothofagus*. However, Lago Augusta and Lago Edita are further from the Andean Cordillera and therefore became ice free much earlier (c. 16 kcal yr BP) in a cooler and less humid environment making it less suitable for forest development. Arboreal development was more protracted at Lago Augusta with a punctuated rise until around c. 11.5 kcal yr BP when rapid expansion occurred. The Lago Edita record shows a similar developmental pattern with *Nothofagus* showing a continuous presence, but in low abundance, until around c. 11 kcal yr BP where it showed rapid expansion. This temporal delay in rapid arboreal expansion compared to Cerro Ataud could be attributed their more easterly position long the precipitation gradient and therefore less humid with lower temperatures at the higher elevation in the Chacabuco Valley (~444 and 575 m). Two sites north of Lago Buenos Aires also display similar arboreal development; a lake site at Lago Churrasco (45°41’ S 71°49’ W, 800 m asl) and peat mire at Mallín Pollux (45°41’ S 71°50’ W, 640 m asl) ~20 km southeast of Coyhaique (Markgraf et al., 2007; Moreno et al., 2019). The Lago Churrasco record shows a steady development of *Nothofagus* from around c. 16 kcal yr BP until closed canopy is achieved around c. 10 kcal yr BP with Mallín Pollux displaying a more punctuated and prolonged development until around c. 10 kcal yr BP where dense closed canopy forest is reached. All of these sites suggest similar forest expansion in the Aysén region with temporal development seemingly linked to the spatial positioning on the precipitation gradient.

The only presence of *Pediastrum* in the entire Cerro Ataud record is found in the basal section suggesting the site was initially a freshwater lake environment. The combination of *Pediastrum’s* almost immediate decline, the concurrent rise in Cyperaceae, the absence of lacustrine mud in the stratigraphy and the accumulation of organic sediments seen in LOI data suggests a rapid period of hydroseral succession allowing Cyperaceae to colonise the bog surface. As the cold-tolerant taxa quickly diminished, an increasing presence of polypod ferns (Polypodiaceae) is seen in the record around c. 13 kcal yr BP suggesting the onset of warmer temperatures in the region (Schneider et al., 2010). This is concurrent with a sharp rise in charcoal within the sediment indicating the availability of drier fuel in the region, which conflicts with the well-preserved pollen indicating a relatively humid environment. This probably reflects increased seasonality with warmer drier summers creating drier wood for fuel leading to a moderate increase in fire activity, seen in many sites in the Aysén region (Holz and Veblen, 2012), coupled with wetter winters that maintains the pollen preservation as seen by the lighter coloured less well humified peat in the stratigraphy. The continued forest development persisted in the Early Holocene until c. 9.3 kcal yr BP where *Nothofagus* had reached ~94%. The dominance and reduced light to the understory of this densely closed canopy forest most likely perpetuated the decline of all other taxa in this period.

An arboreal decline is seen in the Mid Holocene with *Nothofagus* regressing to ~50% between c. 9.3-8.1 kcal BP. The decline is amplified in the pollen diagram when Cyperaceae is included into the TLP giving an improved local pollen signal to that of the almost uninterrupted *Nothofagus* throughout most of the record (Fig.3.5). This over representation of *Nothofagus* is seen at the lake sites of Lago Augusta, Lago Edita and Lago Churrasco where there is no local pollen signal, therefore this arboreal decline is not apparent at these sites (Villa-Martinez et al., 2012; Moreno et al., 2019). There is an increase of Cyperaceae at Cerro Ataud to ~35%, concurrent to the contraction of *Nothofagus* with increased light in the understory from the opening of the forest canopy allowing an increase in Poaceae. A simultaneous return to darker more humified peat in the stratigraphy and a modest ~7% drop in pollen preservation indicates a drop in effective moisture in Central Patagonia at this time. The marginal reduction of humidity is concomitant with a similar decline at Mallín Pollux that probably indicates increased regional seasonality with drier summers during this period but the persistence of *Nothofagus* at Cerro Ataud (~50%) and Mallín Pollux (~35%) indicates sufficient moisture to maintain the open canopy forest at these sites.

There is forest recovery between c. 8.1-7.7 kcal yr BP as *Nothofagus* out competes almost all taxa at Cerro Ataud, increasing to its maximum extent (~98%) to form a dense closed canopy once again, indicating a return to humid conditions reflected in the stratigraphy with lighter coloured less well humified peat and well preserved pollen. These humid conditions are also inferred at Mallín Pollux with arboreal expansion to a more modest extent (~85%), reflecting its location further east along the precipitation gradient. The almost complete dominance of dense closed canopy forest continued at Cerro Ataud until c. 5.2 kcal BP when a brief ~10% drop in *Nothofagus* is seen. There is a simultaneous spike in charcoal, the highest seen in the record, together with marginal increases in grassland taxa such as Poaceae and Asteraceae Subf. Asteroideae and a small peak in Cyperaceae. This suggests there was an increase in palaeo-fire activity at this time reducing the density of the forest cover allowing an opportunity for the brief development of some grassland species. This short event is concurrent in other areas of Central Patagonia; ~50 km north east in La Frontera (46°52’ S 71°52’ W, 997 m asl) (McCulloch et al 2016) and 20 km north east in Lago Augusta (Villa-Martinez et al 2012) suggesting a brief period of warm and dry conditions allowing drier fuel to become available in the region.

The forest canopy is again restored before another brief reduction around c. 4.5 kcal yr BP, allowing Poaceae and Cyperaceae to simultaneously increase. The relative stability of arboreal cover since c. 7.7 kcal yr BP now turns to a steady decline from c. 4 kcal yr BP. There is a corresponding drop in pollen preservation and rise in corroded and degraded pollen grains suggesting drier conditions in this period leading to the reduction of *Nothofagus* and the opening up of the forest canopy. It could also suggest cooling temperatures with the expansion of other taxa including the cold-adapting *Podocarpus* (Henríquez et al., 2017), which had been present in marginal amounts throughout the record but now had the opportunity to develop (~9%). Other non-boreal taxa also took advantage of the increased light to expand such as Poaceae, *Empetrum rubrum, Acaena* andto a lesser extent Polypodiaceae with the main beneficiary being Cyperaceae (~25%). This period of climate variability is coetaneous with Mallín Pollux and La Frontera where an augmented response is seen in the records showing significant forest decline during this period, but this variation is absent from Lago Augusta and Lago Churrasco. The characteristics and locations of Mallín Pollux and La Frontera can account for this disparity as they are all further along the west-east precipitation gradient from Cerro Ataud, increasing their sensitivity to changes in humidity. However, Lago Augusta and Lago Churrasco are lake sites without a local vegetation signal allowing the *Nothofagus* signal to dominate the record.

Coeval to the contracting forest cover at Cerro Ataud is a significant increase in *Myriophyllum* which shows a steady expansion to its highest levels in the record which could suggest a return to shallow freshwater lake conditions. The ephemeral nature of Cerro Ataud suggests increased seasonality, with vegetation responding to these changing conditions with no local pollen signal when the site is flooded; only *Nothofagus* from the regional landscape. Cyperaceae appears to be the only local pollen signal when the site becomes a shallower fen which also benefits the shallow rooting *Myriophyllum*. This is the advantage of including Cyperaceae in the TLP count as *Nothofagus* dwarfs the pollen signal and masks the true nature of local vegetation. This fen site seems to be dominated by water, but the increased seasonality is drying it out in drier summers, and it is this constant wetting and drying that is probably preserving the pollen and not constant levels of regional humidity. The transitory nature of standing water at Cerro Ataud can be seen throughout the record, with stratigraphical evidence showing the organic content hovering just above or below the classification of true peat (Kazemian et al., 2011). It therefore remains around a lacustrine peat threshold throughout the record with a stronger Cyperaceae signal indicating periods of reduced humidity and therefore shallower water levels (Fig.3.2).

There is an increase in broken and crumpled pollen grains in the preservation data beginning around c. 3.8 kcal yr BP which could be explained by reduced vegetation cover in close proximity to the site due to fire activity in hot and dry summers. This could have supported increased surface run-off on the surrounding slopes during more humid winters allowing the bog to be inundated in those periods, allowing *Myriophyllum* to take root in the shallow water. The increased surface run-off could have potentially damaged pollen grains during the transportation process.

There is evidence of climate instability in the pollen preservation records at Cerro Ataud with brief spikes of deterioration at c. 4.2-3.3, 2.2, 1 and 0.5 kcal yr BP indicating short-lived periods of rapid climate change indicating warmer and drier conditions at the site. There are also brief periods of *Nothofagus* contraction seen in the pollen records at c. 4.5, 3.8, 1 and 0.5 kcal yr BP that don’t completely match the preservation data but could suggest a degree of resilience in the vegetation to small changes in climate.

As arboreal cover continues to decline at Cerro Ataud, the increasing *Nothofagus* signal from La Frontera appears anomalous, however this is a high montane scrub location with a longitudinal treeline limit which would be expected to respond to smaller changes in the moisture regime, hence the variable nature of forest cover at this site. The increasing arboreal signal from c. 2 kcal yr BP at La Frontera seems to counter that of declining *Nothofagus* at Cerro Ataud but could reflect an altitudinal migration of the forest-steppe ecotone.

There is a brief resurgence of forest cover c. 800 yr BP that peaks between the two Volcán Hudson eruptions with a corresponding dip in Poaceae and Cyperaceae lasting ~700 years before dropping to contemporary levels. This suggests that the climate was variable during this period and reflects variable climate seen at the two other study sites in the south during this phase.

## Climatic inference at Cerro Ataud

As temperatures increased in the Late glacial and the Patagonian Ice Sheet receded into the contemporary NPI and SPI, increasing humidity from the SWWs and the presence of *Nothofagus* refugia on the retreating eastern margins of the ice allowed the rapid development of arboreal cover at the site after c. 13.4 kcal yr BP. The increasing humidity reflecting the spatial influence of the SWWs in their northerly setting during the LGIT.

This closed canopy forest remained for almost the entire record with the exception of a brief decline at c. 8 kcal yr BP and a steadier decline after c. 4 kcal yr BP but at no time does it drop under 50%. This resilience seems to be contradictory especially when considering the probable reduction in humidity from a poleward migration of the SSWs in the Mid Holocene when they approached their migratory apex in the Southern Ocean around c. 8 kcal yr BP (McCulloch et al, 2020). However only a marginal deterioration is evident from the pollen preservation data suggesting the persistence of humidity at Cerro Ataud in the absence of the SWWs. The characteristics of contemporary *Nothofagus* forests may allow an explanation for the stability seen in the record during the Late glacial and Holocene. This arboreal taxon occurs in Central Patagonia with a precipitation range between 400-1000 mm/yr (Quintanilla, 2005) therefore the Cerro Ataud palynological record would suggest variations in palaeo-precipitation occurred within these parameters to allow such arboreal resilience.

As the SWWs began their equatorward migration from the Southern Ocean after c. 8 kcal yr BP arboreal cover expands once again at Cerro Ataud to closed canopy indicating increased moisture which is supported by well-preserved pollen. However, after c. 4 kcal yr BP there is a steady decline of *Nothofagus* suggesting a reduction of humidity supported by deteriorating pollen preservation which seemingly conflicts with the evidence from the southern study sites for a continued equatorward migration of the SWWs. One explanation for this could be temperature related. As global temperatures continued to fall, as evidenced by the equatorward migration of the SWWs at this time (Schneider et al., 2003; Toggweiler, 2009), it caused re-advancement of ice caps with cold katabatic winds lowering temperatures, creating a local neoglacial effect in Aysén. These colder temperatures could also have contributed to the expansion of the NPI leading to enhanced rain shadow effect, making it drier at Cerro Ataud (Glasser et al., 2004).

The continued presence of the NPI suggests there was, and still is, sufficient precipitation in Central Patagonia to maintain this ice sheet following the retreat of the large Patagonian Ice Sheet in the LGIT, even when the core of the SWWs were ~1000 km to the south in The Drake Passage (Masiokas et al., 2008). Precipitation variability is one of the main factors in controlling the mass balance of these maritime glaciers, reiterating the importance of the humidity supplied by the SWWs (Boex et al., 2013). The proximal location of the NPI positions Cerro Ataud in the western and therefore wetter margins of the longitudinal precipitation gradient (mean annual rainfall in Cochrane is ~805 mm) make it less sensitive to variations in humidity. Any changes in the effective moisture regime created by a poleward shift of the SWWs would therefore buffer the effect on forest cover at Cerro Ataud, keeping the moisture regime within the parameters for optimal growth (400-1000 mm/yr). However, this buffering effect is not reflected in the eastern margins of the precipitation gradient where changing moisture regimes are amplified as the SWWs become more distal from the region and humidity drops in the forest-steppe ecotone as seen in La Frontera and Mallín Pollux (McCulloch et al, 2016; Markgraf et al., 2007), both of which certainly display a more changeable *Nothofagus* signal. La Frontera is a high montane scrub location with a longitudinal treeline limit which would be expected to respond to smaller changes in the moisture regime, hence the variable nature of forest cover at this site. Mallín Pollux is an upland site bordering on the forest/steppe ecotone that is reflected in the sensitivity to climatic change seen in the record when compared to Cerro Ataud.

There appears to be similarities in arboreal cover between Cerro Ataud and those at Lago Augusta and Lago Churrasco (Villa-Martinez et al 2012; Moreno et al., 2019) supporting the assumption of sustained humidity. The vegetation at Lago Augusta and Lago Churrasco range between deciduous *Nothofagus* forest to forest-steppe ecotone and the palynological record indicates a stable forest signal after c. 10 kcal yr BP however these lake sites tend to augment the *Nothofagus* signal as there is reduced localised input. However, the palaeoenvironmental evidence from Cerro Ataud, coupled with previous studies from Lago Augusta and La Frontera appear to suggest the moisture regime in the Aysén region remained humid enough to sustain *Nothofagus* forests at varying extents throughout the Holocene and latter period of the Late glacial.

The persistent influence of the SWWs in the Aysén region while these storm fronts were distal to the area indicates there was increased seasonality with wetter winters in the region causing less evapotranspiration in the colder temperatures and increased snowfall leading to a lasting input of moisture that maintained Cerro Ataud through the drier summer months as a wet site with good pollen preservation. This would account for the insensitivity of Cerro Ataud to climate change in the wetter and therefore more buffered end of the precipitation gradient, contrasting with La Frontera where a more punctuated *Nothofagus* signal is seen. La Frontera is much further east along the precipitation gradient at the borderline of where *Nothofagus* can thrive and therefore responds quicker to even small changes in climate.

Contrasting data from the north in Puerto Marin (~43°S) exhibits distinct contemporary seasonality with very dry summers (~167 mm per month) and more precipitation in winter (~366 mm per month) (Quintana and Aceituno, 2012; Bertrand et al., 2014) suggesting this region is on the northernmost extremities of the SWWs northerly seasonal migratory influence. Despite the northerly location of the Aysén region it remains within the northernmost influence of the seasonal moisture regime supplied by the SWWs with winter precipitation allowing forest cover to endure with only a modest decline evident even during the southernmost migration of these fronts. The stability seen in these records despite the core of the SWWs migrating poleward could support the theory of a wide scale weakening of the SWWs in this region during extreme SAM events rather than a full-scale latitudinal shift (Moreno et al., 2010). The increased seasonality through annual migrations would allow the distribution of precipitation in the region, as seen in the contemporary records to the north in Puerto Marin suggesting that climate change influenced by the SWWs was relatively minimal in central Patagonia.

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| A screenshot of a cell phone  Description automatically generated  Figure 3.8. Summary of SWWs migration and effects on climate and vegetation at Cerro Ataud. |

## Conclusion

The northerly location of Cerro Ataud provides an insight into the nature and timing of climate change on the periphery of the migratory track of the SWWs in central Patagonia. As temperatures began to rise in the LGIT and ice began to retreat from the Chacabuco Valley at around c. 16 kcal yr BP, Cerro Ataud remained ice-bound until sometime before 13.4 kcal yr BP. The vegetation response to ice-free conditions was the rapid development of open canopy forest by around c. 13.2 kcal yr BP suggesting that multiple *Nothofagus* refugia could have survived in climatically constrained circumstances on the ice margins during the LGM. Arboreal dominance continued steadily until full canopy was reached by around c. 11 kcal yr BP and endured for almost the entire record except for two intervals. An evident decline between c. 9.3-8.1 kcal yr BP reflected a reduced moisture regime at Cerro Ataud as the SWWs migrated to the most distal position of their poleward migration into the Southern Ocean. The climatic response to the distal SWWs continued to allow open canopy forest to flourish indicating the persistence of sufficient effective moisture in central Patagonia to support this. After c. 8.1 kcal yr BP there is an aggressive expansion of *Nothofagus* once again until closed canopy is quickly achieved reflecting the equatorward migration of the SWWs and increased humidity in the region. This is sustained until c. 4 kcal yr BP where a punctuated and protracted fall in humidity is seen through declining *Nothofagus* to open canopy forest as the SWWs settle into their contemporary latitudinal position of ~50°S. The evidence from the Cerro Ataud and other Aysén records coupled with those north of this region suggests that although central Patagonia is towards the northerly periphery of the migratory track of the SWWs, it remains humid enough to sustain arboreal cover through increased seasonality throughout the Holocene even during extreme positive SAM events. This suggests that the effects of climate change in central Patagonia due to the poleward migration of the SWWs was minimal.

# Lago Fox

## Introduction

Lago Fox is ideally situated to help understand the timing and nature of earth-atmosphere changes in the southern hemisphere. The southerly maritime location means Lago Fox is particularly sensitive to latitudinal shifts in the SWWs (Garreaud et al., 2013) which are a fundamental component of the global atmospheric system as they promote the overturning of the Southern Ocean and the uptake of CO2(section 1.2.3) (Toggweiler et al., 2006; Turney et al., 2016; Fogwill et al., 2019).

The high relief of the Cordillera Darwin produces winter precipitation that helps to sustain relatively small maritime icefields and create an orographic precipitation gradient along the western flanks of the mountain chain (McCulloch, 2010). This forms a hyper-humid region in the west (~8000 mm per yr) and a pronounced rain shadow in the lee with moisture levels decreasing north-eastwards (to ~500 mm per yr, ~160 km northeast of the Andean Cordillera) (Schneider et al., 2003). This precipitation gradient is reflected in the diversity of ecotones in the Magallanes region that range from Magellanic Moorland and Evergreen Forest in the west and south west through to Steppe in the east and north east (Fig.1.5). The precipitation gradient in the Magallanes region does not chart a simple east-west bearing as seen in the more northerly Cerro Ataud study site where the Andean Cordillera follows a north-south direction. At these higher latitudes, the Andes curve eastwards along the southern extent of Tierra del Fuego forming the Cordillera Darwin, constraining the precipitation gradient into a south west-north east course (Tuhkanen, 1992) (Fig.1.2).

The palaeoclimatic history of Patagonia reconstructed from records of glacial fluctuations and ecological changes is dominated by changes in the strength and latitudinal position of the SWW storm tracks (Fletcher and Moreno, 2011). The timing of latitudinal shifts of the SWWs during the LGIT and Holocene is becoming better understood (Toggweiler, 2009; Lamy et al., 2010; Moreno et al., 2014; McCulloch et al., 2020). However there remains gaps in our knowledge in this region of the Southern Hemisphere and our understanding of the impacts of changes in the precipitation gradient at a more focused landscape scale is less well informed. Recent work by Mansilla et al., (2018) suggests that relatively small-scale shifts in the focus of the SWWs may result in significant ecological changes, especially in the drier extents of the precipitation gradient in the Magallanes region.

The sensitivity to regional changes in climate is reflected in the many glacial advances and retreats recorded during the Late Quaternary (section 4.2.1). The warming trend following the LGM prompted the latest major ice retreat from this region and allowed the accumulation of organic sediments at the study site. The palaeoenvironmental records obtained from Lago Fox will help to circumscribe the nature and intensity of the SWWs and also constrain the timing of any latitudinal migration of these fronts in this region and help build a synthesis of their movement along the north-south transect (47°S-55°S) during the Late glacial and Holocene. The spatial vegetation response to changes in the effective moisture regime of Lago Fox should be seen as the increased precipitation from the core of the SWWs moves along a latitudinal range, creating wet and dry phases that should be evident in the sediment record. These spatial data combined with an effective chronology will also help to constrain the timing of the migration and using data from other sites in the region will help to develop the characteristics of the precipitation gradient on Isla Dawson in response to the shifting SWWs that could help predict how ecotones and vegetation communities may respond to future climate scenarios.

## Study Site

### Isla Dawson

The Magallanes region is a heavily glaciated landscape that has experienced numerous ice advances throughout the Quaternary. The extent and timing of glacial oscillations in the Strait of Magellan has been the focus of considerable research since the pioneering work of Caldenius (1932), who was the first to identify a series of landforms in the region associated with multiple glacial advances. Much of our current understanding of changes to the ocean-atmosphere system in the southern hemisphere have originated from reconstructing these glacial fluctuations with research building on the work of Caldenius (Auer, 1956; Clapperton et al, 1995; McCulloch and Bentley, 1998; Bentley et al, 2005; McCulloch et al, 2005b). This has developed the geomorphological mapping and chronology of these advances by identifying five glacial advance stages (A-E) that have been mapped in some detail (McCulloch et al, 2005a; Kaplan et al 2008).

Glacial advance stage ‘A’ occurred before the LGM (sometime earlier than c. 90 kcal yr BP) with stages B-E representing advances during the LGM and LGIT. Glacial advance stages ‘B’ and ‘C’ have been dated as c. 25.2-23 kcal yr BP and 22.4-20 kcal yr BP respectively (McCulloch et al 2005a) and were extensive, flowing northwards from the Cordillera Darwin through the Magellan Strait and forming moraine limits at the Peninsula Jan Mazia and Bahía Inútil (Glasser, 2004) (Fig 4.1). Moraine limits on the western side of the Magellan Strait just north of Punta Arenas are linked to glacial advance stage ‘D’ and are associated with similar moraines on the eastern side of the Magellan Strait just north of Porvenir which were part of an advance around c. 17.5 kcal yr BP (Bentley et al, 2005; McCulloch et al, 2005b). There is a suggestion of a glacial advance stage ‘E’ which is thought to have occurred before the onset of the Holocene between c. 15.3-11.7 kcal yr BP based on a set of evidence for ice-dammed lakes in the central section of Magallanes. This is conveyed by glacial lacustrine sediments found above a key tephra layer and raised shorelines around the region. The moraine limit for glacial stage ‘E’ was thought to be the northern peninsula of Isla Dawson (McCulloch and Bentley, 1998; McCulloch et al, 2005b). The evidence of these glacial stages indicates the climatic variability in this region driven by global temperatures and humidity, both of which are inextricably linked with the waxing and waning of such a maritime glacial environment.

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| A close up of a map  Description automatically generated  Figure 4.1. Magallanes region showing Late-glacial ice limits and the present ice fields in the Cordillera Darwin  (adapted from Bentley *et al.,* 2005). |

The configuration of islands and channels within the Magellan Straits is ideal for the formation of ice-dammed lakes. During the LGM, global sea levels were around c.120 m lower than present day and the shallow body of water north of the Segunda Angostura would have presented a dry land barrier to the Atlantic during this period (McCulloch et al, 2005b) with Isla Dawson in the south helping to shape the Magellan Strait into two narrow channels either side of the island. This configuration meant that only two relatively narrow channels needed to be blocked by advancing glacial ice from the Cordillera Darwin to isolate the northern section of the Magellan Strait and form an ice-dammed lake. It is the lacustrine signal within sediment cores and raised shorelines that identifies this feature between c. 15.3-11.7 kcal yr BP, with marine clays and silts seen in palaeoenvironmental records at Puerto del Hambre and Caleta Eugenia (McCulloch and Davies, 2001; McCulloch et al., 2019). However the hypothesis of a glacial advance stage ‘E’ is contentious and has been questioned by some workers (Fontana and Bennett, 2012; Hall et al, 2013) who have not seen this re-advance in their research at Isla Santa Inés in the western Magellan Strait and the north side of Cordillera Darwin and so remains unclear and requires further investigation.

Isla Dawson lies in the south-central section of the marine flooded glacial trough that forms the Straits of Magellan. The west coast of Isla Dawson is flanked by Paso del Hambre and the east coast by Canal Whiteside (Fig.1.2). The northern tip of Isla Dawson is a low altitude peninsula which rises southward to ~110 m asl. The peninsula preserves many glacial landforms associated with the retreat of the Magellan glaciers after the LGM in the form of moraines, palaeo-meltwater channels and kettle holes now occupied by lakes and bogs (McCulloch and Bentley, 1998; Bentley et al., 2005).

The dynamic variation of these maritime glaciers to small changes in global temperatures makethis region an ideal location for studying climate change. Evidence from the Lago Fox record will build on previous research in this region (McCulloch and Davies, 2001; Mansilla, 2015) by providing new palaeoenvironmental data and chronologies showing the sensitivity and vegetation responsive to environmental change during the LGIT and Holocene (Section 1.5).

### Lago Fox

Lago Fox is located on Isla Dawson <5 km south of Puerto Harris at the southern/wetter end of the precipitation gradient (Fig.1.2 and 1.5), with precipitation evenly distributed throughout the year (~841 mm/yr) with mean temperatures of 9.8°C in January (Austral summer) and 1.2°C in July (Austral winter) (Tuhkanen et al., 1989–1990) The study site is an ombrotrophic mire (Section 2.3) 200 m south west of Lago Fox (53°52’08.33” S, 70°26’45.22” W, altitude 52 m asl). The mire is oval shaped (~320 x 150 m) and was surveyed by measuring peat depths along a 50 m grid using a gouge to determine the deepest point of the bog, where a 950 cm core was sampled to an impenetrable base. The eastern flank of the bog has steep relief colonised by *Nothofagus betuloides* forest with low gentle slopes surrounding the remaining perimeter. The mire is characterized by a hummocky surface with pools of standing water (Fig.2.4). The wet peat bog surface vegetation is dominated by *Sphagnum magellanicum* (Sphagnaceae) and some moorland species are present, such as *Astelia pumila* (Asteliaceae), *Donatia fascicularis* (Stylidiaceae) and *Drosera uniflora* (Droseraceae). *Empetrum rubrum* (Ericaceae) is dominant along with sedges such as Cyperaceae increasing towards the periphery. Dead stands of *Nothofagus* are found in the wetter margins of the bog. The large size of the bog at Lago Fox indicates a substantial pollen source catchment area therefore representing a good regional pollen signal (Prentice, 1985).

## Materials and Methods

### Sediment coring and laboratory methods

The sediment cores were obtained using a 5.5 cm diameter and 50 cm long Russian corer (Jowsey, 1966). Each core section was sealed in polythene layflat tubing and stored at a constant 4°C. The gross stratigraphic characteristics of the sediment record was briefly described in the field, then in the lab using Troels-Smith notation with organic content determined by loss-on-ignition (Section 2.5).

80 sub-samples (1 cm3) were taken from the core and prepared for pollen analysis using standard protocols (Moore et al., 1991) (Section 2.3.1). A minimum total of 300 TLP grains were identified per sample, excluding Cyperaceae, aquatics, spores and algae (section 2.3.2). The identification of pollen and spores was supported by photographs of pollen and spores (Heusser, 1971; Villagrán, 1980; Wingenroth and Heusser, 1984; Moore et al., 1991) and a pollen reference collection. Pollen and spore diagrams were produced using Tilia and Tilia-Graph software, version 2.0.41 (Grimm, 2011). Local pollen assemblage zones (LPAZ) were mainly defined using land pollen >2% and constrained cluster analysis (CONISS, Grimm, 1987). Pollen, spores and algae concentrations determined by adding a known quantity of *Lycopodium clavatum* spores to each sample(Stockmarr, 1971). The concentration values (No. grains cm-3) and sediment accumulation (cmyr-1) were used to calculate the total pollen and charcoal accumulation rate (influx: No. grains or particles cm-2yr-1). Charcoal particles between ˃10 and ˂180 μm were counted and measured alongside the pollen as a proxy of past fire activity (Section 2.4) (Whitlock and Larsen, 2001).

Relative changes in pollen preservation also provide useful support for the palaeoclimatic inferences made from the pollen assemblages. Five hierarchical categories of land pollen preservation were recorded in this study: well preserved or normal, broken, crumpled, corroded and degraded (Tipping 1987; McCulloch and Davies, 2001; Mansilla et al., 2018) (Section 2.3.4) (Fig.2.8).

Three tephra layers were identified within the sediment stratigraphy of the core (Fig.4.2). An acid digestion technique was used to segregate the tephra from the sediment for optical investigation (Section 2.6.2.2) (Dugmore et al., 1992). The identification of the tephra layers was established by major element geochemical analysis of the clean glass shards (minimum of 10 per sample) using the SX100 Cameca Electron Microprobe at The [University of Edinburgh](http://www.ed.ac.uk/) (Hunt and Hill, 1993; Hayward, 2012) (Fig.4.3).

## Results

### Stratigraphy

The Lago Fox site was cored to an impenetrable base at 950 cm. At the base of the core there is bluish-grey clays and silts up to 936 cm. The core then grades between 936-922 cm to an organic lacustrine mud that persists up to 654 cm. The lacustrine sediments are then overlain by light coloured less well humified peat up to 622 cm where is changes to darker, more humified peat which persists up to 242 cm. It then becomes changeable with less well humified peat from 242-68 cm then darker peat to 38 cm followed by less well humified peat to the surface of the mire (Fig.4.2). Three visible tephra layers are seen in the sediment column between 907-906 cm, 438-430 cm and 308-300 cm (Section 4.4.2). The organic content was determined from loss-on-ignition (LOI550 %) and can be divided into four sections: 1) 950 cm to 922 cm is <10% organic content, 2) 922 cm to 768 cm the organic content fluctuates between 10% and 20%, 3) 768 cm to 654 cm the organic content varies between 20% and 40%, 4) 654 cm to surface has a high organic content >80% (Fig.4.2).

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| A close up of a map  Description automatically generated  Figure 4.2. Lago Fox sediment profile  The profile displays organic content determined by LOI550, sediment stratigraphy and the LPAZ’s determined from the percentage pollen diagram (Fig.4.5) by CONISS with BACON age-depth model (Blaauw and Christen, 2011). It also shows tephra layers within the core; Vn Reclus (R1), Vn Hudson (H1) and Mnt Burney (MB2). |

### Chronology

The Lago Fox record was constrained by 8 AMS radiocarbon dates from in-situ peat (Section 2.6.1.2) and supplemented by three well dated tephra dates (Table.4.1).

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| Table 4.1. Radiocarbon ages, calibrated age ranges and median ages for the Lago Fox record.  A screenshot of a cell phone  Description automatically generated |

Tephrochronology is a powerful dating technique using the identification and correlation of tephra layers, each of which form a time parallel isochron (Dugmore et al., 2005). This study uses three previously identified and well dated tephras to give a more robust chronology. The geochemical analysis allowed the correlation from this study with previous research that presented radiocarbon ages for eruption events. The tephrochronology for Lago Fox is based on three distinct tephra layers that have originated from three discrete volcanoes. Tephra found at 907-906 is geochemically matched to an eruption from Volcán Reclús (R1) from within the AVZ (Sagredo et al., 2011). ; 438-430 cm is geochemically matched to an eruption from Volcán Hudson (H1) from within the SVZ (Stern et al., 2016) and the other between 308-300 cm is geochemically matched to an eruption from Mount Burney (MB2) from within the AVZ (McCulloch, 1994). These R1, H1 and MB2 tephras are correlated to isochrons from Lago Lynch in Tierra del Fuego (Mansilla et al., 2018) (Fig.4.3). The Lago Lynch tephras were all correlated with recognised dates in the published literature; R1 (Sagredo et al., 2011), H1 (Stern et al., 2016) and MB2 (McCulloch, 1994).

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| A screenshot of a cell phone  Description automatically generated  Figure 4.3. Geochemical analysis of Lago Fox tephra  Percentage totals of individual glass shards for SiO2 versus TiO2/Fe showing the correlation of the Lago Fox tephras; LF 300-308 cm (MB2), LF 430-438 cm (H1) and LF 906 cm (R1) using MB2, H1 and R1 tephra data from Lago Lynch as criterion (Mansilla et al., 2018). |

When visible within the core, MB2 is a coarse white tephra and following preparation the glass shards are transparent and vesicular (Fig.4.4a). The geochemical analysis of MB2 indicates it is a rhyolitic tephra with SiO2 between 74.6-77.7 wt.%, TiO2 ≤ 0.12 wt.% and Fe ≤ 1.48 wt.%. H1 is a visible dark green coarse tephra with green-brown platy glass shards (Fig.4.4b). The geochemical analysis of H1 indicates it is an andesitic tephra with SiO2 between 63-65.2 wt.%, TiO2 ≤ 1.33 wt.% and Fe ≤ 5.13 wt.%. R1 is a creamy-white fine silt layer when seen in the core (Fig.4.4) with semi vesicular transparent glass shards (Fig.4.4c). The geochemical analysis of R1 indicates it is a rhyolitic tephra with SiO2 between 74.9-77.6 wt.%, TiO2 ≤ 0.18 wt.% and Fe ≤ 1.48 wt.%.

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| A picture containing table, sitting, photo, man  Description automatically generated  Figure 4.4. Lago Fox tephra  Top photograph shows a core section from Lago Fox (900-950 cm) with a clear creamy-white layer of R1 tephra present. a) glass shard from MB1 layer, b) glass shard from H1 layer and c) glass shard from R1 layer. |

Age depth modelling is discussed in section 2.6.3 and based on these discussions it was decided that the best and most robust option for the age-depth model for Lago Fox would be to use the Bayesian age-depth modelling software, BACON (Blaauw and Christen, 2011). The weighted mean ages (WMA) from Bacon modelling were used to provide the age-depth axis (Cal yr BP) for the pollen diagrams produced using the Tilia v.2.0.41 program (Grimm, 2011) (Fig.4.2). The age-depth model suggests the basal age is estimated to be c. 15,600 cal yr BP.

### Pollen Stratigraphy

Seven Local Pollen Assemblage Zones (LPAZ’s) were identified for the Lago Fox core from the percentage pollen data (Fig.4.5) and constrained cluster analysis (CONISS, Grimm, 1987) and these LPAZs are applied to all the stratigraphic figures.

#### LPAZ LF-1 (936-920 cm; c. 15.7-15.3 kcal yr BP)

This basal LPAZ is a freshwater lake environment surrounded by a treeless post glacial landscape dominated by grass and heathlands. Non-arboreal taxa dominate this basal LPAZ with *Gunnera* the principal taxa. *Gunnera* is a specialist pioneer species that flourish in cold environments (Pisano 1977) and quickly colonises the site with an initial ~29% TLP rising sharply towards the upper boundary (~51%). Other herbaceous and shrub taxa thriving in this cold environment are Poaceae (~30%) and *Empetrum rubrum* (~15%) with smaller amounts of *Acaena* (~8%) and Asteraceae (Subf. Asteroideae) (~3%). Other herbs are present in small amounts including Caryophyllaceae, Amaranthaceae, Ranunculaceae, Saxifragaceae and Apiaceae (all <1%). The freshwater algae *Pediastrum,* that favours the clear waters of post glacial water bodies is prevalent at ~50% indicating a freshwater lake environment (Komárek and Jankovská, 2001). Also present are small amounts of the aquatic *Myriophyllum*, which increases abruptly (~20% to 60%) towards the top of the zone and also Polypodiaceae (~10%). There is a trace amount of *Nothofagus dombeyi* type in a small spike <2% which may have been transported from refugia further afield, mostly probably from Tierra del Fuego (Mansilla et al., 2016). This LPAZ has very low organic content at <10% which is typical of early established post glacial pioneer vegetation communities. The pollen land influx is also low (~593 grains cm-2 yr-1) (Fig. 4.6). And the pollen is very well preserved with an average of ~88% normal state (Fig.4.7).

#### LPAZ LF-2 (920-760 cm; c. 15.3-12.6 kcal yr BP)

This lake environment is now surrounded by expanding grasslands with forest development later in the LPAZ. A clear change from LF-1 is seen with increased taxa at the site suggesting the development of a vegetation community. The pollen assemblage continues to be characterised by non-arboreal, taxa such as Poaceae, which has become well established and is now the dominant species (~50% TLP). Asteraceae (Subf. Asteroideae) is also thriving (increasing to ~30%) but falls abruptly to ~5%, which could suggest a brief return to colder conditions between c. 13.9-13.2 kcal yr BP, before increasing again to ~25% towards the upper boundary. Other herbaceous taxa are present such as *Gunnera* (~12%), *Empetrum rubrum* (~10%), *Acaena* (~4%) and Caryophyllaceae (~2%). There are also trace amounts of Cyperaceae (~2%), Rubiaceae, Saxifragaceae, Apiaceae, *Drapetes muscosa,* Amaranthaceae*,* Apiaceae andAsteraceae (Subf. Cichorioideae) (all <2%). Although this LPAZ is dominated by non-arboreal taxa, an early development of *Nothofagus* can be seen in a small spike of ~7% around c. 14.3 kcal yr BP, which rises steadily culminating at ~26% at the upper boundary indicating the establishment of *Nothofagus* forest from around c. 12.7 kcal yr BP. *Pediastrum* continues in abundance (average ~50% but ranging from ~30-70%) indicating the persistence of a freshwater lake environment. Polypodiaceae remains at ~10% while *Myriophyllum* falls considerably to ~5% (Fig.4.5). A tephra layer is present at 907 cm geochemically matched to Volcán Reclus (R1) (c. 15.4 kcal yr BP). Organic content has marginally increased in this LPAZ, varying between 10-20% and the land pollen influx has also risen (~1,045 grains cm-2 yr-1) reflecting the more established vegetation community at the site (Fig.4.6). The pollen in this zone is again very well preserved with an average of ~88% normal state (Fig.4.7).

#### LPAZ LF-3 (760-580 cm; c. 12.6-10.5 kcal yr BP)

This LPAZ is dominated by dense forest cover with diminishing grasslands and lowering lake levels. There is a marked change in the vegetation community characteristics in this LPAZ from LF-2 with increasing dominance of arboreal taxa concurrent with a decline in grassland and herbaceous taxa. LF-3 is dominated by *Nothofagus* which rises sharply from around c. 12.7 kcal yr BP (~26% TLP) at the lower boundary to an apex at c. 11.4 kcal yr BP (~88%) before declining to ~50% by the upper boundary, suggesting the development of open canopy forest through to closed canopy by the mid-point of the LPAZ followed by a return to open canopy once again. The decline of *Nothofagus* is concurrent with the development of the hemiparasite *Misodendrum* (~5%) which thrives on *Nothofagus* in open canopy forests. As a consequence of arboreal expansion, herbaceous and grassland taxa declined with Poaceae displaying an inverse association with *Nothofagus*, declining from ~30% to ~5% around c. 11.4 kcal yr BP, then increasing back to ~30% as *Nothofagus* declines. There are also decreasing amounts of Asteraceae (Subf. Asteroideae) (~7%), *Empetrum* (~5%), *Acaena* (~2%), *Gunnera* (~2%), Rubiaceae (1%) and Saxifragaceae (<1%) with the disappearance of *Drapetes muscosa* during this forest expansion. There is a brief rise in Caryophyllaceae (~12%) between c. 12.3-11.6 ka cal yr BP and Cyperaceae emerges in the apex of *Nothofagus* rising from ~5% to ~9%. *Pediastrum* also declines from ~30% to zero by around c. 10.6 kcal yr BP indicating the end of lake conditions in the latter stages of this zone. Polypodiaceae remains steady at ~10% before rising abruptly around c. 10.8 kcal yr BP at the upper boundary (Fig.4.5). The first instance of charcoal is found in small amounts of ~40 particles cm-2 yr-1 throughout LF-3, rising sharply towards the upper boundary concomitant with the increase in Polypodiaceae (~400 particles cm-2 yr-1). There is a marked shift in the record around c. 11.3 kcal yr BP with a sharp rise in organic content seen within the sediment from ~25% to >80%. This is concurrent with a stratigraphical transition from lacustrine mud to less well humified peat and a rapid deterioration in pollen preservation from ~90% to ~41%, with around ~30% attributed to corroded or degraded pollen grains, indicating reduced humidity. Considering this evidence and the disappearance of *Pediastrum* suggests that hydroseral succession from lake to bog has occurred which is supported by increased pollen influx (~2,621 grains cm-2 yr-1). A large proportion of the increased pollen influx is from Cyperaceae which would have colonised the surface of the newly formed bog. The pollen preservation continues to deteriorate towards the upper boundary (~30%) and there is further transition in the stratigraphy from less well humified peat to darker peat which is concurrent with a sharp fall in *Nothofagus* following its apex, all indicating a changing moisture regime in the region.

#### LPAZ LF-4 (580-330cm; c. 10.5-5.0 ka cal yr BP)

The lake has transformed into a bog and the forest canopy opens up in LF-4 allowing the understory to flourish. The characteristics of the vegetation community have once again changed in this LPAZ from the arboreal dominance of LF-3 to an increase of grassland and herbaceous taxa in LF-4. *Nothofagus* continued its steady decline seen in the latter part of LF-3 from around c. 11.4 kcal yr BP (~88% TLP) to c. 10 kcal yr BP (~28%). It then fluctuates between ~30-50% before rising steeply to ~80% at the upper boundary (c. 5 kcal yr BP). *Misodendrum* remains relatively constant throughout LF-4 at ~4% before declining to zero at the peak of *Nothofagus* at the upper boundary, which is consistent with this epiphyte preferring open canopy. Poaceae is dominant in this LPAZ ranging between ~50-20% before falling to ~5% at the upper boundary (c. 10 kcal yr BP). Asteraceae (Subf. Asteroideae) is persistent but variable, rising from ~2% at the lower boundary to a peak of ~18.5% at c. 9.2 kcal yr BP then declining to ~9% at the upper boundary. *Acaena* and *Gunnera* are both re-established (~10%), with Gunnera showing a marked increase following the eruption of Volcán Hudson (H1) at c.8 ka cal yr BP but disappearing together around c. 7 and 6 kcal yr BP respectively. *Empetrum* remains in low abundance but begins to rise after the H1 eruption at c. 8 kcal yr BP. There is an increase in Cyperaceae to ~9% but this falls to <1% towards the upper boundary at around c. 7 kcal yr BP. Other herbaceous taxa present in the record in LF-4 are Asteraceae (Subf. Cichorioideae) with a little spike of ~6% at c. 6 kcal yr BP and trace amounts of Amaranthaceae, Saxifragaceae and Apiaceae. The abrupt rise in Polypodiaceae seen in LF-3 continues in this LPAZ up to ~80% before gradually disappearing towards the upper boundary at c. 5 kcal yr BP. However, there is a brief hiatus in Polypodiaceae that coincides with the H1 eruption. The pollen is poorly preserved in this LPAZ (average ~33% normal state) but improves towards the upper boundary (~95%). The deteriorating pollen preservation seen at the end of LF-3 increases in LF-4 with tangible changes in the nature of pollen degradation with a larger percentage of corroded and degrade pollen grains seen during this LPAZ of up to 25% indicating desiccation and reduced bog surface wetness. The decline reaches a low point around c. 10.3 kcal yr BP (~33) and continues to fluctuate between ~34-46% until around c. 6.9 kcal yr BP where a steady improvement is seen until c. 5 kcal yr BP where it reaches ~97%. A significant rise in charcoal content is seen within the sediment from c. 10.2-8 kcal yr BP (oscillating between ~1,892 and 421 particles cm-2 yr-1) suggesting an increase in fire activity and is concurrent with this poorly preserved pollen and the rise in Polypodiaceae (Fig.4.7). This is the only significant charcoal content found within the entire record. The organic content in LF-4 is high, fluctuating between ~80% and 100% reflecting the site as a peat bog but the land pollen influx declines from LF-3 (from ~2,621 to ~966 grains cm-2 yr-1). This decline is accounted for by a large fall in *Nothofagus* and Poaceae pollen influx, although both show an increase towards the upper boundary (c. 5 kcal yr BP).

#### LPAZ LF-5 (330-210 cm; c. 5.0-2.7 kcal yr BP)

This LPAZ is characterised by a variable degree of forest cover and the re-establishment of heathland. The diversity is very much reduced from previous zones, with LF-5 being almost completely dominated by two species; *Nothofagus* and *Empetrum*. There is a decrease in *Nothofagus* to ~50% TLP in the early stage of this LPAZ (c. 4.1 kcal yr BP) following the MB2 eruption at c. 4.2 kcal yr BP, but it does recover to the levels seen at the boundary with LF-4 (~85%) by c. 3.2 kcal yr BP. There is an abrupt rise to ~70% followed by a sharp fall to ~15% in the heathland species *Empetrum*, again inversely proportional with the rise and fall of *Nothofagus* and is reflected in the pollen influx for the two species. LF-5 is also characterised by the absence of many taxa that have been prominent in previous LPAZ’s such as Poaceae, Asteraceae (Subf. Asteroideae), *Acaena*, *Gunnera* and Cyperaceae as closed canopy forest and heathland dominate the landscape in this period. Again, this is supported by the absence of the majority of grassland and herb taxa in the pollen influx. There are also no Polypodiaceae present after its dominance in LF-4, which is coeval with the absence of any charcoal particles within the sediment. The organic content of the sediment record remains high (~85-100%) but the stratigraphy varies from peat (c. 5-3.3 kcal yr BP) to less well humified peat (c. 3.3-2.7 kcal yr BP) and the land pollen influx increases dramatically (~7,151 grains cm-2 yr-1) most of which is attributed to *Nothofagus* and *Empetrum* (Fig.4.6). There is also a small percentage of Cyperaceae which would have been colonising the increasing area of heathland. The preservation of the pollen is good but does begin to fall steadily after the deposition of the MB2 tephra from ~95-75%, with ~15% of that attributed to broken grains.

#### LPAZ LF-6 (210-62 cm; c. 2.7-1.1 kcal yr BP)

This LPAZ is again dominated by forest and heathland with the emergence of pools of standing water on the bog surface. LF-6 is characterised by two taxa as seen in LF-5 and is again dominated by closed-canopy forest and heathland. *Nothofagus* starts at ~77% TLP at the lower boundary culminating at ~80% at the upper boundary but fluctuates throughout the zone. It declines to ~47% at c. 2.4 kcal yr BP before rising again to ~81% at c. 2.2 kcal yr BP followed by another drop to ~59% at c. 2.1 kcal yr BP recovering to ~90% by c. 1.7 kcal yr BP. It oscillates again to ~72% at c. 1.6 kcal yr BP before finishing the LPAZ at ~80%. *Misodendrum* appears in trace amounts (~2%) coeval to the low points of *Nothofagus*. The prevalence of *Empetrum* endures and continues to have an inverse association with the oscillating *Nothofagus*; ranging between ~10-50% throughout the zone. Again, this LPAZ is conspicuous by the absence of Poaceae, Asteraceae (Subf. Asteroideae), *Acaena*, *Gunnera*, Cyperaceae and charcoal particles. However, the freshwater algae *Pediastrum* returns in several small peaks (~6%) perhaps suggesting small pools of standing water on the bog surface. The pollen continues to be well preserved, fluctuating between ~65–85%, with ~20% attributed to broken/crumpled grains but shows a gradually punctuated decline that seemingly contradicts the increasing water on the bog surface and the fibrous nature of the peat in this LPAZ (Fig.4.7). Organic productivity continues to be high (>90%) while the land pollen influx falls to ~2828 grains cm-2 yr-1 but remains dominated by *Nothofagus* and *Empetrum*.

#### LPAZ LF-7 (62-0 cm; c. 1.1 kcal yr BP to present)

There is a degree of heathland and forest decline seen in the most recent LPAZ with the return of grasslands. The characteristics of this assemblage are again similar to LF-5 and LF-6 with regards to the dominant taxa. *Nothofagus* continues to be the principle species but it begins with a sharp decline to ~55% at the lower boundary. It then recovers to ~78% at c. 600 cal yr BP before declining again close to the surface. *Misodendrum* also persists at low levels, albeit at slightly higher levels than in LF-6 (~4%). *Empetrum* again seems to counter the *Nothofagus* by sharply increasing in the early stages to ~45% then diminishing to ~15% around c. 600 cal yr BP before recovering close to the surface. The disparity between this LPAZ and LF-5 and LF-6 is that Poaceae makes a noticeable return at c. 1.1 kcal yr BP (~6%) along with Polypodiaceae (~4%) and Cyperaceae which rises towards ~5% at the surface. There is also a very small peak in charcoal content at the lower boundary (~152 particles cm-2 yr-1). Organic content remains above 90% (Fig.4.2) with the land pollen influx increases to ~4,889 grains cm-2 yr-1 supported by increased pollen influx from Poaceae, Asteraceae (Subf. Asteroideae), *Gunnera* and Cyperaceae. The pollen remains relatively well persevered in this LPAZ (average of ~69%) as it continues its oscillating but progressive deterioration since the MB2 eruption but contains an increasing amount of broken/crumpled grains.

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| A screenshot of a social media post  Description automatically generated  Figure 4.5. Lago Fox summary pollen and spore diagram |

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| A close up of a piece of paper  Description automatically generated  Figure 4.6. Lago Fox pollen accumulation rate (influx) diagram for selected taxa |

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| A screenshot of a cell phone  Description automatically generated  Figure 4.7. Lago Fox percentage pollen preservation diagram with charcoal influx. |

#### Summary of vegetation change

As the ice retreated from Lago Fox sometime before c. 15.7 kcal yr BP the post glacial landscape was colonised by grassland taxa and herbs like *Gunnera*, Poaceae, *Empetrum* and *Acaena*. The site was initially a freshwater lake environment supported by the presence of *Myriophyllum* and *Pediastrum*. A vegetation community was quickly established by around c. 15.3 kcal yr BP dominated by grassland taxa Poaceae and Asteraceae (Subf. Asteroideae) with arboreal taxa seen for the first time by the emergence of *Nothofagus* around c. 14.3 kcal yr BP. *Nothofagus* continued to expand until closed canopy forest was achieved around c. 11.4 kcal yr BP outcompeting the majority of other taxa, indicated by a comprehensive trend of decline in grassland and herb species.

Significant changes are seen from c. 11.3 kcal yr BP with a steady decline in *Nothofagus* concurrent with increasing Poaceae and many other grassland and herb taxa and also a sharp rise in Polypodiaceae. These changes are coeval with the deterioration of pollen preservation, the disappearance of aquatic taxa and a change from lacustrine mud to peat in the stratigraphy, indicating hydroseral succession had taken place at the site. These changes in the vegetation community persisted until around c. 5 kcal yr BP when pollen preservation began to improve, and full canopy forest was again reached with grassland taxa and herbs all declining.

Following the MB2 eruption (c. 4.2 ka cal yr BP) the site is dominated by two species; *Nothofagus* and *Empetrum*. Both are ubiquitous until the present but seem to have an inverse relationship where one will increase coeval to the other’s decline. *Pediastrum* returns in small amounts, suggesting pools of standing water on the bog surface which seemingly contradicts the punctuated but protracted decline in pollen preservation to the present.

## Interpretation of the vegetation record

### Late glacial period

Following the LGM that included glacial advance stages ‘B’ and ‘C’ (c. 25.2-23 kcal yr BP and 22.4-20 kcal yr BP respectively), the warming climate after glacial stage D initiated the retreat of the Magellan glaciers in the Late glacial period around 17.5 kcal yr BP (McCulloch et al 2005a), which is consistent with the cosmogenic and radiocarbon ages of c. 17 kcal yr BP obtained from the southern margins of the Cordillera Darwin (Hall et al.,2013) and evidence from Antarctic ice core records suggesting regional warming between c. 17-15 kcal yr BP (Jouzel et al., 2007). The Lago Fox site became ice free sometime before c. 15.7 kcal yr BP and thereafter the accumulation of organic lacustrine sediments began to fill the kettle hole suggesting more favourable climatic conditions than during glacial stage D.

During primary succession of the deglaciated landscape and throughout the Late-glacial period, Lago Fox was a freshwater lake environment, supported by the presence of the aquatic taxa *Pediastrum* and *Myriophyllum* in the record and lacustrine mud seen in the stratigraphy. The organic content suggests a low amount of productivity within the lake with the presence of aquatic pollen indicating that temperatures were warm enough for seasonal productivity. The lake is likely to have been surrounded by *Empetrum rubrum* heathland, which is known to colonise de-glaciated landscapes (Pisano 1977). However, around c. 15.5 kcal yr BP *Empetrum* began to diminish and was succeeded by Poaceae and *Gunnera*, also successful pioneer species of post glacial environments indicating the steppe/tundra nature of the landscape (Section 1.5.2).

Despite warming temperatures in the LGIT the presence of the cold tolerant taxa *Empetrum* and Poaceae suggests the Late glacial in this region was still relatively cold supported by the relatively cold temperatures from Antarctic ice core records (Jouzel et al., 2007). Despite the steppe/tundra landscape, the presence of the wetland herb *Gunnera* indicates the environment remained moist enough for this species to survive. These conditions are supported by the high percentage of normal pollen grains (Section 2.3.5) found in this phase (~85%). The low organic content (<20%) and low land pollen influx (~593 grains cm-2 yr-1) during this period are indicative of the treeless and pioneer nature of the surrounding vegetation.

There was an isolated trace of *Nothofagus* that was most probably the result of transportation from a neighbouring area of glacial refugia across Canal Whiteside in Tierra del Fuego rather than the establishment of the species on Isla Dawson (Mansilla *et al*., 2016). Although the moisture in this phase was sufficient for the establishment of *Gunnera*, the more humid conditions required by *Nothofagus* had not yet been reached.

Although *Gunnera* and *Empetrum* heathland persisted throughout LF-2 they were now outcompeted by grassland taxa with Poaceae becoming well established by the time of the Volcán Reclus eruption (R1) (c. 15.4 kcal yr BP) and was now the dominant species throughout the LPAZ. The presence of other grassland and herb taxa including Asteraceae (Subf. Asteroideae), *Acaena* and Caryophyllaceae may suggest a marginally warming environment, however there was a striking decline in Asteraceae (Subf. Asteroideae) between 14.5-13.4 kcal yr BP that could suggest a brief return to cooler temperatures. The early establishment of *Nothofagus* beginning at c. 14.3 kcal yr BP indicates an increase in effective moisture in the region, which is consistent with the amount of well-preserved pollen within LF-2 (~88%).

### Early-Holocene period

The increasing dominance of *Nothofagus* in LF-3 now suggests a transition from steppe tundra to the onset of more temperate and humid Early Holocene conditions. This led to full canopy forest cover (>80%) between c. 12.5-11.3 kcal yr BP and was concurrent with the decline of most heath and grassland taxa. There was a subsequent decline in *Nothofagus* after c. 11.1 kcal yr BP and the simultaneous appearance of *Misodendrum* *spp*., which thrives in more temperate conditions on a number of *Nothofagus* species particularly in open canopy forest (Markgraf et al., 2002). The understory was now less shaded allowing grassland taxa such as Poaceae, Asteraceae (Subf. Asteroideae) and Cyperaceae to flourish. These dynamic vegetation changes suggested a reduction in moisture supported by decreasing levels of the aquatic *Pediastrum*.

The dense forest canopy began to open up around c. 11.3 kcal yr BP concurrent with a deterioration of pollen preservation (~30%) suggesting a reduction of effective moisture in the region. There is also a marked increase in levels of organic content in the sediment at this point (from ~45% to 88% LOI550) supported by the transition from lacustrine mud to less well humified peat in the stratigraphy. This evidence indicated that hydroseral succession was taking place and that increasing amounts of Cyperaceae were expanding across the newly dried out surface of the bog. As humidity continued to decrease in the region, forest cover continued its decline and the less well humified peat of the bog slowly transitioned to darker peat indicating a drier environment.

### Mid-Holocene period

The warm and dry conditions of the Early-Holocene were augmented in this ‘arid’ phase typified by the demise of the forest canopy from closed to open between c. 10.5-6.0 ka cal yr BP, with *Nothofagus* reduced to an average of ~35% and to negligible influx levels, concurrent with a rise in grassland species such as Poaceae, Asteraceae (Subf. Asteroideae) and *Acaena*. Reduced levels of effective moisture were also implied by the complete decline in *Pediastrum* and the continued deterioration in pollen preservation, down to ~35%. The declining moisture levels were concurrent with the onset of high concentrations of charcoal particles within the core (c. 10.5-8 kcal yr BP), suggesting the availability of drier fuel in the landscape and greater frequency of fires (Markgraf and Huber, 2010; Mansilla *et al*., 2016). There is further evidence of a more temperate climate in this phase with a contemporaneous rise in Polypodiaceae between c. 10.8-6 kcal yr BP. This species has been ever-present in small amounts (~10%) since the Late-glacial but prefers a warmer climate and is not tolerant to shade so adapts well to open canopy woodland and is therefore able to flourish in this warmer phase (Schneider et al., 2010).

There is another dynamic change in the moisture regime around c. 5 kcal yr BP with an increase in *Nothofagus* coupled with the demise of grassland taxa and increasing levels of well-preserved pollen (~95%) indicating the return of humid conditions. The disappearance of Polypodiaceae around c. 5 kcal yr BP suggests cooler temperatures are now affecting the site but the increased shading of full canopy forest could also account for the demise of this species. There was a brief period of arboreal decline following the eruption of Mount Burney (MB2) at c. 4.2 kcal yr BP that covered the region in a thick layer of volcanic ash reducing the organic content in the sediment to ~8%. This was concomitant with increasing *Empetrum* heathland and could be considered to be an effect of the eruption. These trends were also seen at another site on Isla Dawson at Rio Grande (Mansilla, 2015) and on Tierra del Fuego at Punta Yartou and Lago Lynch (Mansilla et al., 2016, 2018). Some studies suggest an association between volcanic eruptions and suppressed or damaged vegetation (Fesq-Martin et al., 2004; Kilian et al., 2006; Fontana and Bennett, 2012), however in these cases it is likely to be climatically induced as the declining/inclining trends marginally preceded the eruption in all instances.

### Late-Holocene period

*Empetrum* heathland had become firmly established at Lago Fox after the MB2 eruption. The stratigraphy was now showing less well humified peat around c. 3.3 kcal yr BP indicating a more humid environment and *Pediastrum* had also reappeared in small amounts suggesting pools of standing water on the bog surface by c. 2.7 kcal yr BP. The onset of variable woodland canopy coverage and fluctuating pollen preservation from c. 5 kcal yr BP to the present indicates changing environmental conditions in this phase inferred by rapid fluctuations in moisture and temperature regimes (Section 4.6.4). Around ~20% of the deteriorated pollen grains are attributed to broken or crumpled grains that suggests damage during the transportation process that may indicate increased surface run-off on the slopes surrounding the bog through augmented precipitation and reduced vegetation cover. *Empetrum* heathland was now well established all the way to the present, albeit with varying levels of abundance (~10-73%) but with diminishing amounts of standing water, with the demise of *Pediastrum* around c. 1.4 kcal yr BP indicating less humid conditions at this stage.

This was coeval with a sharp reduction in *Nothofagus* and growth of *Misodendrum* around 900 cal yr BP. The open woodland canopy allowed the re-emergence of taxa such as Poaceae, Cyperaceae and the shade intolerant Polypodiaceae. This declining humidity was reflected in the stratigraphy with a change from less well humified peat to darker and consolidated peat between c. 1100-600 cal yr BP with decreasing levels of pollen preservation (~65%). These drier conditions were coupled with the return of small amounts of charcoal in the sediment suggesting increased fire activity (Markgraf and Huber, 2010; Mansilla *et al*., 2016), which could well have been anthropogenic in nature.

## Climatic inferences at Lago Fox

The Lago Fox pollen record is dynamic, with frequent and rapid changes throughout with the palaeoenvironmental data showing four clear stages of palaeoclimatic development. Initially there is a post-glacial environment with pioneer species emerging in a cold steppe tundra landscape (c. 15.6-12.5 kcal yr BP). This is followed by more humid conditions that allow the establishment of forest around c. 14.4 kcal yr BP but is succeeded by an arid phase that reduced the forest canopybetween c. 11.2-6 kcal yr BP. There is then a phase of more humid/cooler but variable climatic conditions that endured from around c. 5 kcal yr BP until the present.

Two study sites from progressively drier sections of the precipitation gradient on Isla Dawson are also utilised to compare and analyse the varying moisture regimes along the south west-north east precipitation gradient in the region. Rio Grande (53°39’ S, 70°30’ W, 79 m asl) (Mansilla, 2015) to the north of Lago Fox and Estancia Esmeralda II (53°30’ S, 70°35’ W, 60 m asl) (Fig.1.5) (McCulloch and Davies, 2001) in the north eastern steppe region of the island are utilised in the discussion as they employed the same methods and approaches as in Lago Fox, allowing a more robust reconstruction of the nature and timing of changing paleoclimates in southernmost Patagonia. Other sites within the region are also employed to support the Lago Fox data and build upon the developing palaeo research in Patagonia.

### Cold/Dry Steppe Tundra

Antarctic ice core records show a warming phase of around ~8°C in the Magallanes region sometime after c. 17 kcal yr BP (Blunier and Brook, 2001; Jouzel et al., 2007; Lemieux *et al.,* 2010; Caniupán *et al.,* 2011) leading to glacial retreat after glacial stage D (McCulloch *et al.,* 2005b) (section 4.2.1) and ice free conditions at Lago Fox sometime before c.15.7 kcal yr BP.

During the Late-glacial c. 15.6-12.5 kcal yr BP the record suggests Lago Fox was a freshwater lake environment surrounded by heathland and other pioneer species typical of recently deglaciated environments. This post glacial landscape was cooler and drier than present due to the northerly focus of the SWWs at this stage (McCulloch *et al*., 2000; Bertrand et al., 2014). At this time, the SWWs were beginning their poleward migration from the CLD, where they had relocated during the LGM (Hulton *et al.*, 2002) and their zone of high precipitation had a marginal effect on the climate of Isla Dawson. However, the moisture regime remained sufficiently moist for the wetland herb *Gunnera* to thrive and enable well-preserved pollen in the record which can be attributed to the penetration of humidity from a more easterly airflow from the South Atlantic during this period of weaker SWWs, as evidenced by isotopic evidence (Xia et al., 2018) as the core of the SWWs were positioned in the north (McCulloch et al., 2020). This post-glacial vegetation community is also seen at Rio Grande (Mansilla, 2015) and Estancia Esmeralda (McCulloch and Davies, 2001) on Isla Dawson and within the Magallanes region at Punta Yartou (53º54’ S, 69°26’ W 165 m asl) and Lago Lynch (53°51’ S, 70°68’ W 51 m asl) on Tierra del Fuego (Mansilla et al., 2016, 2018) and also on the mainland at Puerto del Hambre (53°37’ S, 70°56’ W 6 m asl) (McCulloch and Davies, 2001), all reflecting this cold and relatively dry steppe tundra environments.

There is a tenuous vegetational response to a short phase of colder conditions in Lago Fox around c. 14-12.8 ka cal yr BP that is coeval to an ACR signal seen in Antarctic ice core records (Blunier et al., 1997; Mulvaney et al., 2012; Gest et al., 2017) and is also seen in palaeoenvironmental records from Rio Grande on Isla Dawson and at Lago Lynch on Tierra del Fuego. The almost complete absence of vegetation response is likely due to the insensitivity of dominant steppe vegetation which were tolerant to relatively small-scale temperature changes as seen in the ~1°C reduction during the ACR suggested by the John Ross Island (JRI) ice core (57°41’S) (Mulvaney et al., 2012).

### Early establishment of *Nothofagus* forest

The post glacial vegetation community endured throughout the Late-glacial until around c. 14.3 kcal yr BP when there was the early establishment of *Nothofagus* at Lago Fox indicating warming temperatures and increased humidity at the site. In the Early Holocene the record shows a developing open canopy forest expanding to full canopy by c. 11.5 ka cal yr BP. This stage of forest development indicates an increase in effective moisture, suggesting the SWWs had migrated further south and were beginning to influence the vegetation of the Magallanes region by exposing Isla Dawson to the apex of its precipitation (Sugden et al., 2005; Fletcher and Moreno, 2011).

The pollen in this stage is very well preserved indicating it was deposited in humid conditions. The orographic nature of this increased humidity is distributed in diminishing levels along the precipitation gradient from the wetter Lago Fox (proximal to the Andean Cordillera), through Rio Grande (Mansilla, 2015) to the arid Estancia Esmeralda (distal from the mountains) (McCulloch and Davies, 2001) leading to delayed forest establishment further from the Cordillera Darwin. *Nothofagus* is seen in trace amounts at Rio Grande from around c. 14 kcal yr BP but its development and expansion are not seen until c. 12.7 kcal yr BP. At Estancia Esmeralda there are trace amounts of *Nothofagus* in the record from around c. 12 kcal yr BP but does not show expansion until c. 9 kcal yr BP which is a significant temporal lag compared to Lago Fox and to a lesser extent to Rio Grande. This temporal lag is seen at other sites in the Magallanes region with forest establishment around c. 13.5 kcal yr BP at Punta Yartou (~20 km to the east of Isla Dawson on Tierra del Fuego), c. 13.3 kcal yr BP at Lago Lynch (~65 km east) and c. 10.5 kcal yr BP at Puerto del Hambre (~40 km to the northwest on the mainland). The staggered vegetational response across the precipitation gradient shows the disparity in moisture distribution and illustrates the protracted migration of the forest/steppe ecotone as the SWWs increase their influence on the region by delayed forest development and expansion with increased distance from the Cordillera Darwin.

### Arid phase

The forest expansion was followed by a significant period of contraction between c. 11.2-6 kcal yr BP, concurrent across all sites on Isla Dawson, indicating a reduction in effective moisture which is reflected in the deterioration of pollen preservation.

At Lago Fox this dry period commenced around c. 11.2 ka cal yr BP indicated by a reduction in *Nothofagus*. There is a short resurgence of the species at c. 10.8 ka cal yr BP before it declines into open canopy forest by c. 10.1 ka cal yr BP that was sustained until c. 6 ka cal yr BP. The lake had now dried out and formed a bog that was colonised by many taxa including Cyperaceae. There was a striking rise in charcoal in the sediment during this arid phase (~400-1900 particles cm-2 yr-1) which was in stark contrast to the paucity of charcoal throughout the Lago Fox record (ranging from ~0 to 100 particles cm-2 yr-1). The increased but punctuated amounts of charcoal indicate favourable conditions for fire ignition over a two-thousand-year period, which suggests environmental change during this phase, indicated by a reduction in humidity at this site. The abundance of Polypodiaceae throughout this arid phase also suggests a warmer climate (Schneider et al., 2010).

This dry period also affects the other sites along the precipitation gradient. The Rio Grande record (Mansilla, 2015) showed reduced forest cover from around c. 11 kcal yr BP but extends beyond that of Lago Fox to around c. 4 kcal yr BP. Estancia Esmeralda (McCulloch and Davies, 2001), which only had a maximum forest cover of ~30% shows a smaller decline in canopy between around c. 8.5-4 kcal yr BP. This arid phase is also seen in the records at Punta Yartou, Lago Lynch (Mansilla et al 2016, 2018) and at Puerto del Hambre (McCulloch and Davies, 2001). The palaeoenvironmental records from this phase suggests a decrease in effective moisture in the region exhibiting a shift of the forest/steppe ecotone (towards the Andean Cordillera) indicating the SWWs are no longer directly influencing the vegetation on Isla Dawson and had continued their meridional migration depriving the site of its core of higher precipitation.

### Late Holocene Climate Variability

The arid phase concludes with forest expansion and the demise of grassland taxa around c. 5 kcal yr BP at Lago Fox indicating the return of more humid and cooler conditions. This infers the SWWs had now begun to migrate equatorward from the Southern Ocean (McCulloch et al., 2019) and the influence of the storm fronts were providing increased precipitation to the region. The temporal delay in forest expansion at Rio Grande (c. 3.7 kcal yr BP) (Mansilla, 2015) and Estancia Esmeralda II (c. 2.5 kcal yr BP) (McCulloch and Davies, 2001) again displays the protracted shifting of the forest steppe ecotone seen along the precipitation gradient on Isla Dawson. The palaeoenvironmental evidence not only reflect the wetter and cooler conditions, they also show increasing variability with oscillating abundance of *Nothofagus* in all three sites throughout this period suggesting the levels of effective moisture was fluctuating. Following c. 5 kcal yr BP the pollen preservation record from Lago Fox shows a protracted and punctuated decline from > 95% to ~65% at present. There are seven periods of rapid climate change evident from the pollen preservation record leading to drier conditions throughout this decline between; c. 4.7-3.8 kcal yr BP, c. 3.3-2.8 kcal yr BP, c. 2.4-2.2 kcal yr BP, c. 2-1.8 kcal yr BP, c. 1.7-1.5 kcal yr BP, c. 1.3-1.1 kcal yr BP and c. 900-500 cal yr BP (Fig.4.7). There are also five significant periods in the vegetation record where *Nothofagus* declines during this period (Fig. 4.5) but not all match the pollen preservation which suggests a degree of resilience in the vegetation records or possible temporal lags. These periods of rapid climate change suggest drier and warmer conditions that would be reflected in a relatively brief poleward focus of the SWWs during a general equatorward migration. This indicates that the SWWs equatorward migration was responding to sub millennial episodes of warming climate leading to increased seasonality in the region with probably increased winter precipitation during these warmer periods.

*Empetrum* heathland had now become established at Lago Fox with no, or declining grassland species such as Poaceae indicating the SWWs were now migrating further north of Isla Dawson towards their present latitude of ~50°S (McCulloch et al*.*, 2000). The highly humid conditions of the SWWs core were no longer directly influencing the regional climate and reduced humidity was shifting the forest/steppe ecotone sufficiently south west, depriving Estancia Esmeralda II (the most distal from The Cordillera Darwin) of moisture, as shown by a prominent reduction of forest cover at the site (McCulloch and Davies, 2001). The variability in palaeoclimate suggests that the migration of the SWWs to their current position took some time to stabilize at its present latitude of ~50°S.

It is likely that as global temperatures stabilised in the mid to late Holocene, the sub-tropical and polar fronts influence on the latitudinal position of the SWWs would have diminished somewhat, moving them north and south in smaller augmentations until they settled into their contemporary position. These brief periods of rapid climate change are indicative of a relatively short-lived poleward focus of the SWWs during the general equatorward migration indicating that in the last c. 5 kcal yr the equatorward migration was responding to sub millennial episodes of warming climate causing increasingly irregular SAMs. The palaeoenvironmental records from the study sites suggest this pattern continued until the culmination of the SWWs migration to its current location (~50°S). Nevertheless, these fronts continue to act upon the SWWs as they migrate north to ~45°S in Austral winter and to ~50°S in Austral summer.

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| A screenshot of a cell phone  Description automatically generated  Figure 4.8. Summary of SWWs migration and effects on climate and vegetation at Lago Fox. |

## Conclusion

The palaeoenvironmental record from Lago Fox on Isla Dawson reveals a salient interpretation of latitudinal shifts in the SWWs and reflects a convincing pattern of regional climate change during the Late glacial and Holocene in this southerly location. As ice began to retreat from Lago Fox sometime before c.15.7 kcal yr BP the warming temperatures of the LGIT produced a steppe/tundra environment colonised by pioneer species typical of post glacial landscapes. It remained a relatively cold and drier environment than present day in the absence of the SWWs humidity, which was reflected in the vegetation response to such conditions. The transition from the colder environments of the Late glacial to the warmer and more temperate Early Holocene conditions marked the beginning of forest development at Lago Fox and reflected the increasing humidity from the SWWs on its poleward migration from the north by supplying the region with increased precipitation. These humid conditions were distributed in diminishing amounts across the precipitation gradient as evidenced by the records at Rio Grande and Estancia Esmeralda. There is a marked transformation from these humid conditions in the Early Holocene to that of the ‘arid’ environment of the Mid Holocene with a distinct reduction in pollen preservation and forest cover between c. 10.8-6 kcal yr BP and evidence of fire activity at the site. The combined evidence suggests a clear reduction in effective regional moisture with a migrating forest/steppe ecotone towards the Andean Cordillera, reflecting the continued poleward migration of the SWWs and the contracting latitudinal spread of storm fronts as they shift southward to their apex. An equally prominent period of forest expansion in the Late Holocene suggests that humid conditions had returned with the SWWs now migrating equatorward towards their contemporary latitudinal position, providing increased precipitation and climatic variability in the area as they pass over the region and follow an oscillating conclusion to their contemporary latitudinal position.

# Punta Burslem

## Introduction

The configuration of continental landmass in the polar regions lead to distinctive climates in the mid-high latitudes of the northern and southern hemispheres. In the north, the continents cluster around the Arctic Ocean generating sea ice in the Arctic Ocean, whereas in the south, Antarctica is the only large landmass which is located centrally and surrounded by the vast Southern Ocean. The paucity of land allows the prevailing SWWs almost uninterrupted passage to circumnavigate Antarctica. The surface friction of the SWWs on the ocean surface drives the ACC which in turn promotes upwelling of CO2 into the atmosphere making it a fundamental component of the global atmospheric system (Toggweiler et al*.*, 2009; Marshall and Speer, 2012; Turney et al., 2016; Fogwill et al., 2019). The core of the SWWs currently lies at ~50°S but they latitudinally migrate seasonally with positive and negative SAMs (Abram et al., 2014) and is the main process for distributing precipitation in Andean Patagonia. This seasonal migration produces a wider latitudinal range of the SWWs and reduced wind speeds in northern and central Patagonia during Austral winter (June-August) while southern Patagonia has increased precipitation and wind speeds during Austral summer (December-February) (Garreaud et al., 2013). This latitudinal migration is augmented according to global temperatures with increased equatorward migration during a cooling climate and increased poleward migration during a warming climate (Toggweiler et al*.*, 2006). Modelling of the Patagonian ice sheet suggests the SWWs migrated a further ~5° of latitude northwards during the Last Glacial Maximum (Hulton et al., 2002), likely reducing the amount of CO2 vented into the atmosphere from the Southern Ocean leading to cooler global temperatures (Anderson et al*.*, 2009) (Section 1.3).

Our understanding of palaeoclimatic change in Patagonia is improving with increasing levels of research in the region (Markgraf and Huber, 2010; Ponce et al., 2011; Borromei et al., 2016; Mansilla et al., 2016, 2018; Musotto et al., 2016a, 2016b) but the timing and nature of the migratory tracks of the SWWs during the Late glacial and Holocene remain less understood. A positive SAM induces greater wind velocities in the Southern Ocean creating a greater upwelling of CO2 from deep below the surface and into the atmosphere leading to increased global temperatures. During global warming trends this southerly migration is augmented with the possibility of subsequent positive feedback mechanisms (Section 1.2). Therefore, the southern extent of the SWWs migration during the Holocene could reveal significant information of palaeoclimate and could reflect future global warming scenarios for South America. This study will determine if the core of the SWWs migrated as far as Isla Navarino or further into the Southern Ocean. To date there has only been two palaeoecological studies from Isla Navarino (Heusser, 1989; McCulloch et al., 2019) so it is anticipated that this new palaeoenvironmental record from the island (~55°S) south of The Beagle Channel will build on this research and help to constrain the SWWs southernmost migratory extents during the Holocene.

## Materials and Methods

### Study area: Isla Navarino

Isla Navarino is located at the southern extremity of Patagonia, south of the Canal Beagle (~55°S) (Fig.1.2 and 1.5). It is one of the southernmost regions on Earth with Cape Horn (Cabo de Hornos) only 30 km to the south, separating it from Antarctica. It is one of the largest islands in the Tierra del Fuego archipelago, the largest of which, Isla Grande de Tierra del Fuego lies to the north of the Canal Beagle. This channel is an ice-scoured trough formed through glacial abrasion from successive glacial episodes by the ‘Beagle Glacier’ an outlet glacier from the Cordillera Darwin Ice Cap (Rabassa et al.,2000; 2008b). The glacial sequence in this region is based upon the Magellan Strait sequence of glacial stages A-E (Section 4.2.1) (McCulloch et al, 2005a; Kaplan et al 2008).

### Punta Burslem

The study site is an ombrotrophic bog located near Pta Burslem on the northern coastline (54°54’05.62” S, 67°57’11.39” W, altitude 54 m asl) approximately 25 km west of Puerto Williams (Fig.2.5). The Servicio Hidrográfico y Oceanográfico de la Armada de Chile map name the point as Punta Burshem. However, it is thought to have been named Punta Burslem during the voyage of HMS Beagle in reference to Charles Darwin’s wife, Emma Wedgwood, who had an association with the town of Burslem in Staffordshire, England (Risopatrón, 1924). It was chosen for its proximal location to the Cordillera Darwin and therefore situated in the more humid section of the precipitation gradient. The orographic nature of the moisture regime creates a hyper humid region as the saturated SWWs are forced up and over the mountains in the west and south west where the majority of the moisture condenses and falls as precipitation, with a subsequent rain shadow effect in the lee of the mountains.

The bog was probably formed as a kettle hole at the end of the LGM and is enclosed within an oval shaped basin (~230 x 160 m) with the enclosed character suggesting it will be sensitive to changes in precipitation. The surface of the bog is characterised by a complex of hummocks that are mostly covered with *Empetrum rubrum and Gaultheria microphylla* and hollows mostly filled with pools of water and *Sphagnum* moss (Fig.2.6). The southern rim of the bog has steep relief with gentler slopes around the remaining edges mostly colonised by *Nothofagus antarctica* with *Chilliotrichum spp* shrubs colonising the margins of the bog. Open canopy *Nothofagus pumilio* forest surrounds the basin with a profusion of the hemi-parasite *Misodendrum* and a scattering of *Ribes magellanicum* and *Berberis microphylla* in the more open spaces. The considerable size of the bog at Pta Burslem indicates a large pollen source catchment area therefore representing a good regional pollen signal (Prentice, 1985).

### Sediment coring and laboratory methods

The deepest point of the bog was estimated and cored to an impenetrable base of 1100 cm; the deepest point of Pta Burslem was estimated by probing with a gouge in a grid formation prior to coring. The sediment cores were obtained using a 50 cm long D-section Russian corer 5.5 cm in diameter (Jowsey, 1966) and a continuous 1100 cm core from the centre of the Pta Burslem mire with glacial sediments at the base was retrieved. The stratigraphic characteristics of each 50 cm core section was recorded, sealed in layflat tubing and returned to the University of Stirling where they were stored at a constant 4 °C.

The organic content was estimated by Loss on Ignition with dried sediment samples combusted at 550°C for 4 hours (LOI550). 98 sub-samples (1 cm3) were taken from the core at a resolution of between 4 cm and 16 cm and prepared for pollen analysis using standard techniques (Moore et al., 1991) (Section 2.3.1). A minimum total of 300 TLP grains were identified per sample, excluding Cyperaceae, aquatics, spores and algae and the identification of pollen and spores was supported by photographs of pollen and spores (Heusser, 1971; Villagrán, 1980; Wingenroth and Heusser, 1984; Moore et al., 1991) and a pollen reference collection. The pollen and spore data were presented using Tilia software version 2.0.41 (Grimm, 2011). The pollen data are divided into Local Pollen Assemblage Zones (LPAZ) determined by changes in Land Pollen (constrained by cluster analysis on TLP >2%) (Grimm, 1987).

Pollen, spores and algae concentrations were estimated by adding a known quantity of *Lycopodium clavatum* spores to each sample(Stockmarr, 1971). The total pollen and charcoal accumulation rate (influx: No. grains or particles cm-2 yr-1) was determined using the the concentration values (No. grains cm-3) and sediment accumulation (cmyr-1) (Fig.5.4). Charcoal particles between ˃10 and ˂180 μm were counted and measured alongside the pollen as a proxy of past fire activity (Whitlock and Larsen, 2001).

The physical condition of fossil pollen within the sediment was also considered, as it can infer the environmental conditions in which it was deposited. When assessing the palaeoenvironmental conditions of the study site they were placed into five preservation categories; normal, broken, crumpled, corroded and degraded (Berglund and Ralska- Jasiewiczowa, 1986; Tipping, 1987) (Section 2.3.5) (Fig.2.8).

One cryptotephra layer was found during the pollen identification process and in mineral residue during the LOI550 process (Fig.5.1). The tephra was segregated from the sediment by acid digestion in preparation for optical investigation (Dugmore et al., 1992) and the mineral content was then assessed using light and polarising microscopy. The major element geochemical composition of each tephra sample was categorized by electron microprobe analysis to determine its origins using the SX100 Cameca Electron Microprobe at The [University of Edinburgh](http://www.ed.ac.uk/) (Hayward, 2012). A minimum of 10 tephra shards were analysed to provide a representative geochemical signature (Hunt and Hill, 1993). Comparisons were made with geochemical data from previous studies to enhance the tephra identification process (McCulloch, 1994; Stern, 2008; Mansilla, et al., 2016, 2018) (Appendix A) (Fig.5.2).

## Results

### Stratigraphy

The Pta Burslem stratigraphy comprises bluish-grey clays and silts at the base between 1100-1082 cm likely deposited during the latter stages of the kettle hole development. This is overlain by lacustrine mud which increases from LOI550 <10% at 1082 cm to ~40% organic content by 1028 cm. Organic content plateaus between 1028 cm and 910 cm then increases until the lacustrine phase transitions into less well humified peat (LOI550>80%) at 882 cm and then turns to darker more humified peat at 808 cm and switches between these two states of peat six times towards the surface (Fig.5.1).

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| A close up of a map  Description automatically generated  Figure 5.1. Punta Burslem sediment profile  The profile displays organic content determined by LOI550, sediment stratigraphy and the LPAZ’s determined from the percentage pollen diagram (Fig.5.3) by CONISS with BACON age-depth model (Blaauw and Christen, 2011). It also shows the tephra layer within the core from Vn Hudson (H1). |

### Chronology

There were no visible tephra layers within the sediment but an investigation to find possible crypto tephra layers within the record was undertaken to refine the chronology by using an acid digestion technique to disaggregate the glass shards from the organic content within the sediment in preparation for EMP analysis (Dugmore et al., 1992) (Section 2.6.2), To focus the area of investigation, the LOI and acid digestion data in conjunction with a rudimentary age-depth model was used to target areas within the sediment column, focusing on R1, H1 and MB2 . One cryptotephra layer was identified at 595 cm (Fig.5.1).

Eight AMS radiocarbon dates from in-situ peat (Section 2.6.1.2) were used to constrain the chronology of the Pta Burslem record (Table. 5.1). The radiocarbon chronology is helped by the presence of a cryptotephra layer at 595 cm that is linked to the H1 eruption dated to 7241±23 14C yr BP (Stern et al., 2016).

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| Table 5.1. Radiocarbon ages, calibrated age ranges and median ages for the Pta. Burslem record.  A screenshot of a cell phone  Description automatically generated |

This study uses a previously identified and well dated tephra to enhance the chronology. The geochemical analysis allowed the correlation from this study with previous research (Section 4.4.2). The tephrochronology for Pta Burslem is based on one cryptotephra layer. Investigations found other cryptotephra within the sediment core but in insufficient quantities to perform geochemical analysis on the Electron Probe Microscope. Tephra found at 596 cm is geochemically matched to an eruption from Volcán Hudson (H1) from the SVZ (Stern et al., 2016) (Fig.5.2). This data was correlated to H1 tephra from Lago Lynch and Punta Yartou (Mansilla et al., 2016; 2018). This cryptotephra consists of dark green-brown platy glass shards, similar to the ones seen at Lago Fox (Fig.4.2b). The geochemical analysis of this andesitic tephra is almost identical to Lago Fox with SiO2 between 63.3-65.8 wt.%, TiO2 ≤ 1.34 wt.% and Fe ≤ 5.21 wt.%.

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| A screenshot of a social media post  Description automatically generated  Figure 5.2. Geochemical analysis of Punta Burslem tephra  Percentage totals of SiO2 versus TiO2/Fe for individual glass shards showing the correlation of the H1 tephra from Punta Burslem (PB 590 cm) with Lago Lynch (LL H1) and Punta Yartou (PY H1) (Mansilla et al., 2016; 2018). |

Age-depth models were constructed using Bayesian modelling software BACON (Blaauw and Christen, 2011) and the pollen diagram was constrained using an age-depth axis (cal yr BP) from the median ages (Section 2.6.3). The age-depth model suggests the basal age is estimated to be c. 17 kcal yr BP (Fig. 5.1).

### Pollen Stratigraphy

Eight Local Pollen Assemblage Zones (LPAZ’s) were identified for the Pta Burslem core from the percentage pollen data (Fig.5.3) and constrained cluster analysis (CONISS, Grimm, 1987) and these LPAZs are applied to all the stratigraphic figures.

#### LPAZ PB-1 (1095-925 cm; c. 16.8-12.6 cal yr BP)

Following the retreat of ice, the preliminary LPAZ is predominately an open heath and grassland. The initial pollen assemblage at Pta Burslem began sometime after c. 16.8 kcal yr BP and is dominated by well-preserved herb and shrub pollen (~97% normal). *Empetrum rubrum* heathland dominates (~55%), peaking around c. 14.8 kcal yr BP but then begins a gradual decline towards the upper boundary of the LPAZ (c. 12.6 kcal yr BP). Poaceae is also prevalent (averaging ~25%), starting around ~10% and although steadily increasing throughout PB-1, shows a step wise increase, peaking at ~40% around c. 15 kcal yr BP. Other specialists of cold Steppe/Tundra environments Asteraceae (Subf. Asteroideae), Asteraceae (Tribe Nassauviaeae)*, Gunnera*, Caryophyllaceae and *Acaena* are present at the lower boundary at around c. 16.8 kcal yr BP. Asteraceae (Subf. Asteroideae) maintains an almost constant presence of ~14% throughout PB-1, with Asteraceae (Tribe Nassauviaeae)*, Gunnera*, Caryophyllaceae and *Acaena* all thriving at the beginning of PB-1 (~15%, 12% , 7% and 5% respectively) but all diminishing to <3% by the upper boundary except *Acaena* which shows a slight increase and also the appearance of Amaranthaceae in trace amounts. The basin was occupied by the shallow rooting aquatic *Myriophyllum* initially <10% but peaking at ~30% towards the middle of the LPAZ (c. 14.6 kcal yr BP) declining to <10% again by around c. 12.6 kcal yr BP. The algae *Pediastrum*, which favours clear post glacial water bodies (Komárek and Jankovská, 2001) is also dominant with proportions of ~40% at the start of PB-1 rising to and remaining stable at > 80% for the remainder of the LPAZ. This evidence indicates the site was a freshwater lake as temperatures began to rise in the LGIT. Although the organic content initially increased to ~40% LOI550 the Land Pollen Influx (LPI) remained low throughout the LPAZ (~526 grains cm-2 yr-1) (Fig.5.4).

#### LPAZ PB-2 (925-884 cm; c. 12.6-12.2 cal yr BP)

This LPAZ is again characterised by open heath and grassland with trees becoming established later. Non-arboreal taxa continue to dominate this LPAZ with *Empetrum rubrum* beginning PB-2 at ~48% although declining to ~20% by around c. 12.2 kcal yr BP. Poaceae starts and finishes PB-2 at ~17% peaking at ~25% around 12.4 kcal yr BP. There is a small expansion of Asteraceae (Subf. Asteroideae) to ~20% before declining to ~10% by c. 12.2 kcal yr BP with a corresponding increase in the ground cover *Acaena* ~25% but is short lived as it declines quickly by c. 12.2 kcal yr BP*. Gunnera* has declined to trace amounts since PB-1 and an appearance of *Galium* type is seen in marginal quantities. *Nothofagus* emerges tentatively at the lower boundary (~4%) rising gradually to ~10% before expanding abruptly to ~43% by c. 12.2 kcal yr BP indicating the establishment of an open canopy forest. *Myriophyllum* peaks at > 60% at the lower LPAZ boundary and then together with *Pediastrum* show a striking decline until they disappear towards the upper boundary (c. 12.2 kcal yr BP) concurrent with a rise in Cyperaceae and fern spores (Polypodiaceae). Organic content within the sediment increased in PB-2 to ~60% as the stratigraphy begins to show a transition from lacustrine mud to very light coloured less well humified peat. There is also an increase in pollen influx ~1871 grains cm-2 yr-1 reflecting the more established vegetation community at the site. The pollen in this zone is again very well preserved with an average of ~93% normal state (Fig.5.5).

#### LPAZ PB-3a (884-834 cm; c. 12.2-11.7 cal yr BP)

This sub-LPAZ is typified by swiftly changing landscapes that shifted between forest and open grasslands. The dynamic nature of PB-3a shows pollen proportions swinging rapidly between taxa throughout. The pollen assemblage is generally dominated by the same taxa as PB-2 but the equilibrium has changed with *Nothofagus* being the most prominent variable showing two marked reductions followed by rapid increases. It fluctuates from ~43% to ~17% by c. 12 kcal yr BP and then expands to ~48% before falling back again to ~14% by c. 11.8 kcal yr BP, then increases again towards the upper boundary. *Empetrum rubrum* briefly reverses its decline from PB-2 increasing modestly to ~34% but continuing its general downward trend since PB-1. Poaceae increases swiftly to ~75% by around c. 11.8 kcal yr BP before declining to ~46% by the upper boundary. Asteraceae (Subf. Asteroideae) is present in lower proportions (~11-4%) but also fluctuates alongside the tree cover, rising to ~29% just after the large peak in Poaceae. The abundant nature of *Acaena* seen in PB-2 has now declined to trace amounts in PB-3a. Cyperaceae and Polypodiaceae maintain a consistent presence (~7% and ~10% respectively) with *Sphagnum* appearing in trace amounts and with aquatic taxa disappearing during this sub-LPAZ suggests the end of lake conditions at the site. This is supported by the stratigraphy with a transition from the less well humified light coloured peat from PB-2 to a darker but still less well humified peat and increased organic content to ~88% indicating hydroseral succession has taken place. Although pollen preservation remains relatively high in this sub-LPAZ (~83% normal), there is a noticeable decline from PB-2 suggesting drier conditions at this time. Pollen influx marginally decreases to ~1103 grains cm-2 yr-1

#### LPAZ PB-3b (834-775 cm; c. 11.7-11 cal yr BP)

This sub-LPAZ continues the dramatic fluctuations in tree cover and open grasslands but forests begin to dominate towards the latter stages. *Nothofagus* peaks (~69%) at the lower sub-LPAZ boundary and then rapidly declines to ~16% by c. 11.6 kcal yr BP. The sharp decline in Poaceae seen in the latter stages of PB-3a is briefly reversed, rising to ~41% together with a small peak in Asteraceae (Subf. Asteroideae) (~20%) during the drop in *Nothofagus* (c. 11.6 kcal yr BP)but both decline (~19% and ~8% respectively) towards the sub-LPAZ boundary at c. 11 kcal yr BP. This marks the last of the rapid high-magnitude fluctuations in *Nothofagus* which then begins a steady rise to ~60% and is sufficient to support the presence of the hemiparasite *Misodendrum*. *Empetrum rubrum* increases to ~8% and the other principal herbaceous and shrub taxa, *Acaena* and *Gunnera* persist but with substantially reduced (<5%) proportions. Polypodiaceae and *Lycopodium* rise to a peak of ~40% and ~5% respectively at the start of the sub-LPAZ and then gradually decline as tree cover increases. Mid-way through this sub-LPAZ (c. 11.4 kcal yr BP) *Pediastrum* returns to the record suggesting pools of standing water on the bog surface and increased humidity at the site, supporting the increase in tree cover. There is a rise in Cyperaceae to the highest seen in the record (~12%) suggesting the colonisation of the newly formed bog surface and trace amounts of Apiaceae but declines again with the increase in *Pediastrum*. Organic content continues to increase during this sub-LPAZ to ~91% with darker and more humified peat seen in the stratigraphy and the land pollen influx remains constant at ~1082 grains cm-2 yr-1 (Fig.5.4). The pollen preservation remains almost unchanged in this phase (~81% normal). The influx of Charcoal particles has been consistently very low from the start of PB-2, however, in PB-3b the charcoal influx values make a small but distinct rise towards the upper boundary at c. 11 kcal yr BP.

#### LPAZ PB-4 (775-668 cm; c. 11-9.4 cal yr BP)

This LPAZ is characterised by dense forests with decreasing abundance of grasslands. *Nothofagus* continues to increase towards the mid-point of the LPAZ, reaching a peak of ~86% at c. 10.3 kcal yr BP before declining to ~79% by c. 9.4 kcal yr BP and is accompanied by trace amounts of *Misodendrum*. Poaceae correspondingly declines then increases in an inversely proportional fashion to *Nothofagus*. During the first half of PB-4 *Pediastrum* makes a resurgence and then virtually disappears from the record by around c. 10.2 kcal yr BP, suggesting the standing pools of water on the surface of the bog have disappeared by this point. The influx of charcoal particles also peaks at the start of this LPAZ, reaching maximum levels of the entire record (~1870 particles cm-2 yr-1) and pollen preservation begins a significant decline around c.10 kcal yr BP. PB-4 also sees a general decline of grassland and herb taxa as forest cover continues to expands. *Empetrum* remains throughout the LPAZ but in low abundance (~5%) while Asteraceae (Subf. Asteroideae), *Acaena* and *Gunnera* have all regressed from PB-3b. Polypodiaceae shows a punctuated decline before recovering around c. 10 kcal yr BP and the declining trend in Cyperaceae shown in PB-3b continued into this LPAZ but a recovery is seen coeval with the disappearance of *Pediastrum* around c. 10.2 kcal yr BP. Organic content remains the same as PB-3 at ~91% with pollen influx marginally increasing to ~1286 grains cm-2 yr-1. The rise in charcoal particles seen towards the end of PB-3b continues in PB-4, rising rapidly to the highest peak in the record of ~1620 grains cm-2 yr-1 then shows a comparably sharp decline to ~250 grains cm-2 yr-1 before rising again to ~680 grains cm-2 yr-1 by c. 10.6 kcal yr BP (Fig 5.4).

#### LPAZ PB-5 (668-495 cm; c. 9.4-6.4 cal yr BP)

The dense forests of PB-4 were in decline in this LPAZ allowing the expansion of open grasslands and heath. The decline in *Nothofagus* seen at the upper boundary of PB-4 continues during this LPAZ, falling from ~78 % to a nadir of ~44% at the time of the deposition of the H1 tephra layer at c. 8 kcal yr BP and corresponds to the lowest point of pollen preservation in the record (~54%). Although PB-5 represents the LPAZ with the poorest pollen preservation, there remains a variability in the condition of the pollen seen in the record (Fig.5.5). From the nadir around c. 9 kcal yr BP, the preservation increases to ~70% at c. 8.1 kcal yr BP but deteriorates to ~60% by c. 7.4 kcal yr BP. There is another improvement to ~73% at 6.9 kcal yr BP before again showing marginal deterioration towards the upper boundary. A large percentage of the pollen is degraded (~25%) and corroded (~16%) indicating desiccation. The arboreal decline is punctuated by two short peaks (~70%) at c. 8.5 and c. 7.7 kcal yr BP respectively and decline in tree cover is coeval with the marginal increase of the hemi-parasite *Misodendrum*. The declining *Nothofagus* again corresponds to an increase in Poaceae and Asteraceae (Subf. Asteroideae) from ~13% to ~28% and ~8% to ~31% respectively. Other taxa show a continued presence throughout PB-5; *Empetrum* remains relatively constant at ~5% but peaks at ~10% following the H1 eruption, Cyperaceae also remains fairly constant around ~6% with Polypodiaceae showing a punctuated decline from ~20-10%. There are also trace amounts of *Acaena*, *Gunnera*, Apiaceae and Saxifragaceae with the return of minor peaks in *Pediastrum* coeval with the spikes in *Nothofagus*, suggesting small pools of standing water on the bog surface. The reduction in tree cover continues until around c. 7 kcal yr BP after which *Nothofagus* shows a steep increase again, returning the forest to full canopy (~81%) by c. 6.2 kcal yr BP. Charcoal remains present in the record at ~170 grains cm-2 yr-1. Organic content remains unchanged during this LPAZ at ~87% but the land pollen influx declines to ~686 grains cm-2 yr-1.

#### LPAZ PB-6 (495-359 cm; c. 6.4-3.9 kcal yr BP)

Forests were once again dominant and expanded towards closed canopy towards the latter stages of this LPAZ, leading to reduced grasslands. *Nothofagus* was the leading taxon starting at the lower boundary of PB-6 at ~81% and steadily increased reaching ~93% by c. 4.2 kcal yr BP which was concurrent with the virtual exclusion of all herbaceous taxa with Poaceae, Asteraceae (Subf. Asteroideae), *Empetrum, Gunnera*, *Acaena*, Cyperaceae and Polypodiaceae all showing downward trends. Charcoal influx started with a high peak of ~740 particles cm-2 yr-1 at c. 6.4 kcal yr BP but was only episodically present throughout the rest of the LPAZ. Organic content in this LPAZ and to the surface continued to be above ~95% and the land pollen influx values increased to ~1789 grains cm-2 yr-1. There is rapid improvement in pollen preservation by c. 5.8 kcal yr BP (~88%) followed quickly with a steady deterioration to ~68% by c. 4.8 kcal yr BP. This variable nature continued with rapidly improved preservation by c. 4.6 kcal yr BP (~90%) which is again followed by deterioration by the upper boundary.

#### LPAZ PB-7 (359-103 cm; c. 3.9-2 kcal yr BP)

The characteristics of this LPAZ are of dense forest cover with the loss of most other vegetation types. The region surrounding Pta Burslem is now wholly dominated by *Nothofagus* (~96%) leading to an almost complete absence of all other species. Grassland and herbaceous taxa still exist but only in trace amounts including Poaceae, Asteraceae (Subf. Asteroideae)*, Gunnera* and *Acaena* with Cyperaceae and Polypodiaceae also showing a marginal presence. *Empetrum* is the only other taxa showing a greater presence (> 2%) throughout PB-7 and marginally increasing after c. 2.7 kcal yr BP. As the *Nothofagus* proportions increase, *Misodendrum* declines and by c. 3 kcal yr BP disappears from the LPAZ suggesting the forest canopy is now too dense for its survival. The high proportion of *Nothofagus* is reflected by the very high pollen preservation and accumulation rates of peat. The preservation made a continued improvement from the lower boundary to around c. 2.9 kcal yr BP (~97%) and ended PB-7 at ~86% with two brief periods of deterioration at c. 3.6 kcal yr BP and 2.2 kcal yr BP (~85% and ~82% respectively). At this time land pollen influx achieve their highest values for the entire record (mean ~6665 grains cm-2 yr-1), largely contributed by *Nothofagus*.

#### LPAZ PB-8 (103-0 cm; c. 1980-Present)

There is now a gradual decline in forest cover in this LPAZ, punctuated by two distinct periods of rapid contraction which allows heathland to gain a foothold at the site. *Nothofagus* continues to be the dominant taxa in PB-8 with overall proportions >90%, but with two prominent forest reductions shown between c. 1.8-1.3 kcal yr BP (~79%) and one between c. 700-350 cal yr BP (~72%) with corresponding increases in heathland (*Empetrum*) peaking during these periods (~19% and ~27% respectively). Trace amounts of herbaceous taxa return to the record in PB-8 including *Misodendrum,* Asteraceae (Subf. Asteroideae), *Rumex* and *Gunnera*. Organic productivity continues unchanged in this LPAZ at ~98% but the total land pollen influx has decreased to ~2528 grains cm-2 yr-1. The state of pollen preservation is again varied in this LPAZ with an initial deterioration to ~70% by c. 1.8 kcal yr BP before improving to ~86% by c. 1.5 kcal yr BP. This is again followed by more deterioration by c. 1.1 kcal yr BP (~76%) then improving by c. 700 cal yr BP (~90%) and a marginal decline to the present.

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| A screenshot of a cell phone  Description automatically generated  Figure 5.3. Punta Burslem summary percentage pollen and spore diagram |

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| A picture containing object, antenna  Description automatically generated  Figure 5.4. Punta Burslem pollen accumulation rate (influx) diagram for selected taxa |

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| A screenshot of a cell phone  Description automatically generated  Figure 5.5. Punta Burslem percentage pollen preservation diagram with charcoal influx. |

#### Summary of vegetation change

As the ice retreated from Pta Burslem sometime before c. 17 kcal yr BP the site was a freshwater lake environment supported by the presence of the aquatics *Myriophyllum* and *Pediastrum* in the record.The stratigraphy also showed lacustrine mud between c. 16.8-12.2 kcal yr BP with a low carbon content within the sediment. The lake would have been surrounded by mainly *Empetrum rubrum* heathland and by grassland taxa like Poaceae and Asteraceae (Subf. Asteroideae) with other cold tolerant taxa such as *Gunnera*, Caryophyllaceae and Asteraceae (Tribe Nassauviaeae) which are typical of post glacial landscapes.

These non-arboreal taxa continued to dominate the region until around c. 12.6 kcal yr BP when *Nothofagus* emerged and began expanding until open canopy forest was reached around c. 12.2 kcal yr BP. At this time the declining *Myriophyllum* and *Pediastrum* had disappeared from the record indicating hydroseral succession had taken place supported by the stratigraphy showing a change from lacustrine mud to peat. Cyperaceae was concurrently expanding in the record suggesting it was colonising the newly formed bog surface. There followed a period of rapid high magnitude fluctuations in *Nothofagus,* concurrent with a deterioration in pollen preservation, until around c. 11.4 kcal yr BP where a steady expansion is seen culminating in closed canopy forest by c. 10.3 kcal yr BP. At this time *Nothofagus* was outcompeting most other taxa with grassland species showing a general decline in the record. Contrastingly there was an increase in Polypodiaceae, reaching a peak around c. 11.7 kcal yr BP and then showed a slow but punctuated decline. There is a coeval rise in *Pediastrum* until c. 10.2 kcal yr BP as Polypodiaceae begins its gradual decline, which coincides with a small improvement in pollen preservation in the record but also a seemly conflicting rise in charcoal in the sediment.

The record shows a marked forest contraction between c. 9.5-6.4 kcal yr BP suggesting another change in the moisture regime in the region coeval with a deterioration in pollen preservation. In this period there is a clear increase in grassland taxa like Poaceae and Asteraceae (Subf. Asteroideae) with a marginal increase in *Acaena* and *Gunnera* and continued presence of charcoal in the sediment. After c. 6.4 kcal yr BP there is a steady expansion of *Nothofagus* until closed canopy forest is again reached around c. 5.8 kcal yr BP. This had a detrimental effect on most other taxa as grassland and herb taxa decline to trace amounts or disappeared altogether by around c. 3.9 kcal yr BP. This again suggests a change in the moisture regime in the region and coincides with improving pollen preservation in the record. This forest cover is maintained until the present with the exception of two brief but distinct periods of tree reduction with a corresponding rise in *Empetrum* heath between c. 1.8-1.3 kcal yr BP and 700-350 cal yr BP (~72%).

## Interpretation of the vegetation record

Although there are increasing numbers of palaeoenvironmental records from Fuego-Patagonia and the Canal Beagle area, they are occasionally blurred by using different approaches or methods and over varying intervals that restrict the ability to compare between sites. A study site from Caleta Eugenia (Fig.1.5) in the eastern sector of Isla Navarino (McCulloch et al., 2019), using the same methods and approaches as in Pta Burslem is employed to compare and analyse the varying moisture regimes along the west-east precipitation gradient in tandem with other study sites in the region from the published literature allowing a more robust reconstruction of the nature and timing of changing paleoclimates in southernmost Patagonia.

### Late glacial environment

The basal age taken from the contact between the organic lacustrine sediment and the underlying bluish-grey clay/silt provides a minimum age of c. 17 kcal yr BP for ice retreat from Pta Burslem and the western region of Isla Navarino. This age is consistent with cosmogenic and radiocarbon ages obtained from the southern margins of the Cordillera Darwin (Hall et al., 2013) and evidence from Antarctic ice core records suggesting a regional warming beginning around c. 17 kcal yr BP (Jouzel et al., 2007). This relatively older age from Pta Burslem could be related to its proximal location to the Cordillera Darwin and therefore wetter end of the precipitation gradient. This would have allowed earlier development and preservation of vegetation that could be radiocarbon dated and was also seen in the Magellan Straits (McCulloch et al., 2005). Organic sedimentation began sometime after 16.8 kcal yr BP with the post-glacial environment characterised by a treeless landscape dominated by cold tolerant steppe vegetation with *Empetrum* heath-grassland, including dryland flora of Asteraceae Subf. Asteroidea and *Acaena*. Between c. 16.8 and 12.2 kcal yr BP there appears to be little change in the cold-tolerant land vegetation. The presence of *Myriophyllum* and *Pediastrum* suggest the site was a freshwater lake environment. However, there are changes in the proportions suggesting fluctuating lake levels, indicating an increase by c. 14.6 kcal yr BP, enabling an expansion of the shallow water rooting *Myriophyllum*. The shallow-lake period persisted until c. 13.6 kcal yr BP followed by gradually decreasing lake levels that eventually drove back *Myriophyllum* to a minimum at c. 12.7 kcal yr BP.

This phase in the development of the site at Pta Burslem coincides with the timing of the Antarctic Cold Reversal (ACR) c. 14.4-12.7 kcal yr BP (Gest et al., 2017). It is unclear if the ACR was responsible for the decline in *Myriophyllum* but water levels, higher or lower, would have contributed to its demise. Except for the evidence of changes in abundance of aquatic flora at Pta Burslem and slightly reduced pollen preservation at Cta Eugenia (McCulloch et al., 2019), there is no clear response of the terrestrial vegetation to the ACR found in the pollen records at both of these sites. This is likely due to the insensitivity of dominant steppe vegetation which were tolerant to relatively small-scale temperature changes as the ~1°C reduction during the ACR suggested by the John Ross Island (JRI) ice core (57°41’S) (Mulvaney et al., 2012).

Following the lake level decrease during the ACR levels began increasing again between c. 12.7 and 12.5 kcal yr BP facilitating a large expansion of *Myriophyllum* followed by an equally rapid decline by c. 12.1 kcal yr BP concurrent with a reduction in heathland taxa as *Nothofagus* and *Acaena* colonise the slopes surrounding the site and Cyperaceae replaces the *Myriophyllum* as the site develops into a fen. This evidence suggests a post-ACR warming climate with the rapid increase in *Myriophyllum* indicating lowering lake levels to their optimal growing conditions in shallow water, but steadily decreasing levels lead to hydroseral succession. This is also reflected in the demise of *Pediastrum* and the rapid stratigraphic changes from lacustrine mud to peat which was probably accelerated by climatic warming between the ACR and the Holocene.

The Pta Burslem record suggests the transition between the colder environments of the Late glacial and temperate conditions of the Holocene (between c. 12.5 and 11.7 kcal yr BP) was not marked by a smooth progression. The establishment of *Nothofagus* forest reflects a ‘flickering switch’ punctuated by three significant periods of rapid woodland expansion followed by equally rapid contraction coeval with an inversely proportional response with *Empetrum*. The evidence presented suggests a continuation of warming conditions. The swift decline in tree cover could be an increased local pollen signal from *Empetrum* as it was able to colonise the drying surface of the site. Through this transition period, although there are distinct changes in the stratigraphy as lighter less well humified peat grades into darker less well humified peat which developed into peat, a subtle reduction in levels of effective moisture is identified as vegetation shifts form heath to grass. This is probably in response to rising temperatures, which marginally lag the ice core records at JRI (Mulvaney et al., 2012) but are synchronous with sea surface temperatures (SST) (41°00’S) (Lamy et al., 2010). There is a brief but significant rise in humidity at Cta. Eugenia (McCulloch et al., 2019) seen in rapidly improving pollen preservation (~27-45%) concurrent with the flickering switch at Pta. Burslem, but *Nothofagus* did not become established here for another ~1500 years which is in keeping with other records for the establishment and distribution of *Nothofagus* forest (Borromei, 1995; Heusser, 1998; Borromei et al., 2016). This temporal lag is likely a reflection of wetter conditions at Pta. Burslem which is located on the western extent of the precipitation gradient favouring the spread of *Nothofagus* from refugia located to the north (Mansilla et al., 2016; Premoli et al., 2010). The moisture regimes of both sites are reflected in the pollen preservation data with Pta. Burslem exhibiting better preserved pollen grains than Cta. Eugenia.

### Early Holocene forest expansion

The density of *Nothofagus* forest continues to increase around Pta. Burslem after c. 11.7 kcal yr BP leading to a corresponding reduction in herbaceous taxa as they are out competed for light and moisture. Warmer conditions are inferred by SSTs, that peak around c. 10.5 kcal yr BP (Lamy et al., 2010) and supported by the expansion of polypod ferns (Polypodiaceae), but even these are gradually supressed in the pollen record by an augmenting forest canopy, reducing the available light to the understory. The return of probably small standing pools of water on the bog surface is indicated by the reappearance of *Pediastrum* between c. 11.3 and 10.5 kcal yr BP. The return of standing water at the site, despite warmer climatic conditions, suggests that for ~850 years there was also a substantial increase in precipitation along the north-western coast of Isla Navarino. This is not replicated at Cta Eugenia which continued to show deterioration in pollen preservation indicating reduced moisture with warming temperatures probably restricting the easterly migration of the forest-steppe ecotone towards the drier end of the precipitation gradient. In contrast to the increasing humidity at Pta Burslem, there is evidence of higher influx of charcoal between c. 11 and 10.5 kcal yr BP which, regardless of the speculation regarding the source of ignition, points to the availability of drier fuel. This seems counter intuitive as an increase in moisture, forest and charcoal would suggest that wetter wood would be less likely to burn, however this may reflect the greater availability of woody fuel and/or the increase of seasonal fire activity (Moreno et al., 2012). This may suggest greater seasonality in the temporal distribution of moisture, however, the evidence for fire during this period is limited.

Coeval to this increased humidity at Pta Burslem there is contrasting moisture regimes seen to the north of Canal Beagle. In the northern Magallanes region (~52°S), the Ultima Esperanza area was experiencing increased fire activity and a lowering of lake levels after c. 11,600 cal a BP (Moreno et al., 2012). There is substantial forest contraction and fire activity in the central Magallanes region (~53°S) from Isla Dawson c. 11,700 cal a BP (McCulloch and Davies, 2001) and Lago Lynch c. 11,050 cal a BP (Mansilla et al., 2018). There is also significant contraction of forest cover and fire activity in the southern Magallanes region at Pto. Harberton from c. 11 kcal yr BP (Markgraf and Huber, 2010).

After c. 10.4 kcal yr BP there is a rapid disappearance of *Pediastrum* at Pta Burslem suggesting the pools of standing water had dried up as *Nothofagus* forest reaches a peak of ~86%. There then follows a period of sustained forest contraction as humidity begins to decrease.

### Mid-Holocene ‘arid’ phase

The shift to drier conditions that started at the end of the early Holocene continued in this phase as *Nothofagus* forest declined further with other herbaceous taxa, such as Poaceae and Asteraceae Subf. Asteroideae showing a corresponding increase. The persistence of aerobic conditions at the mire surface as a result of reduced moisture levels is strongly demonstrated by the deterioration in the state of the pollen preservation to its lowest in the record at both Pta. Burslem and Cta. Eugenia (McCulloch et al., 2019). Again, the progression of vegetation change was not smooth but punctuated by periods of forest recovery. The period of most marked drier conditions was between c. 9.5 and 6.4 kcal yr BP and is coeval with evidence for warmer surface waters and retreat of extant ice shelves along the Antarctic Peninsula (Mulvaney et al., 2012). The eruption of Volcán Hudson (H1) occurred at the nadir of this period (*c.* 8 kcal yr BP). The H1 tephra was a cryptotephra in the Pta Burslem core but had a measurable quantity of tephra in the LOI550 profile. Volcán Hudson is located ~1600 km to the north of Isla Navarino which suggests the H1 eruption was very large and probably had a significant impact on the flora, fauna and human population of the region (Stern, 1991).

### Late Holocene climate variability

After c. 6.4 kcal yr BP the forest gradually expanded again until full canopy was restored at Pta. Burslem towards the end of the mid-Holocene around c. 3.9 kcal yr BP suggesting the gradual return of more humid conditions. During this recovery phase *Misodendrum* is able to thrive when the forest is still relatively open. The extent of woodland cover at Cta. Eugenia was significantly less (*Nothofagus* ~20% TLP) and so the expansion of woodland is more gradual at this end of the precipitation gradient and closed woodland is not achieved until c. 3000 cal a BP. The Late Holocene is characterised by this complete dominance of *Nothofagus* closed canopy forest which led to the virtual exclusion of all herbaceous taxa competing for light, including the polypod ferns and *Misodendrum*.

Although the forest cover appears stable in the Late Holocene, there are periods of rapid climate change seen in the pollen preservation records of both Pta Burslem and Cta Eugenia (McCulloch et al., 2019). These occur between c. 5-4.7 kcal yr BP, 4.3-3.3 kcal yr BP, 2.6-1.8 kcal yr BP and 1.3-1.1 kcal yr BP suggesting drier conditions during these periods, however not all of these are reflected in vegetation changes in the pollen records. This suggests a degree of vegetation resilience to relatively small changes in climate which would have indicated brief poleward focus of the SWWs.

The period of generally cooler and wetter conditions persisted until c. 2 kcal yr BP which was followed by a period punctuated by two relatively small contractions of forest cover and corresponding expansion of heathland at c. 1510 and c. 475 cal yr BP which suggests potentially cooler and drier conditions at the bog surface leading to the expansion of *Empetrum*. These periods at c. 1510 and c. 475 cal yr BP may have a tenuous link to neoglacial and Little Ice Age glacier advances (Aniya, 1996) and reflect cooler temperatures from the JRI ice core record (Mulvaney et al., 2012). This cooling could reflect the Little Ice Age signal with colder drier conditions at Pta. Burslem and Cta. Eugenia. Also, the Pta Burslem and Cta. Eugenia records are consistent with periods of more Atlantic moisture flow to southern Tierra del Fuego reconstructed from isotopic evidence (Xia et al., 2018).

## Climatic Inferences at Punta Burslem

Glaciological and palaeoenvironmental studies for Patagonia show that during the LGM the SWWs had likely migrated northward by ~5° from their current focus at ~50°C (Hulton et al., 2002; Lamy et al., 2010; McCulloch et al., 2000). The additional moisture brought by the SWWs was able to sustain large glaciers that coalesced into one continuous ice sheet that extended from the Chilean Lakes Region (~39°S) to Tierra del Fuego (~55°S) during the LGM. Such a large latitudinal spread was sustained by the expanding belt of the SWWs as the polar front was pushed northward (Anderson et al., 2009). As climatic temperatures began to rise in the LGIT, consistent with the warming trend evidenced in Antarctic ice core records (Mulvaney et al., 2012; Gest et al., 2017), the subtropical high pushed the polar front southward, reducing the moisture supply to the Chilean Lakes Region (~41°S) leading to the collapse of the Patagonian ice sheet and the eventual formation of the current North and South Patagonian Icefields (Hulton et al., 2002). As temperatures continued to rise into the Early Holocene an arid phase began affecting many regions of Patagonia but as the SWWs continued their poleward migration they also created distinct wet phases through the focused humidity of these fronts as they continued on their journey south. These wet and dry phases are evident from the record at Pta Burslem and can help to track their migration temporally until their current location ~50° and are summarised in Figure 5.6.

As regional temperatures began to rise at the start of the Late-glacial, the margins of The Canal Beagle glacier retreated to the Cordillera Darwin sometime after c. 16.8 kcal yr BP (Caniupán et al., 2011). At this stage Pta Burslem was a treeless heathland with typical pioneer plant species of a post-glacial landscape suggesting it was a cold steppe tundra environment and probably lower humidity than present day as the core of the SWWs were positioned in the lower latitudes and had a minimal effect on the moisture regime and climate of this Austral region. Yet there was sufficient humidity to sustain some wetland taxa which most probably penetrated from the south eastern Atlantic (Xia et al., 2018). The Early Holocene was a time of dynamic change with the establishment of *Nothofagus* at Pta Burslem (c. 12.2 kcal yr BP) which rapidly expanded and contracted over a period of ~1000 years before developing firstly into open, then full canopy forest by c. 10.8 kcal yr BP indicating an increase in effective moisture at the site. This collective evidence suggests that the core of the SWWs were acting upon Pta Burslem producing maximum precipitation while to the north it was leading to drier conditions as these storm fronts continued their poleward migration during this thermal maximum. This evidence is consistent with other records from central Tierra del Fuego that show a relatively coeval establishment and development of *Nothofagus* forest (Mansilla et al., 2016; 2018). However, regions to the north of Pta. Burslem were experiencing a concurrent reduction in humidity as the frontal core of the SWWs continued to contract as it migrated poleward. Lowering of lake levels and increased fire activity at Ultima Esperanza area (~52°S), and forest contraction and increased fire activity in central and southern Magallanes region (~53-54°S) all suggest a reduction in effective moisture (Moreno et al., 2012; McCulloch and Davies, 2001; Mansilla et al., 2018). The temporal lag of forest development at Cta. Eugenia reflects the orographic nature of the precipitation gradient with full canopy forest achieved ~1600 years after Pta. Burslem (McCulloch et al., 2019).

The Mid-Holocene record shows a reduction in humidity starting around c. 9.6 kcal yr BP triggering a decline of *Nothofagus* that opened up the forest canopy (between c. 9.5 and 6.4 cal yr BP) allowing the resurgence of grassland species. The presence of charcoal during this period of the record suggests an increase in fire activity at the site throughout the arid phase at Pta Burslem. This arid phase is also seen in south-eastern Tierra del Fuego (Musotto et al., 2016a, 2016b), central and central-western Tierra del Fuego (Mansilla et al., 2016; 2018), Peninsula Brunswick and Isla Dawson (McCulloch and Davies, 2001). The reduction in effective moisture suggests the SWWs had moved away from the site, perhaps continuing on its poleward migration and could reflect the maximum phase of poleward contraction and intensification of the SWWs. This arid phase is very distinct as the belt of SWWs notably contracts on its poleward migration, concentrating the zone of high precipitation into a smaller latitudinal range making it more evident in the record (Garreaud et al., 2013). This extremely positive SAM would have augmented the ACC and increased CO2 degassing into the atmosphere, with warmer global temperatures (Turney et al., 2016) causing a subsequent rise in SSTs in the Southern Ocean leading to a reduction of sea ice around the Antarctic Peninsula (Bentley et al., 2009). This period in the Mid Holocene could reflect future global warming scenarios as current research suggests an increasing positive SAM over the past 40 years, coeval with globally warming temperatures (Toggweiler, 2009; Thompson et al., 2011).

The return of humid conditions around c. 6.4 kcal yr BP suggests that the SWWs *had* continued to migrate south and were now returning, bringing a sustained increase in effective moisture back to the region resulting in forest expansion once again. Towards the end of the Mid Holocene the forest had returned to full canopy with the exclusion of almost all other grassland and herb taxa (~ 5 kcal yr BP).

The Late Holocene shows a period of relative stability in the vegetation records with full canopy forest indicating a humid environment, however it masks the short-lived periods of rapid climate change seen in the pollen preservation records indicating brief warm periods. The apparent vegetation stability suggests a resilience to small changes in climate, however this is interrupted twice in the last ~2000 years with sharp dips in *Nothofagus* and coeval expansions of heath suggesting periodic drops in effective moisture and cooling temperatures possibly reflecting the Little Ice Age signal and an equatorward shift of the SWWs, but this recovered by the present day. This brief period of climatic instability is also seen at Lago Fox and could be explained by latitudinal fluctuation of the SWWs until their current position was reached, or more Atlantic moisture flow along weaker SWWs to Southern Tierra del Fuego and Canal Beagle.

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| A screenshot of a social media post  Description automatically generated  Figure 5.6. Summary of SWWs migration and effects on climate and vegetation at Pta Burslem. |

## Conclusion

The palaeoenvironmental record from Pta. Burslem on Isla Navarino reflects a compelling pattern of regional climate change during the Late glacial and Holocene. Its southernmost location in the Canal Beagle (~54°S) also provides a valuable insight into the intensity and latitudinal shifts of the SWWs in this period. As global temperatures started to increase in the LGIT, the SWWs began their poleward migration from their northerly position during the LGM whilst Pta. Burslem remained ice-bound until around c. 16.8 kcal yr BP. As the ice retreated the post glacial environment remained relatively cold and dry and the landscape was initially colonised by Steppe/Tundra pioneer species in the absence of the humidity of the SWWs. The record cautiously suggests a drop in effective moisture coinciding with the ACR between c.14.5 and c. 13.6 kcal yr BP before the transition to Holocene conditions that heralded a warmer and more temperate climate by c. 11.6 kcal yr BP. The development of *Nothofagus* into an established forest canopy around c. 10.4 kcal yr BP suggests increasing levels of humidity, which was reflected in sites located at the same latitude (~54-55°S) in Tierra del Fuego and Canal Beagle. Combined evidence of the increased moisture regime at Pta. Burslem and the concurrent reduction in humidity at sites north of the region indicates the full force and precipitation of the SWWs core was influencing the vegetation in western Isla Navarino. A defined ‘arid phase’ is evidenced between c. 9.7 and c. 6.0 kcal yr BP which indicates that the SWWs migrated into the Southern Ocean for around ~3.7 kcal years in the Mid Holocene, augmenting the ACC and upwelling of CO2 into the atmosphere leading to an increased warming trend and instability of Antarctic ice-shelves. This has implications for future global warming scenarios that command further research. The return of humid conditions after c. 5.5 kcal yr BP heralded the return of the SWWs as they began the short equatorward migration to their contemporary position of ~50°S, then a period of instability as they settled into their contemporary position of ~50°S.

***This data chapter has been published in Quaternary Science Reviews and can be found in Appendix C.***

# Palaeoenvironmental Synthesis

This chapter will provide a synthesis of the palaeoenvironmental records from the three study sites at Cerro Ataud, Lago Fox and Punta Burslem (Fig.1.2) and integrate their conclusions with those established in the literature (Fig.1.5 and 1.6) to present an enhanced understanding of the migration of the SWWs in the mid-high latitudes of Patagonia since the end of the LGM. It will reconstruct the spatial and temporal sequence of environmental change produced by this migration along a latitudinal transect from 47°S to 55°S and will also reflect on the subsequent effect the shifting SWWs had on the longitudinal precipitation gradient during their migration.

## Synthesis of palaeoenvironmental change in Southern Patagonia (~47°S to ~55°S) during the Late glacial and Holocene

It is generally established in the literature that the SWWs have a major influence on the climate of the southern high latitudes (Toggweiler et al*.*, 2006, 2009; Bentley et al., 2009; Rojas et al., 2009; Fletcher and Moreno 2011; Sydeman et al., 2014; Fogwill et al., 2019) but agreement on their temporal and spatial characteristics is by no means unanimous (Section 1.6.1). The timing and nature of climatic changes during the Late glacial and Holocene in SSA and the response of vegetation communities have been under-researched when compared to the northern hemisphere but are beginning to be better understood. This chapter will build on the increasing climate research in the southern hemisphere by providing a synthesis of the climatic inferences for Southern Patagonia based on the conclusions of palaeoenvironmental evidence from the three study sites and integrate their conclusions with those established in the literature. It will provide a brief recap of the characteristics of the SWWs and then describe their influence on the ecology and climate in the high latitudes.

The suite of palaeoenvironmental evidence in this study show the extent of spatial and temporal environmental change across this region of Patagonia during the Late glacial and Holocene. It is possible to reconstruct the sequence of environmental change across this region by using a robust chronology that can connect all three sites with the migration of the SWWs during this period.

### Late glacial period (c. 17-11.7 kcal yr BP)

Following the LGM and the onset of warming temperatures, evidence for the reorganisation of the ocean-atmosphere system suggests a southward migration of the SWWs during the LGIT, in response to shifts in the sub-tropical high and the polar convergence zone (Sugden et al., 2005). Antarctic ice core records, SSTs and palaeoenvironmental records suggest that climatic temperatures began to rise in Patagonia in the Late glacial sometime after c. 18.8 kcal yr BP leading to the retreat of glacial mass from the Andean Cordillera (Lamy et al., 2010; Caniupán et al., 2011; Mulvaney et al., 2012; Gest et al., 2017). In the absence of additional moisture provided by the northerly position of the SWWs during the LGM, the equilibrium of the internal mass balance of the Patagonian Ice Sheet shifted as summer ablation outpaced winter accumulation, leading to relatively swift glacial retreat (Benn and Evans, 2013). The southern regions of Magallanes experienced a marginally lagged temporal response to this climatic warming probably caused by their proximal location to the cooler temperatures of the polar convergence zone, with evidence showing the retreat of the Magellan glaciers around c. 17.7 kcal yr BP (McCulloch et al., 2005b).

Pta Burslem was the first of the three sites in this study to become ice-free sometime before c. 17 kcal yr BP followed by Lago Fox before c. 15.7 kcal yr BP while Cerro Ataud remained ice-bound for longer, probably due to its more proximal location to the NPI, becoming ice-free sometime before c. 13.4 kcal yr BP. The warming pulse led to plant colonisation in the post glacial landscapes of Pta Burslem and Lago Fox, with both vegetation communities showing similar characteristics. They were both treeless environments colonised by typical pioneer species emerging in a relatively cold steppe tundra landscape but humid enough to sustain some wetland taxa. They were initially freshwater lake environments, supported by the presence of *Pediastrum* and *Myriophyllum* in the record and were likely to have been surrounded by heathland and wetland herbs. This evidence suggests the SWWs had only a marginal influence on the ecology of the Magallanes region when they began migrating poleward at this time as the high degree of precipitation in the core of these storm fronts continued to sustain glacial mass in the CLD (Hulton et al., 2002). Therefore, relatively cold temperatures at Lago Fox and Pta Burslem were probably the limiting factor for ecological development. However, the presence of wetland taxa suggests there was a degree of humidity in the region to allow their development. Isotopic evidence (Xia et al., 2018) suggests this localised effective moisture was most probably from more easterly airflows from the Atlantic as the core of the SWWs were positioned in the north (McCulloch et al., 2020).

There was a shift towards more mesic conditions at Lago Fox and Pta Burslem after c.15 kcal yr BP with grassland taxa becoming increasingly dominant. The absence of any significant changes in the pollen preservation records suggests this transformation is likely to have been caused by an increase in temperature in the region. As temperatures continued to rise in the Late glacial there is tentative evidence of a brief reversal of global temperatures between c. 14.5 kcal yr BP and c. 12.8 kcal yr BP in the Pta Burslem and Cta Eugenia records (McCulloch et al., 2019) with a reduction of aquatic taxa and pollen preservation respectively which could reflect a reduction of humidity. This pattern is consistent with a brief hiatus in the poleward migration of the SWWs in response to climatic cooling in the Late glacial and is coeval with a ~1°C drop in temperature during the ACR seen in the JRI ice core records (Mulvaney et al., 2012). This brief cooling period would be sufficient to have triggered a short-term equatorward migration of the SWWs. The dominance and insensitivity of cold tolerant steppe vegetation to small temperature variations may be the reason there are no marked response to climatic cooling during the ACR found in the terrestrial vegetation record at Pta Burslem. There is a marked increase in the cold resistant dryland herb Asteraceae (Subf. Asteroideae) seen in the Lago Fox and Rio Grande records (Mansilla, 2015) that could be tenuously linked to an ACR signal, but this is not replicated at Pta Burslem.

Steppe tundra landscape persists until the emergence of arboreal taxa at Lago Fox around c. 14.3 kcal yr BP and later at Pta Burslem around c. 12.6 kcal yr BP. There is no significant change in pollen preservation during this initial development suggesting the rising temperatures after the ACR were responsible for the initial expansion. The establishment of *Nothofagus* at Lago Fox was gradual, especially during the latter stages of the ACR with only trace amounts at Pta Burslem but both began rapid expansion to open canopy forest after the ACR. The expansion of *Nothofagus* forest suggests a strengthening of the SWWs as they recommenced their poleward migration, after the relatively brief ACR reversal, with Lago Fox reaching open canopy forest by c. 12.7 kcal yr BP and Pta Burslem by 12.2 kcal yr BP. The arboreal expansion can be associated to increasing humidity as the SWWs migrate south towards the Magallanes region. The apex of arboreal cover indicates the maximum precipitation from the SWWs core was now influencing Lago Fox around c. 11.4 kcal yr BP. The concurrent arboreal expansion at Pta Burslem was more dynamic with salient spikes of growth and decline with a simultaneous but brief expansion of *Nothofagus* seen at Cta Eugenia (McCulloch et al., 2019) as it transitioned into more temperate conditions. This suggests that Isla Navarino was subjected to increasing seasonality as the SWWs migrated closer leading to wetter summers and drier winters (Fig.6.1).

In Central Patagonia the warming temperatures of the LGIT led to the poleward retreat of the Patagonian Ice Sheet formed during the LGM into the contemporary NPI and SPI. Ice was also retreating from the flanks of the Andean Cordillera as evidenced from the east in Chacabuco Valley, which became ice free by c. 16 kcal yr BP (Villa-Martinez et al 2012; Henríquez et al., 2017).

The Chacabuco records show a typical post glacial landscape of pioneer species, similar to that seen in the southern study sites, comprising dwarf shrubs and herbs but only a small assemblage of arboreal taxa. Concurrent records from Cerro Ataud show the site remained ice bound for longer possibly due to the proximal location to the NPI until sometime before c. 13 kcal yr BP. As the ice retreated from the site a rapid colonisation of *Nothofagus* followed, suggesting the existence of *Nothofagus* refugia survived in climatically constrained circumstances on the receding eastern margins of the NPI during the LGM (Markgraf et al, 1993; Mansilla et al, 2016) and is supported by genetic analysis across the entire latitudinal distribution of the *Nothofagus* species inferring a continuous presence of the taxa during the LGM (Premoli et al., 2010). The gradually rising temperatures and increasing humidity, in the well-established Late glacial would have been favourable conditions for the rapid establishment of *Nothofagus* forest in the post glacial landscape of Cerro Ataud, greatly influenced by the northerly position of the SWWs on their poleward migration in the LGIT. This spontaneous arboreal colonisation was not seen in the post glacial landscape of Lago Augusta and Lago Edita in The Chacabuco Valley (Villa-Martinez et al 2012; Henríquez et al., 2017) mainly because of the colder and less humid environment when the ice retreated around c. 16 kcal yr BP, however by 12 kcal yr BP forest expansion had begun at both of these sites suggesting a warmer pulse with increased humidity. The hastening nature of colonisation at Cerro Ataud is striking and indicates the archetype climatic conditions were ideal for arboreal expansion at that time. The ~1000 cal yr delay in forest expansion between sites could be attributed to less humid conditions along the precipitation gradient and the higher elevation in The Chacabuco Valley (~444 and 570 m) and therefore colder conditions than the lower elevation at Cerro Ataud.

In summary, the increasing temperatures of the LGIT initiated a poleward migration of the SWWs from their northerly position in the LGM. As the ice began to retreat, the landscapes of Pta Burslem and Lago Fox were so distal of the migrating SWWs they were marginally influenced by the high moisture content of their core. Effective moisture in this region probably came from an easterly airflow from the Atlantic allowing some mesophytic vegetation to survive in this mainly steppe/tundra landscape dominated by pioneer species for most of the Late glacial period. Contrastingly, Cerro Ataud remained ice-bound for longer by virtue of its proximal location to the NPI. However, when the ice finally retreated sometime before c. 13 kcal yr BP the palaeoenvironmental conditions were ideal for rapid arboreal colonisation with sufficient moisture from the SWWs for forest expansion as they passed through the region on their southward migration. The early establishment of *Nothofagus* forests at Lago Fox and Pta Burslem is driven by the increasing moisture from the core of the SWWs as they continue their poleward migration from the lower latitudes.

### Early Holocene Period (c. 11.7-8.6 kcal yr BP)

The abrupt and rapid forest expansion in the Late glacial at Cerro Ataud continued but at a slower and steadier rate in the Early Holocene, with *Nothofagus* expanding between c. 12.7-9.5 kcal yr BP, inferring sufficient moisture remained from the poleward bound SWWs to sustain this arboreal growth. This was coetaneous with a steady decline in all other taxa as the forest canopy gradually reduced the amount of available light in the understory.

The establishment of *Nothofagus* forest seen at Pta Burslem in the latter stages of the Late glacial continued to expand leading to full canopy forest cover by c.10.4 kcal yr BP, and was concurrent with the decline of all heath-grassland taxa suggesting the full focus of the precipitation from the poleward bound SWWs were now fully influencing the region. The slender temporal delay of ~1 kcal yr between sites can be attributed to the protracted poleward migration of the SWWs as the moisture laden core gradually moved south from Lago Fox to Pta Burslem.

A shift to drier conditions is inferred as the SWWs moved poleward away from Isla Dawson around c. 11.4 kcal yr BP. Arboreal cover began a simultaneous decline at Lago Fox in the absence of the high moisture content of the SWWs core, evidenced by the deterioration of pollen preservation and declining abundance of *Pediastrum*. Hydroseral succession is inferred by the replacement of lacustrine sediments with peat and the emergence of Cyperaceae as it colonised the surface of the newly formed bog.An increasing amount of charcoal within the record is also seen suggesting reduced humidity leading to increased fire activity between c. 10.5-8 kcal yr BP which is mirrored in several other sites in the region. In the northern Magallanes region (~52°S), the Ultima Esperanza area was experiencing increased fire activity and a lowering of lake levels after c. 11,600 cal a BP (Moreno et al., 2012). There is substantial forest contraction and fire activity in the central Magallanes region (~53°S) from Isla Dawson c. 11,700 cal a BP (McCulloch and Davies, 2001) and Lago Lynch c. 11,050 cal a BP (Mansilla et al., 2018). There is also significant contraction of forest cover and fire activity in the southern Magallanes region at Puerto. Harberton from c. 11 kcal yr BP (Markgraf and Huber, 2010).

As arboreal cover is contracting in the Magallanes region, the only two palaeoenvironmental records from Isla Navarino show a concurrent increase in effective moisture with expanding arboreal cover at Caleta Róbalo (54°56’ S, 67°38’ W) (Heusser, 1989) around c. 11.5 kcal yr BP and Cta Eugenia (McCulloch et al., 2019) around c. 11 kcal yr BP. This collective evidence suggests that the core of the storm fronts was acting upon Pta Burslem producing maximum precipitation while to the north it was leading to drier conditions as the SWWs continued its poleward migration and temperatures increased.

Following the apex of forest expansion at Pta Burslem around c. 10.4 kcal yr BP there began a rapid loss of *Pediastrum* at the site followed by a sustained period of forest reduction indicating the SWWs had continued to migrate poleward into the Drake Passage and away from the region depriving the area of its high levels of moisture. This is supported by deterioration of pollen preservation and increased amounts of charcoal seen in the record at this time, indicating a drier environment with increased fire activity. This vegetation response is almost identical to that of Lago Fox when the core of the SWWs migrated south from that site. The continuation of reduced arboreal cover and poor pollen preservation at Lago Fox is confirmation that the SWWs did not move north from Pta Burslem, but instead continued to migrate poleward into the Southern Ocean.

In summary, the Early Holocene palaeoenvironmental evidence from all three sites show a sustained period of forest expansion between c. 13-12.2 kcal yr BP indicating a warmer and more humid environment. As the SWWs continued to migrate poleward the northern site of Cerro Ataud was influenced by the increased moisture as the core passed through the region on its southbound journey by steady arboreal growth but was not overly affected as it continued on its meridional journey. The wet and dry signals seen in the sediment record of southern study sites are more prominent, clearly identifying the SWWs passage through Lago Fox around c. 11.5 kcal yr BP and Pta Burslem around c. 10.4 kcal yr BP and then into the Drake Passage and Southern Ocean as the changing moisture regimes produce vegetation responses of expanding and contracting arboreal cover.

### Mid Holocene Period (c. 8.6-5.9 kcal yr BP)

The decline of forest cover seen in the Pta Burslem record at the end of the Early Holocene period extended into the Mid Holocene as the shift to drier conditions continued. The progression of vegetation change showed a reduction of *Nothofagus* after c. 10.4 kcal yr BP with expanding grassland steppe inferring lower levels of effective moisture. This was supported by the deterioration of pollen preservation at Pta. Burslem indicating the persistence of aerobic conditions at the mire surface allowing desiccation of the pollen grains as they were deposited. Humidity was also lower at Cta Eugenia where pollen preservation showed a trend of deterioration until c. 8.6 kcal yr BP when rising sea levels interrupted the palaeoenvironmental record (McCulloch et al., 2019).

The warm and dry conditions of this ‘arid’ phase were augmented at Lago Fox. This was characterised by the opening up of the forest canopy, with *Nothofagus* reduced to its lowest level in the record between c.10-6 kcal yr BP coeval with a rise in grassland species such as Poaceae, Asteraceae and *Acaena*. The disappearance of *Pediastrum* implied a reduction of effective moisture and the continued deterioration in pollen preservation and humified peat in the stratigraphy signified the region was no longer influenced by the humidity of the SWWs which were continuing on their southerly migration into the Drake Passage and the Southern Ocean at this time. The declining moisture levels were concurrent with the onset of high concentrations of charcoal particles within the core, suggesting the availability of drier fuel in the landscape and greater frequency of fires (Markgraf and Huber, 2010; Mansilla *et al*., 2016). There is further evidence of a warmer climate in this phase with a contemporaneous rise in Polypodiaceae that favours a warmer climate and is not tolerant to shade so adapts well to open canopy woodland and is therefore able to flourish in this warmer phase (Schneider et al., 2010).

Meanwhile the Cerro Ataud record showed closed canopy forest was sustained in the Aysén region until a brief opening of the canopy between c. 9.3-8.1 kcal BP where *Nothofagus* showed a significant decline. The augmented light within the understory allowed the expansion of Cyperaceae and an increase in Poaceae. This period indicated a declining moisture regime in Central Patagonia, which is reflected in a modest drop in pollen preservation and suggests an association to the distal location of the SWWs on their poleward migration from the central region. Concurrent palaeoenvironmental records from Isla Navarino indicate that the apex of the SWWs poleward migration was somewhere beyond the Drake Passage and into the Southern Ocean at this time, coetaneous with the declining humidity at Cerro Ataud (McCulloch et al, 2020) suggesting the moisture associated with these polar fronts were at their most distal point from this region. Yet there appears to be a continued localised resilience in the moisture regime at Cerro Ataud with open canopy forest despite the distal location of the SWWs core, suggesting there remained sufficient moisture to maintain an open canopy forest in the absence of these storm fronts. These characteristics are also coetaneous with forest contraction north of Cerro Ataud at Mallín Pollux at 45°S (Markgraf et al., 2007) where Nothofagus declines from c. 9.3-7.9 kcal yr BP before recovering to dense forest cover by c. 7.5 kcal yr BP.

Arboreal cover shows rapid recovery at Cerro Ataud following the brief opening of the canopy with *Nothofagus* expanding to closed canopy by c. 7.5 kcal yr BP. This level of dense forest is maintained throughout the Mid Holocene period with the exclusion of most other taxa supported by a return to well preserved pollen in the record. This is coetaneous with the start of the equatorward migration of the SWWs from the Southern Ocean that would have influenced the moisture regime despite the distal location. However, during such a southerly migration of the SWWs it would be expected that Aysén would experience a significant reduction of precipitation but the apparent resilience of *Nothofagus* and continuation of well-preserved pollen might be explained through increased seasonality in the region. Drier summers but wetter winters with colder temperatures, less evapotranspiration and increased snowfall, at a higher elevation than Lago Fox and Pta Burslem, could lead to a lasting mire surface wetness that persists throughout the summer months allowing pollen to remain well preserved. This could allow *Nothofagus* to dominate the pollen signal giving an unrealistic interpretation of the landscape at that time. If this is true, then Cerro Ataud would not be considered a sensitive site to changes in climate as opposed to La Frontera towards the easternmost extremes of the precipitation gradient that show concurrent variations in arboreal coverage during the same period.

The arid conditions at Lago Fox and Pta Burslem continued with a deterioration in pollen preservation between c. 9.5 and 6.4 kcal yr BP seen at Pta Burslem. This prominent drier phase reflects the maximum phase of poleward migration of the SWWs into the Southern Ocean. This extremely positive SAM would have enhanced the ACC, increasing degassing of CO2 into the atmosphere leading to an internal feedback mechanism raising global temperatures further, augmenting SSTs in the Southern Ocean triggering a reduction of sea ice around the Antarctic Peninsula (Bentley et al., 2009; Turney et al., 2016). The culmination of the southernmost point of the SWWs poleward migration would not have been a uniform reversal to an equatorward migration. As global temperatures reached a thermal maximum around c. 8 kcal yr BP (Renssen et al., 2012), there would have been a period of instability before a cooling trend was established, producing positive and negative SAMs leading to the SWWs migrating north and south in this period. This can be seen in the palaeoenvironmental records in southern Patagonia with brief periods of arboreal expansion and improved pollen preservation within the arid phase. This is evident in the Pta Burslem record with a brief expansion of *Nothofagus* between c. 9.4-8.7 kcal yr BP, a spike at c. 8.2 kcal yr BP and another expansion between c. 8-7.8 kcal yr BP (Fig.5.3) with improved pollen preservation between c. 8.5-7.9 kcal yr BP (Fig. 5.5). At Lago Fox *Nothofagus* expansion is seen between c. 10-9.8 kcal yr BP and c. 8.8-8 kcal yr BP (Fig.4.5) with brief periods of improved pollen preservation peaking at c. 10, 9.5 and 8.8 kcal yr BP (Fig.4.7). These characteristics are also seen on Tierra del Fuego at Lago Lynch with forest expansion seen between c. 9.9-9.6 kcal yr BP and c. 8.7-8.5 kcal yr BP and improved pollen preservation between c. 9.7-9.5 kcal yr BP and c. 8.8-8.6 kcal yr BP (Mansilla et al., 2018).

After the apex of this thermal maximum around c. 8 kcal yr BP Pta Burslem once again shows expansion of Nothofagus forests and a corresponding reduction in grassland taxa suggesting an increase in effective moisture to the region again. Simultaneous improvement in pollen preservation also indicated the SWWs had reached the apex of their poleward journey in the Southern Ocean and had now, with globally cooling temperatures, embarked on an equatorward migration that was beginning to influence Isla Navarino with increased precipitation from the intensified storm fronts within their core. The arboreal recovery influenced by the returning SWWs allowed the rapid restoration of closed canopy forest in the region by c. 7 kcal yr BP and continued expansion for the remainder of the Mid Holocene and well into the Late Holocene (c. 3 kcal yr BP). A direct comparison with Cta Eugenia (McCulloch et al., 2019) is problematic as the marine incursion endured until c. 6.5 kcal yr BP however as relative sea levels lowered there appears to be period of forest contraction which is contrary to Pta Burslem and sites to the north of Canal Beagle that show expanding arboreal cover indicting more humid conditions (Markgraf and Huber, 2010; Musotto et al., 2016a; Mansilla et al., 2018). However, there is steady forest expansion between c. 5-3 kcal yr BP that suggests a temporally lagged increase in humidity at the site. Again, this temporal lag is indicative of its location in the drier part of the precipitation gradient. As Isla Navarino is exposed to the maximum precipitation from the core of the SWWs at c. 6.2 kcal yr BP, Lago Fox to the north continues to endure lower levels of effective moisture with open canopy forest and poor levels of pollen preservation.

The arid phase exhibited in the Lago Fox record is the most striking and enduring of all three study sites. It portrayed an unambiguous and more prolonged decline of arboreal cover than Pta Burslem, with *Nothofagus* reduced to ~30% at c. 9 kcal yr BP and a simultaneous rise in grassland taxa including Cyperaceae and a marked increase in Polypodiaceae. Supporting this evidence is a stark deterioration in pollen preservation with corroded and degraded pollen at their highest throughout the record and is linked with a marked rise in charcoal content within the sediment, indicating increased fire activity. This suite of evidence indicates a clear reduction of effective moisture in the region at a time when the SWWs were exerting their influence on Isla Navarino and then the ACC during their poleward migration into the Southern Ocean.

The distinct climatic signals at Lago Fox and Pta Burslem highlight the temporal disparities of the two sites, separated only by a slender latitudinal margin, and suggests the SWWs were being squeezed into a smaller latitudinal range as they migrate south and north through this southerly region with a more focused core producing higher precipitation and wind speeds (Garreaud et al., 2009; Lamy et al., 2010). This produced very distinctive changes in the vegetation response at a landscape scale leading to well-defined changes in palaeoenvironmental records to clearly identify wet and dry signals in the peat stratigraphy to track the temporal and spatial migration of the SWWs as they passed through this region. These changes are seen in other records in Isla Dawson and Tierra del Fuego (McCulloch and Davies, 2001; Mansilla, 2015; Mansilla et al., 2016, 2018) but not with such a striking disparity as between Lago Fox and Pta Burslem which is a refinement on what was previously understood in terms of the nature and the timing of these shifts in the SWW’s.

In summary, the Mid Holocene palaeoenvironmental evidence from the study sites show an unambiguous arid phase in the early part of this period with reduced arboreal coverage, increased grassland taxa and deteriorating pollen preservation. These changes were more subtle in Cerro Ataud (c.9.5-8.4 kcal yr BP) but were especially striking in Lago Fox (c. 11.4-6 kcal yr BP) and Pta Burslem (c. 10.4-7.4 kcal yr BP). The evidence shows that the migrating SWWs had a major influence on the ecology of the southern sites as they passed through on their poleward and then equatorward migration with relatively swift temporal responses to varying moisture regimes over one degree of latitude. This indicates the core of the SWWs was more focused and/or increased in intensity with maximum precipitation and wind speeds as they reached these high latitudes. As the SWWs reached the apex of their poleward migration they would have influenced the ACC and raised SST in the Southern Ocean influencing the Antarctic ice shelves around the continent. As the thermal maximum was reached the SWWs would have experienced a period of instability moving between positive and negative SAMs until a global cooling trend was established which initiated their equatorward migration.

### Late Holocene Period (c. 5.9 kcal yr BP-Present)

Following the thermal maximum and the apex of the SWWs poleward migration into the Southern Ocean, cooling temperatures reversed this migration and the core of the storm fronts started gradually migrating north and began influencing the regional climate of Isla Navarino and Isla Dawson once again. This coincided with a marked reduction of charcoal in the sediment and progressively improving pollen preservation in these regions all indicating a more humid environment. Restoration of forest cover is seen in the Pta Burslem record with the region returning to closed canopy cover by c. 6.4 kcal yr BP. In the less humid part of the precipitation gradient at Cta. Eugenia there is a temporal lag in forest expansion as the forest/steppe ecotone migrated gradually eastward, with full canopy forest cover not being achieved until c. 3 kcal yr BP following the marine incursion (McCulloch et al., 2019).

There is a short temporal lag of around ~1.1 kcal yr between Pta Burslem and Lago Fox as the SWWs slowly migrate equatorward leading to a surge of arboreal expansion at Lago Fox beginning around c. 6 kcal yr BP culminating in closed canopy forest again by c. 5 kcal yr BP. This forest restoration encounters a brief hiatus in productivity around the time of the MB2 eruption at c. 4.2 that covered the region in a thick layer of volcanic ash significantly reducing the organic content in the sediment (Fig.4.2). This allows *Empetrum* heathland to expand at the site, however by around c. 3.2 kcal yr BP *Nothofagus* had returned to pre-eruption levels of canopy cover as heathland declined, although it had gained a foothold at the site and would remain at varying levels of abundance until the present. As the region was again subjected to maximum precipitation from the core of the SWWs the forest/steppe ecotone gradually migrated north east along the precipitation gradient on Isla Dawson. Forest cover at Rio Grande and Estancia Esmeralda showed delayed recovery reaching their maximum cover by around c. 4 kcal yr BP albeit a progressively reduced cover with increased distance from Lago Fox as humidity weakened along the precipitation gradient (McCulloch and Davies, 2001; Mansilla 2015).

During this period of change in the south, Cerro Ataud is relatively stable between c. 7.6-5.2 kcal yr BP with dense closed canopy forest almost completely dominating the region to the exclusion of most other taxa. This is also echoed at Lago Augusta, Lago Edita and Mallín Pollux (Villa-Martinez et al, 2012; Henríquez et al., 2017; Markgraf et al., 2007) and to a lesser extent in La Frontera, where Nothofagus still dominated but with reduced coverage (McCulloch et al, 2016). This evidence infers that the moisture regime was sufficient for these arboreal taxa to flourish even with the core of the SWWs located so far south in the Magallanes region.

This stability continued at Cerro Ataud until around c. 5.2 kcal yr BP when a brief, but significant decline in *Nothofagus* is seen, concurrent with the largest deterioration in pollen preservation in the record and a salient rise in charcoal in the sediment. This evidence supports an ephemeral warm period that led to increased fire activity in the region that reduced the forest cover by ~10% at Cerro Ataud. This evidence is also seen at Lago Augusta and La Frontera (Villa-Martinez et al., 2012; McCulloch et al., 2016) supporting a regional warm/dry climate at this time. However, the explanation for this transient warm period is uncertain as there is no clear evidence that the SWWs deviated in their equatorward migration at this time to cause a change in climate in the Aysén region. At this time the core of the SWWs was in the Magallanes region as evidenced by the distinct wet and dry signal in the sediment records with strong and steady forest expansion seen at both the Lago Fox and Pta Burslem with no indication of a deviation in the SWWs equatorward migratory pattern.

In the Aysén region this defined wet and dry signal is not seen with only a modest drop in the forest cover seen at Cerro Ataud around c. 8kcal yr BP and a more prolong decline after c. 4 kcal yr BP. The level of arboreal resilience seems paradoxical given the distinct vegetational response seen in the Magallanes region over ~1° range of latitudinal migration of the SWWs. This would suggest that the SWWs had a minimal effect on climate in this region since the ice retreated. However, this signal is more distinct towards the drier eastern end of the precipitation gradient at the peat mire sites of La Frontera and Mallín Pollux (McCulloch et al., 2016; Markgraf et al., 2007) where vegetation is at the limit of their distribution. This is especially true in the transition zone of the forest steppe boundary where vegetation is particularly sensitive to even small variations in temperature or moisture leading to integration with neighbouring ecotone vegetation. The limiting factor of climate is more sensitive in these margins and can shift the ecotone boundaries at a landscape scale which is evidenced in these palaeoenvironmental records and infers that the SWWs did continue to influence climate in this region.

This suggests there was increased seasonality in Aysén with a persistent influence by the SWWs even during an extremely positive SAM, when a significant reduction in precipitation at Cerro Ataud would probably be expected. During contemporary annual migrations, the core of the SWWs moves north of Aysén in winter and south in summer. However, during colder global temperatures it moves further north leading to increased summer and winter wetness. In the Early/Mid Holocene, warming temperatures invoked a more southerly migration leading to only winter wetness in Aysén. During such a poleward migration, Aysén’s northerly location places it well outside the core of the SWWs but its distal influence during annual migrations could be responsible for wetter winters in the region. This would lead to less evapotranspiration in the colder temperatures and increased snowfall at higher elevations than Lago Fox and Pta Burslem, producing a lasting input of moisture that maintains Cerro Ataud through the drier summer months as a wet site with good pollen preservation. This would account for Cerro Ataud’s apparent insensitivity to climate change in the wetter end of the precipitation gradient, allowing it to be buffered against smaller changes in climate (Fig.6.1).

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| Figure 6.1. The present seasonal latitudinal variation of the SWWs  1: The latitudinal position of Cerro Ataud in summer and winter indicating the region currently has increased humidity in Austral winter with drier summers. It shows a poleward migration of the SWWs leading to extreme seasonality and an equatorward migration the region would become wetter. 2: Lago Fox. 3: Pta Burslem. Produced by reanalysis modelling using Empirical Orthogonal Function (EOF) from (adapted from Garreaud et al., 2013) |

The last ~5 kcal yr BP of the Late Holocene heralded the beginning of climatic instability seen at all study sites lasting until the present. Cerro Ataud has a punctuated and protracted decline of forest cover in the record with a deterioration of pollen preservation and a simultaneous increase in charcoal content in the sediment inferring a reduction in humidity and increased fire activity. Most of the pollen deterioration is associated with crumpled grains usually indicating damage during the transportation process, which could have occurred due to reduced vegetation cover from fire activity in hot and dry summers leading to increased surface run off during the more humid winters (Section 3.4).

This period of climate variability in the Late Holocene is most dynamic at Lago Fox where forest cover fluctuated between open and closed canopy as heathland began to dominate the site. The region was now generally cooler as evidenced by the disappearance of Polypodiaceae and was punctuated with wetter periods with the return of *Pediastrum*, suggesting pools of standing water on the bog surface and also less well humified peat in the stratigraphy indicating a more humid climate. The vegetation record at Pta Burslem and Cta Eugenia (McCulloch at al., 2019) in the Late Holocene is more stable with dense forest cover until around c. 2 kcal yr BP where *Nothofagus* is seen to significantly decline in several distinct episodes allowing *Empetrum* heathland to expand. However, the pollen preservation displays a more punctuated response to humidity with around five relatively brief periods of climate variability (Section 5.4) which are not necessarily seen in the vegetation record and could suggest a degree of resilience in the vegetation to small changes in climate change. These periods of relatively drier and warmer conditions suggest a more poleward focus of the SWWs during these brief interludes implying that the latitudinal positioning of these storm fronts was variable at this time. These variable climatic conditions are also seen in the records at Lago Fox (Section 4.6.4), Rio Grande and to a lesser extent in Estancia Esmeralda and also on Tierra del Fuego at Lago Lynch (Mansilla, 2015; McCulloch and Davies, 2001;Mansilla et al., 2018) indicating a regional pattern of climatic instability and increased seasonality. There are also variable climatic conditions inferred from the Cerro Ataud record in the north (Section 3.4) as forest cover declines along with pollen preservation, although this is mostly due to crumpled and broken grains which does not necessarily suggest drier conditions.

As the SWWs continue to get closer to Cerro Ataud, the palaeoenvironmental evidence seems paradoxical. The approaching SWWs should suggest increasing humidity in Aysén, however the declining forest cover, deteriorating pollen preservation, increased charcoal and Cyperaceae all indicate reduced effective moisture. This is also seen at Mallín Pollux but not at the two lake sites of Lago Augusta and Lago Edita, however these lake sites do not have a local pollen signal and are over-represented by *Nothofagus*, which could give an ambiguous signal. A tenuous explanation for this contradictory evidence could be the effects of cooling as global temperatures continued to fall, evidenced by the equatorward migration of the SWWs at this time (Schneider et al., 2003; Toggweiler, 2009). As temperatures continued to drop in the Late Holocene it led to re-advancement of ice caps with cold katabatic winds lowering temperatures, creating a local neoglacial effect in Aysén which could have supressed arboreal growth. These colder temperatures could also have contributed to expansion of the NPI leading to enhanced rain shadow effect, making it drier at Cerro Ataud (Glasser et al., 2004). However, this neoglacial explanation for reduced humidity cannot be conclusive from the evidence from Cerro Ataud alone and more research will be required to substantiate it.

A short period of forest decline seen at Pta Burslem with deteriorating pollen preservation at both Pta Burslem and Cta Eugenia indicate a cooling trend supported by declining temperatures seen in the JRI ice core record and SSTs after c. 1 kcal yr BP (Lamy et al., 2010; Mulvaney et al., 2012). This is broadly contemporary with the cooling phase during the Little Ice Age which would contradict the temporal leads and lags of the bi-polar seesaw but could be coincidental with the latitudinal variation of the SWWs at this time as they progressed towards their contemporary position of ~50°S.

The climatic instability seen at all three study sites and others in the literature indicate brief periods of warmer and drier conditions in the Late glacial at a time when globally cooling temperatures were driving the SWWs equatorward. These brief periods of rapid climate change are indicative of a relatively short-lived poleward focus of the SWWs during the general equatorward migration indicating that in the last c. 5 kcal yr the equatorward migration was responding to sub millennial episodes of warming climate causing increasingly irregular SAMs. The palaeoenvironmental records from the study sites suggest this pattern continued until the culmination of the SWWs migration to its current location (~50°S). It is likely that as global temperatures began to stabilise to contemporary levels in the Late Holocene, the sub-tropical and polar fronts influence on the latitudinal position of the SWWs would have diminished somewhat, moving them north and south in smaller augmentations until they settled into their contemporary position. Nevertheless, these fronts continue to act upon the SWWs as they migrate north to ~45°S in Austral winter and to ~50°S in Austral summer.

In summary, the Late Holocene palaeoenvironmental evidence shows the initial domination of *Nothofagus* forest at all three study sites. The vegetation records at Pta Burslem show arboreal stability until the last ~2 kcal yr but the pollen preservation records suggest several periods of rapid climate change. Cerro Ataud also shows arboreal stability until c. 4 kcal yr BP where it shows protracted and punctuated decline with several periods of rapid climate change implied by the pollen preservation records. The vegetation and pollen preservation records at Lago Fox are the most dynamic, indicating climate variability throughout the Late glacial. The evidence from all three study sites indicate that the SWWs were reacting to sub-millennial warming episodes that resulted in increasingly variable SAMs until the culmination of the migration to the contemporary position of ~50°S.

### The refined migration of the SWWs from LGM to present

Figure 6.2 shows the projected latitudinal migration of the core of the SWWs since the LGM to present using the palaeoenvironmental data collected from the three study sites on the latitudinal transect from ~47°S to 55°S. It uses the vegetation response to the high levels of precipitation within the core of the SWWs to determine the temporal and spatial nature of these fronts by establishing when each site was exposed to the apex of humidity. The core of the SWWs is very difficult to define in terms of latitudinal spread and figure 6.2 does not attempt to interpret this, it merely indicates the temporal status of the centre point of the core in relation to the three study sites to give an indication of their movement from the LGM to the contemporary position of ~50°S.

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| --- |
| A picture containing sitting, table, computer, blue  Description automatically generated  Figure 6.2. Migration of the SWWs *Core* from LGM to present  Interpreted from palaeoenvironmental evidence from the three study sites using data from several other sites in the published literature showing the poleward migration of the SWWs ***CORE*** from its northerly location in the LGM passing through Cerro Ataud c. 13 kcal yr BP then Lago Fox c. 11.5 kcal yr BP followed by Pta Burslem c. 10.4 kcal yr BP. It then migrated into the Southern Ocean before returning to Pta Burslem c. 6.2 kcal yr BP then Lago Fox c. 5 kcal yr BP to its contemporary position of ~50°S. The annual SAM would move these positions north and south by ~5° at each of these locations in the diagram. N.B the band widths of the core depicted in the diagram are not accurate, just a representation of the temporal positioning of the core of the SWWs. |

# Conclusion

The aim of this thesis was to build on previous research and increase our understanding of the timing and nature of earth-atmosphere changes in the southern hemisphere by providing palaeoenvironmental evidence of the vegetational response to the shifting moisture regimes and precipitation gradients created by the migrating SWWs.

The SWWs are a component of the global atmospheric system that has governed the palaeo and modern climate of Southern South America between 30°S and 60°S (Fletcher and Moreno 2011). Variations in the latitudinal position and intensity of the SWWs are key drivers of climate change in the southern hemisphere and are part of the larger bipolar seesaw mechanism of global climate change (Broecker, 1998; Toggweiler et al*.*, 2006; Wang et al., 2015; Fogwill et al., 2019). The core of the SWWs currently lies at ~50°S but seasonal shifts create varying climatic patterns with increased storm activity in southern Patagonia during a positive SAMs, with less turbulent winters as the SWWs migrate equatorward during negative SAMs (Schneider et al., 2003; Toggweiler, 2009; Lamy et al., 2010). During the LGM the core of the SWW’s moved northward by ~5°S, bringing moister and cooler conditions, which caused the expansion of glacial mass in northern Patagonia (Hulton et al., 2002). At the end of the LGM the SWWs started to return to their present position ~50°S (McCulloch et al. 2000). During the early to mid-Holocene it is hypothesised that the SWWs continued southwards into the Drake Passage and likely delivered warmer SSTs to the Antarctic Peninsula leading to the loss of ice shelves during the early Holocene (Bentley et al., 2009).

Patagonia plays a key role in southern hemisphere palaeoenvironmental research as it is the only continental landmass to intersect the entire migratory track of the SWWs and so is an important area to study past changes in their migration and how it effects the timing and nature of climatic changes during the Late glacial and Holocene. Due to the steep orographic nature of the Andean Cordillera, the SWWs are the main factor in controlling precipitation and moisture regimes of Chilean Patagonia (Quintana and Aceituno, 2012; Bertrand et al., 2014) and the vegetation response to the migrating SWWs is key to circumscribing the temporal and spatial characteristics of these storm fronts. Sediment cores from peat bogs reflect the vegetation response at a regional scale and provide an insight into vegetation history and dramatic transformation during periods of climatic change. They also reflect vegetation response at a local scale which can relate to species composition from the bog surface (Seppä, 2007).

Past migrations of the SWWs would be difficult to reconstruct using records from only one site. Therefore, three deep basin peat-sediment cores taken from an extensive latitudinal transect (~47-55°S) on the eastern flanks of the Andean Cordillera helped to circumscribe the spatial and temporal shifts in the SWWs by reconstructing the latitudinal changes from the vegetation response to these migrating fronts. The study sites at Cerro Ataud, Lago Fox and Punta Burslem (Fig.1.2) were all located at the western, and therefore more humid end of the precipitation gradient, proximal to the eastern flanks of the Andean Cordillera. The relationship between the strength and latitudinal position of the SWWs and the orographic precipitation gradient were able to be analysed by using additional study sites in the literature from the drier regions of the precipitation gradient (Figs. 1.5 and 1.6).

The contribution of this thesis was to refine the continuous temporal and spatial movements of the SWWs from the LGM to the present which culminated in the sequence shown in Figure 6.2. This sequence was derived by pollen analysis from the sediment cores from each of the three study sites and supplemented by other sites in the published literature. The high resolution and sensitivity of the three sediment cores and the strong positive correlation between the SWWs and precipitation (Garreaud et al., 2013) allowed vegetation responses to be reconstructed at each site. *Nothofagus* played a key role in this reconstruction as it has been the dominant vegetation throughout central and southern Patagonia during the Quaternary and remains a key species fundamentally linked to the moisture regimes of the region (Mansilla et al., 2016;2018). This arboreal taxon is a key marker for identifying climatic changes in Patagonia so is of particular interest when reconstructing past vegetation from the fossil pollen record. It is particularly sensitive to humidity and can flourish in climates that exhibit a precipitation range of ~400-1000 mm/yr (Quintanilla, 2005). Pollen preservation and vegetation records, especially *Nothofagus*, played a key role in determining when the full focus of precipitation from the SSWs core was influencing each site, which would establish the temporal and spatial characteristics of the SWWs migration.

The northerly location of Cerro Ataud provided an insight into the nature and timing of climate change on the periphery of the migratory track of the SWWs in central Patagonia. The vegetation response to ice-free conditions was the rapid development of *Nothofagus* forest by around c. 13 kcal yr BP which was reflected in proximal sites at Lago Augusta and Lago Edita (Villa-Martinez et al., 2012; Henríquez et al., 2017). The establishment of arboreal cover at these sites suggested a significant increase in effective moisture at this time and indicated that the core of the SWWs had migrated poleward from the CLD and was now influencing the Aysén region. Dense forest cover endured at this site with only small contractions seen in the entire record, but sensitivity to climate change was seen at other sites in central Patagonia. Prominent changes in arboreal cover were recorded at Mallín Pollux and La Frontera (Markgraf et al., 2007; McCulloch et al., 2016) on the eastern part of the precipitation gradient where vegetation was existing at the limit of their distribution and therefore were more sensitive to small changes in climate.

The palaeoenvironmental records from Lago Fox on Isla Dawson and Pta Burslem on Isla Navarino reveal a compelling interpretation of latitudinal shifts in the SWWs and reflects a convincing pattern of regional climate change during the Late glacial and Holocene in this southerly location. The transition from the colder environments of the Late glacial to the warmer and more temperate Early Holocene conditions marked the beginning of forest development at Lago Fox and reflected the increasing humidity from the SWWs on its poleward migration from the north by supplying the region with increased precipitation by c. 11.5 kcal yr BP. There is a temporal lag in the distribution of this humidity to sites on the drier part of the precipitation gradient at Rio Grande (Mansilla, 2015) and Estancia Esmeralda (McCulloch and Davies, 2001) reflected in their delayed forest development. There is a marked transformation from these humid conditions in the Early Holocene to that of the ‘arid’ environment of the Mid Holocene with a distinct reduction in pollen preservation and forest cover between c. 10.8-6 kcal yr BP indicating the SWWs had continued their poleward migration away from Lago Fox.

The development of *Nothofagus* into an established forest canopy at Pta Burslem around c. 10.4 kcal yr BP suggests increasing levels of humidity and indicates the full influence of the SWWs core was now acting upon the site at this time. Again, there is a temporal lag along the precipitation gradient on Isla Navarino with delayed forest development at Cta Róbalo (Heusser, 1998) and Cta Eugenia (McCulloch et al., 2019) due to decreasing humidity. A defined ‘arid phase’ is evidenced between c. 9.7 and c. 6.0 kcal yr BP which indicates that the SWWs migrated into the Southern Ocean for around ~3.7 kcal years in the Mid Holocene, augmenting the ACC and upwelling of CO2 into the atmosphere leading to an increased warming trend and instability of Antarctic ice-shelves (Bentley et al., 2009). The return of humid conditions after c. 6.2 kcal yr BP heralded the return of the SWWs as they began the short equatorward migration in response to cooling global temperatures. Contemporaneous aridity persisted at Lago Fox but a prominent period of forest expansion in the Late Holocene c. 5 kcal yr BP suggests that humid conditions had returned with the SWWs now migrating equatorward towards their contemporary latitudinal position, providing increased precipitation in the area as they pass over the region. There then followed a period of climatic instability at all of the study sites as the SWW’s settled into their contemporary latitudinal position of ~50°S.

While the key findings reinforce a prevailing set of ideas about the movements of the SWWs, importantly this study has identified that they remained beyond the South American continent influencing the ocean-atmosphere system of the Southern Ocean for ~ 3000 years. This is a significant consideration for future global warming scenarios.

# Future research

This thesis has refined and enhanced our knowledge of the temporal and spatial characteristics of the SWWs latitudinal migration during the Late glacial and Holocene. However, it has also uncovered some exciting and potentially important questions that would merit further research in the future.

The reduction in humidity between c. 9.5 and 6.4 cal yr BP at Pta Burslem indicates the continued poleward migration of the SWWs into the Drake Passage and Southern Ocean for ~ 3000 years. This extremely positive SAM would have augmented the ACC and increased CO2 degassing into the atmosphere, and led to warmer global temperatures (Turney et al., 2016) causing a subsequent rise in SSTs in the Southern Ocean leading to a reduction of sea ice around the Antarctic Peninsula (Bentley et al., 2009). The broader environmental impacts of this augmented positive SAM in the mid-Holocene ‘arid’ phase could correspond to a contemporary scenario of increasingly positive SAM which may have possible future global warming scenarios for climate modelling in southern South America and therefore should be the focus of further research (Marshal, 2003; Moreno et al., 2014). The extent of the poleward migration could be investigated in more detail by new palaeoenvironmental evidence from further south than Isla Navarino.

The climatic explanation of Cerro Ataud in the last c. 4 kcal yr could be enhanced by future research. This is a complex story that requires more than one site to reveal the sequence of events that lead to contracting arboreal cover and deteriorating pollen preservation when there should be increased humidity as the SWWs get closer to this region. The neo-glacial aspect makes sense but is tenuous and requires further substantiation.

This thesis has refined the temporal and spatial characteristics of the SWWs migration from the LGM to present, however additional palaeoenvironmental evidence along the latitudinal range of these storm fronts would help to support this work and enhance it further.

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# Appendix A: Geochemical composition of tephra layers

Cerro Ataud: Volcán Hudson (H1991)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Tephra | SiO2 | Na2O | MgO | Al2O3 | K2O | CaO | FeO | P2O5 | TiO2 | MnO | Total |
| 1 | 65.3268 | 5.9154 | 1.3123 | 15.8956 | 2.8256 | 2.7663 | 4.9432 | 0.3182 | 1.1332 | 0.1831 | 100.6199 |
| 2 | 64.5844 | 5.519 | 1.5008 | 16.2106 | 2.7016 | 3.2419 | 4.8799 | 0.3838 | 1.2381 | 0.1839 | 100.444 |
| 3 | 64.506 | 5.8424 | 1.5024 | 16.3256 | 2.6128 | 2.9722 | 4.9836 | 0.3711 | 1.2138 | 0.1874 | 100.5173 |
| 4 | 64.3923 | 5.9736 | 1.5267 | 15.7836 | 2.6738 | 3.1534 | 4.8861 | 0.3764 | 1.2029 | 0.1795 | 100.1484 |
| 5 | 64.2665 | 6.1989 | 1.5354 | 15.865 | 2.6249 | 3.1164 | 5.1838 | 0.3738 | 1.223 | 0.1772 | 100.5649 |
| 6 | 64.1079 | 5.8887 | 1.4738 | 15.7049 | 2.6528 | 2.9626 | 4.8952 | 0.3604 | 1.2003 | 0.1718 | 99.4185 |
| 7 | 63.9782 | 5.9491 | 1.5346 | 16.0647 | 2.6538 | 3.1044 | 5.023 | 0.3836 | 1.2047 | 0.1941 | 100.0903 |
| 8 | 63.9776 | 5.6467 | 1.458 | 16.3584 | 2.5764 | 3.2087 | 5.0964 | 0.3697 | 1.2446 | 0.1883 | 100.1247 |
| 9 | 63.8683 | 5.8144 | 1.5067 | 15.8073 | 2.8185 | 2.9995 | 5.0716 | 0.4158 | 1.2564 | 0.1683 | 99.7268 |
| 10 | 63.7598 | 5.7679 | 1.4457 | 16.1337 | 2.6813 | 3.1069 | 5.0976 | 0.3632 | 1.2323 | 0.2044 | 99.7928 |
| 11 | 63.7538 | 6.0128 | 1.5153 | 15.8908 | 2.7541 | 3.0379 | 4.9688 | 0.3718 | 1.2008 | 0.1825 | 99.6886 |
| 12 | 63.6789 | 5.7347 | 1.5377 | 15.7889 | 2.7111 | 3.213 | 5.0326 | 0.3673 | 1.2282 | 0.1757 | 99.468 |
| 13 | 63.6259 | 5.9065 | 1.5391 | 15.8906 | 2.7038 | 3.0424 | 5.0741 | 0.3763 | 1.2125 | 0.1892 | 99.5604 |
| 14 | 63.231 | 5.9209 | 1.5296 | 15.7847 | 2.6597 | 3.2205 | 5.2283 | 0.3968 | 1.2264 | 0.1958 | 99.3938 |
| 15 | 63.1604 | 6.1105 | 1.5643 | 16.084 | 2.4657 | 3.2517 | 5.2763 | 0.3965 | 1.2343 | 0.198 | 99.7416 |
| 16 | 63.0804 | 6.0638 | 1.5482 | 15.4739 | 2.4297 | 3.0626 | 4.8945 | 0.3733 | 1.2319 | 0.178 | 98.3362 |

Cerro Ataud: Volcán Hudson (H1971)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Tephra | SiO2 | Na2O | MgO | Al2O3 | K2O | CaO | FeO | P2O5 | TiO2 | MnO | Total |
| 1 | 67.9743 | 5.7619 | 0.7716 | 15.5271 | 3.3302 | 1.7462 | 3.3572 | 0.1341 | 0.6811 | 0.1396 | 99.4233 |
| 2 | 67.9412 | 5.6542 | 0.8491 | 15.1954 | 3.4319 | 1.9772 | 3.3314 | 0.1802 | 0.8572 | 0.1329 | 99.5507 |
| 3 | 67.7205 | 5.6829 | 0.7173 | 15.5516 | 3.6129 | 2.0468 | 3.3471 | 0.1522 | 0.6787 | 0.1323 | 99.6424 |
| 4 | 67.5178 | 6.0387 | 0.8515 | 15.1435 | 3.4828 | 1.868 | 3.5632 | 0.1971 | 0.875 | 0.1263 | 99.6639 |
| 5 | 66.6456 | 5.8584 | 0.7668 | 15.5667 | 3.5559 | 2.0348 | 4.1527 | 0.2026 | 0.775 | 0.1194 | 99.6777 |
| 6 | 65.1734 | 5.7451 | 1.1731 | 15.1147 | 3.0251 | 2.4738 | 4.5529 | 0.3048 | 1.0935 | 0.1461 | 98.8026 |
| 7 | 65.0573 | 5.7564 | 1.4731 | 15.8584 | 2.912 | 2.9584 | 4.9704 | 0.402 | 1.3085 | 0.1485 | 100.8451 |
| 8 | 64.1118 | 5.1252 | 1.3459 | 15.5623 | 4.0492 | 2.8412 | 4.762 | 0.2882 | 0.9365 | 0.1601 | 99.1825 |
| 9 | 64.0942 | 5.6317 | 1.4463 | 16.0021 | 2.6763 | 3.0182 | 4.4977 | 0.3659 | 1.0941 | 0.1707 | 98.9972 |
| 10 | 63.4908 | 6.0222 | 1.3858 | 14.9831 | 2.8582 | 2.8922 | 4.5586 | 0.3477 | 1.1871 | 0.1559 | 97.8816 |
| 11 | 61.8441 | 5.0197 | 2.1399 | 14.7481 | 2.5093 | 3.9215 | 6.2443 | 0.55 | 1.4847 | 0.1781 | 98.6397 |

Cerro Ataud: Volcán Mentolat

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Tephra | SiO2 | Na2O | MgO | Al2O3 | K2O | CaO | FeO | P2O5 | TiO2 | MnO | Total |
| 1 | 75.4725 | 3.5654 | 0.351 | 12.9174 | 1.4276 | 1.7404 | 1.6111 | 0.0453 | 0.3075 | 0.1106 | 97.5487 |
| 2 | 74.9925 | 4.9897 | 0.4119 | 13.4849 | 1.496 | 1.9108 | 1.8728 | 0.0502 | 0.3166 | 0.0938 | 99.6191 |
| 3 | 74.9456 | 5.0686 | 0.4006 | 12.6684 | 1.4324 | 1.8133 | 1.589 | 0.0453 | 0.3117 | 0.1014 | 98.3762 |
| 4 | 74.863 | 5.0966 | 0.4645 | 13.1279 | 1.4875 | 1.8245 | 1.7565 | 0.0392 | 0.3157 | 0.1014 | 99.0769 |
| 5 | 74.7662 | 4.8786 | 0.3612 | 13.2444 | 1.3777 | 1.9033 | 1.7069 | 0.0429 | 0.3105 | 0.1004 | 98.6922 |
| 6 | 74.3844 | 4.9367 | 0.371 | 12.9596 | 1.5104 | 1.7072 | 1.6296 | 0.029 | 0.2826 | 0.0959 | 97.9065 |
| 7 | 74.1778 | 5.1025 | 0.397 | 12.9012 | 1.4143 | 1.8767 | 1.7119 | 0.0432 | 0.3082 | 0.0981 | 98.0309 |
| 8 | 73.9407 | 5.0756 | 0.3862 | 12.9538 | 1.5109 | 1.7149 | 1.7802 | 0.0394 | 0.3033 | 0.1036 | 97.8086 |
| 9 | 73.7371 | 4.8811 | 0.242 | 12.3558 | 1.4127 | 1.4891 | 1.7934 | 0.0437 | 0.3087 | 0.0881 | 96.3516 |
| 10 | 73.5181 | 5.0722 | 0.3887 | 12.7081 | 1.4557 | 1.7459 | 1.7934 | 0.0406 | 0.3086 | 0.0957 | 97.1269 |
| 11 | 72.3779 | 4.9405 | 0.4228 | 12.7108 | 1.5068 | 1.8282 | 1.6106 | 0.074 | 0.3019 | 0.0811 | 95.8546 |

Cerro Ataud: Volcán Hudson (H1)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Tephra | SiO2 | Na2O | MgO | Al2O3 | K2O | CaO | FeO | P2O5 | TiO2 | MnO | Total |
| 1 | 66.8886 | 5.8771 | 1.0292 | 15.4342 | 3.1702 | 2.3358 | 3.9324 | 0.2792 | 1.147 | 0.1353 | 100.229 |
| 2 | 65.8909 | 5.9583 | 1.1244 | 15.4049 | 2.9845 | 2.4346 | 4.379 | 0.2804 | 1.1028 | 0.143 | 99.7029 |
| 3 | 65.8216 | 6.0402 | 1.2734 | 14.924 | 2.9255 | 2.6231 | 4.4883 | 0.2929 | 1.1477 | 0.1514 | 99.6881 |
| 4 | 65.3764 | 6.0441 | 1.1902 | 15.4226 | 2.9842 | 2.631 | 4.3147 | 0.2859 | 1.1515 | 0.1521 | 99.5529 |
| 5 | 65.376 | 5.5785 | 1.2635 | 15.4972 | 3.0224 | 2.8188 | 4.5741 | 0.3439 | 1.2328 | 0.1407 | 99.8478 |
| 6 | 64.946 | 5.8935 | 1.6823 | 15.5175 | 2.8842 | 3.2667 | 4.8299 | 0.3423 | 1.2357 | 0.1512 | 100.7492 |
| 7 | 64.7052 | 5.7754 | 1.1913 | 14.8434 | 2.9755 | 2.4655 | 4.4016 | 0.2945 | 1.1179 | 0.1451 | 97.9156 |
| 8 | 64.6154 | 5.4743 | 1.3904 | 15.4188 | 2.8774 | 2.8851 | 5.0121 | 0.3431 | 1.1908 | 0.1651 | 99.3727 |
| 9 | 64.4391 | 5.9667 | 1.5 | 15.7072 | 2.87 | 2.8689 | 4.7206 | 0.3334 | 1.2096 | 0.1451 | 99.7605 |
| 10 | 64.2096 | 5.7998 | 1.3242 | 15.3149 | 2.8778 | 2.7063 | 4.7363 | 0.3634 | 1.1987 | 0.1507 | 98.6817 |
| 11 | 64.1591 | 5.5986 | 1.5711 | 15.4241 | 2.7445 | 3.4013 | 5.5195 | 0.4102 | 1.3256 | 0.1591 | 100.313 |
| 12 | 63.962 | 5.4651 | 1.2096 | 14.6096 | 2.9971 | 2.553 | 4.6062 | 0.2719 | 1.0679 | 0.1573 | 96.8998 |
| 13 | 63.8476 | 6.01 | 1.5655 | 15.8718 | 2.8085 | 3.1397 | 4.9697 | 0.3912 | 1.3382 | 0.1515 | 100.0937 |
| 14 | 63.7305 | 5.6707 | 1.5373 | 15.5063 | 2.65 | 3.3672 | 5.3442 | 0.4052 | 1.3476 | 0.167 | 99.7258 |
| 15 | 63.6888 | 5.5191 | 1.5772 | 15.5094 | 2.7094 | 3.1809 | 5.0622 | 0.3497 | 1.2597 | 0.1627 | 99.0191 |
| 16 | 63.6777 | 6.0532 | 1.4055 | 15.3037 | 2.7746 | 3.0321 | 4.9439 | 0.3607 | 1.2361 | 0.147 | 98.9344 |
| 17 | 63.5381 | 6.1113 | 1.5437 | 15.5914 | 2.6964 | 3.5081 | 4.8689 | 0.3782 | 1.2712 | 0.1755 | 99.6828 |
| 18 | 63.5185 | 6.2157 | 1.5027 | 15.3027 | 2.7576 | 3.0563 | 5.082 | 0.4142 | 1.321 | 0.1587 | 99.3292 |
| 19 | 62.8762 | 5.3156 | 2.02 | 15.1695 | 2.5815 | 4.0613 | 5.5843 | 0.3369 | 1.2535 | 0.1372 | 99.336 |

Lago Fox: Mount Burney (MB2)

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Tephra | SiO2 | Na2O | MgO | Al2O3 | K2O | CaO | FeO | P2O5 | TiO2 | MnO | Total |
| 1 | 77.802 | 4.259 | 0.245 | 12.059 | 1.756 | 1.507 | 1.191 | 0.026 | 0.198 | 0.028 | 99.071 |
| 2 | 77.756 | 4.578 | 0.277 | 12.119 | 1.713 | 1.522 | 1.171 | 0.033 | 0.213 | 0.039 | 99.421 |
| 3 | 77.474 | 4.533 | 0.322 | 12.825 | 1.769 | 1.591 | 1.340 | 0.034 | 0.211 | 0.038 | 100.135 |
| 4 | 77.394 | 4.468 | 0.272 | 12.048 | 1.749 | 1.518 | 1.178 | 0.032 | 0.209 | 0.032 | 98.898 |
| 5 | 77.198 | 4.421 | 0.273 | 12.323 | 1.668 | 1.648 | 1.196 | 0.028 | 0.200 | 0.039 | 98.995 |
| 6 | 76.798 | 4.331 | 0.278 | 12.214 | 1.599 | 1.440 | 1.144 | 0.030 | 0.201 | 0.034 | 98.068 |
| 7 | 76.793 | 4.581 | 0.302 | 12.452 | 1.708 | 1.757 | 1.440 | 0.035 | 0.234 | 0.032 | 99.335 |
| 8 | 76.333 | 4.381 | 0.269 | 11.696 | 1.771 | 1.465 | 1.230 | 0.028 | 0.187 | 0.046 | 97.406 |
| 9 | 75.967 | 4.325 | 0.271 | 12.171 | 1.658 | 1.504 | 1.185 | 0.017 | 0.200 | 0.038 | 97.336 |
| 10 | 75.787 | 4.136 | 0.279 | 11.951 | 1.625 | 1.544 | 1.258 | 0.034 | 0.211 | 0.033 | 96.857 |

Lago Fox: Volcán Hudson (H1)

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Tephra | SiO2 | Na2O | MgO | Al2O3 | K2O | CaO | FeO | P2O5 | TiO2 | MnO | Total |
| 1 | 65.147 | 5.801 | 1.390 | 15.172 | 2.898 | 2.964 | 4.940 | 0.316 | 1.144 | 0.155 | 99.926 |
| 2 | 64.835 | 6.274 | 1.216 | 15.075 | 2.949 | 2.954 | 4.599 | 0.278 | 1.141 | 0.161 | 99.480 |
| 3 | 64.716 | 5.911 | 1.389 | 15.404 | 2.854 | 3.088 | 5.033 | 0.311 | 1.199 | 0.159 | 100.065 |
| 4 | 64.648 | 5.531 | 1.583 | 15.350 | 2.925 | 3.183 | 5.008 | 0.335 | 1.224 | 0.157 | 99.942 |
| 5 | 64.076 | 5.679 | 1.401 | 15.928 | 2.774 | 3.178 | 4.947 | 0.354 | 1.237 | 0.164 | 99.736 |
| 6 | 64.067 | 5.783 | 1.526 | 15.445 | 2.843 | 3.091 | 4.877 | 0.390 | 1.325 | 0.163 | 99.508 |
| 7 | 64.065 | 5.537 | 1.587 | 15.272 | 2.908 | 3.088 | 4.959 | 0.406 | 1.338 | 0.163 | 99.321 |
| 8 | 64.015 | 5.860 | 1.389 | 15.036 | 2.657 | 2.945 | 4.725 | 0.358 | 1.239 | 0.154 | 98.378 |
| 9 | 63.494 | 5.854 | 1.614 | 15.197 | 2.681 | 3.244 | 5.132 | 0.398 | 1.319 | 0.174 | 99.106 |
| 10 | 63.022 | 5.575 | 1.683 | 15.352 | 2.791 | 3.074 | 5.133 | 0.346 | 1.178 | 0.175 | 98.328 |

Lago Fox: Volcán Reclús (R1)

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Tephra | SiO2 | Na2O | MgO | Al2O3 | K2O | CaO | FeO | P2O5 | TiO2 | MnO | Total |
| 1 | 77.657 | 4.104 | 0.194 | 12.669 | 2.743 | 1.485 | 1.310 | 0.033 | 0.104 | 0.042 | 100.339 |
| 2 | 76.683 | 4.325 | 0.213 | 12.501 | 2.455 | 1.501 | 1.167 | 0.022 | 0.111 | 0.039 | 99.017 |
| 3 | 76.219 | 3.905 | 0.246 | 12.489 | 2.476 | 1.531 | 1.188 | 0.028 | 0.109 | 0.038 | 98.229 |
| 4 | 76.046 | 3.859 | 0.190 | 12.125 | 2.753 | 1.346 | 1.104 | 0.027 | 0.100 | 0.034 | 97.582 |
| 5 | 75.933 | 3.905 | 0.226 | 12.394 | 2.551 | 1.436 | 0.981 | 0.028 | 0.099 | 0.031 | 97.584 |
| 6 | 75.786 | 3.880 | 0.240 | 12.106 | 2.518 | 1.466 | 1.094 | 0.032 | 0.112 | 0.037 | 97.270 |
| 7 | 75.313 | 3.927 | 0.175 | 12.377 | 2.542 | 1.530 | 1.109 | 0.025 | 0.112 | 0.051 | 97.161 |
| 8 | 75.229 | 4.135 | 0.246 | 12.325 | 2.475 | 1.807 | 1.485 | 0.035 | 0.182 | 0.034 | 97.952 |
| 9 | 74.908 | 3.773 | 0.181 | 12.050 | 2.433 | 1.519 | 1.148 | 0.027 | 0.121 | 0.047 | 96.206 |
| 10 | 74.558 | 3.652 | 0.207 | 12.323 | 2.549 | 1.529 | 1.311 | 0.027 | 0.106 | 0.043 | 96.303 |

Punta Burslem: Volcán Hudson (H1)

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Tephra | SiO2 | Na2O | MgO | Al2O3 | K2O | CaO | FeO | P2O5 | TiO2 | MnO | Total |
| 1 | 65.860 | 6.031 | 1.176 | 15.687 | 2.855 | 2.611 | 4.509 | 0.298 | 1.197 | 0.158 | 100.384 |
| 2 | 65.615 | 6.239 | 1.156 | 15.563 | 3.080 | 2.482 | 4.156 | 0.270 | 1.110 | 0.153 | 99.822 |
| 3 | 65.582 | 5.622 | 1.435 | 15.762 | 2.841 | 2.908 | 4.913 | 0.421 | 1.324 | 0.172 | 100.979 |
| 4 | 65.143 | 5.601 | 1.429 | 15.400 | 2.744 | 3.009 | 4.999 | 0.298 | 1.182 | 0.175 | 99.979 |
| 5 | 65.124 | 5.658 | 1.409 | 15.525 | 2.855 | 3.102 | 5.069 | 0.420 | 1.340 | 0.175 | 100.678 |
| 6 | 64.823 | 5.496 | 1.460 | 15.888 | 2.866 | 2.892 | 4.754 | 0.309 | 1.209 | 0.176 | 99.873 |
| 7 | 64.819 | 5.794 | 1.389 | 16.025 | 2.918 | 3.093 | 5.218 | 0.331 | 1.232 | 0.168 | 100.987 |
| 8 | 64.339 | 5.671 | 1.848 | 15.125 | 2.688 | 3.044 | 5.213 | 0.388 | 1.333 | 0.172 | 99.822 |
| 9 | 64.152 | 5.931 | 1.440 | 15.924 | 2.899 | 3.038 | 4.681 | 0.363 | 1.241 | 0.156 | 99.825 |
| 10 | 64.110 | 5.731 | 1.575 | 14.985 | 2.833 | 2.757 | 4.772 | 0.393 | 1.238 | 0.174 | 98.566 |
| 11 | 63.365 | 5.864 | 1.528 | 15.884 | 2.634 | 3.160 | 5.119 | 0.358 | 1.286 | 0.176 | 99.373 |

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# Appendix B: Full percentage pollen and spore diagrams

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| A picture containing rack  Description automatically generated  Cerro Ataud full percentage pollen and spore diagram |

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| A picture containing object, rack  Description automatically generated  Lago Fox full percentage pollen and spore diagram |

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| --- |
| A picture containing antenna, object, rack  Description automatically generated  Punta Burslem full percentage pollen and spore diagram |

# Appendix C: Punta Burslem Publication

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| A screenshot of a social media post  Description automatically generated |

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| A close up of a map  Description automatically generated |

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| A picture containing text, newspaper  Description automatically generated |

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| A close up of a map  Description automatically generated |

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| A close up of text on a white background  Description automatically generated |

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| A screenshot of a cell phone  Description automatically generated |

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| A screenshot of a cell phone  Description automatically generated |

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| A picture containing text, newspaper  Description automatically generated |

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| A close up of text on a white background  Description automatically generated |

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| A screenshot of a cell phone  Description automatically generated |

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| A close up of a newspaper  Description automatically generated |

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| A picture containing text, newspaper  Description automatically generated |

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| A close up of a newspaper  Description automatically generated |

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| A close up of text on a white background  Description automatically generated |

# Appendix D: Alternative Core Sites

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| A close up of a map  Description automatically generated  Main study sites |

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| A picture containing photo, person, covered, sitting  Description automatically generated  A: Rio Lincol was unlikely to contain Late glacial stratigraphy. |

|  |
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| A close up of a mountain  Description automatically generated  B: Lago Fox I did not have a visual Reclús tephra layer. |

A picture containing cake, sitting, person, large

Description automatically generated

C: Pantalon yielded a basal age of 9,800 ± 30 14C yrs BP so would not have met the Late glacial – Holocene criteria for the project. Cerro Bandera was not dated but much of the core was unconsolidated with gloopy sphagnum which would have been impossible to analyse.